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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Sensor Handbook for Automatic Test, Monitoring, Diagnostic, and Control Systems Applications to Military Vehicles and Machinery

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Sensor Handbook for Automatic Test, Monitoring, Diagnostic, and Control Systems Applications to Military Vehicles and Machinery

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Abstract

The Sensor Handbook is intended as a guide for those who design, specify, use, and test military automatic test equipment containing sensors. The handbook addresses measurands and principles of measurement, data acquisition, sensor calibration and testing, environmental considerations, stability, durability, reliability, and error assessment. Sensor manufacturers and sensor calibration and evaluation resources are included, as is an annotated bibliography. The handbook is based largely on the present, proved state-of-the-art. Possible future trends are briefly discussed. The handbook is addressed to the general engineer, system designer, or manager with an engineering background. It does not provide the highly detailed technical information needed by the measurement engineer, although ample references are included for further study.

Key words: automatic test equipment; ATE; calibration; data acquisition; durability; dynamic calibration; environmental testing; evaluation; measurand; reliability; sensor; transducer

FOREWORD

The increasing complexity and cost of weapons and other military systems and the need for greater operational readiness in a world of rapidly changing events, combined with decreases in skilled personnel, dictate the integration of automatic testing into those systems. Following the recommendations of industry/joint-services groups, a Joint Logistics Commanders Panel on Automatic Testing (JLC-AT) was chartered in early 1978. The Panel prepared a study plan defining tasks in all areas of automatic testing [3]. The tasks are divided into three major areas: management, acquisition support, and testing technology, with these objectives:

a. Optimize definition, application, and support of automatic testing hardware and software in the system acquisition management process;

b. Develop systems engineering and logistics tools to enhance the application of automatic testing to the design and support of weapons systems; and

c. Coordinate R&D planning and execution in testing technology and associated software to minimize duplication of effort and achieve common testing technology objectives.

All subtasks needed to make these objectives are described in detail in the "Subtask Descriptions" (Joint Logistics Commanders Panel on Automatic Testing, September 30, 1980). Tasks under the second objective will provide the tools necessary to integrate Automatic Test Equipment (ATE) electronics into military and weapons system acquisition. The tools will include standards, specifications, and guides for controlling the interfaces between automatic test hardware and the systems to be tested. Sensors not only represent a critically important type of interface in these systems, they may be part of the unit-under-test itself.

Task 20600 (Acquisition support-hardware interface) has two subtasks with these objectives:

Subtask 20601: To develop specifications for on-line and off-line ATE interfaces.

Subtask 20602: To develop a Sensor Handbook, including state-of-the-art techniques and devices for electronic and non-electronic testing.

There is a critical need to provide information on the selection, application, testing, and use of sensors as part of ATE systems. This led to an assignment to the NBS staff who had conducted the NBS program on transducers, "InterAgency Transducer Project," to develop a Sensor Handbook to meet the objectives of Subtask 20602. The material which follows comprises the Sensor Handbook (Subtask 20602) as prepared by staff of the National Bureau of Standards at the request, and with the support, of DARCOM-U.S. Army.

The NSIA ATE project "Non-Electronic Testing Task Group" has recommended that this document be revised periodically to keep the information current.

Comments and suggestions on the handbook should be addressed to the author, Electrosystems Division, Center for Electronics and Electrical Engineering, National Bureau of Standards, Washington, DC 20234.

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1. INTRODUCTION

1.1 Purpose and Scope of Sensor Handbook

The Sensor Handbook is intended primarily as a guide and reference for systems engineers who design, specify, procure, review, and manage Automatic Test Equipment (ATE) systems. The book will address such areas as measurands and principles of measurement, ancillary equipment, sensor calibration and testing, error assessment, list sensor-related standards documents, and contain a bibliography and a listing of sensor manufacturers.

The handbook is not intended for measurements engineers and specialists; it is specifically addressed to the general engineer or manager with an engineering background. It will try to provide that type of material which will give reasonable assurance of proper sensor selection, application, and use in military ATE systems. This book will also attempt to point out possible unsuspected pitfalls and problem areas in the use of the sensors. A minimum amount of mathematics and graphics will be used; additional information can be gained from the references cited. It is the author's hope that this book will provide a realistic assessment of the role and characteristics of sensors as critical components of ATE systems.

To achieve optimum continuing usefulness, it is planned to update the handbook periodically. Corrections, comments, and suggestions are welcomed and will be incorporated whenever, in the judgment of sponsors and author, they will tend to enhance the usefulness of the book.

1.2 Contents

The focus of this handbook is on the sensors in their role as interfaces for military ATE systems. As such, the performance of the sensors, to a major extent, determines the performance of the ATE system itself. By extension, the performance of the sensors also has a major bearing on the performance of the military system which is monitored by the ATE system. When they are allowed to be the weakest links in the entire chain, sensors critically influence major military systems and the fulfillment of their missions.

The handbook will attempt to address those sensor considerations which are most likely to influence their selection and use in the ATE systems themselves or in the validation and troubleshooting of ATE. The information in this handbook is also applicable to machinery and process control equipment containing sensors.

In addition to some general coverage of Automatic Test Equipment and sensor selection, major sections will deal with the measurands most likely to be encountered by military ATE systems; these include pressure, motion, flow, temperature, force and torque, level, and humidity. The sections will deal with units, ranges, and principles of measurement in some detail, as well as other factors which must be considered when selecting sensors. Also included are tables listing advantages and disadvantages of the sensing principles discussed. In addition, a sampling of the characteristics of typical commercial sensors is presented in tabular form in an appendix. The sensor output, an electrical signal, generally needs to be conditioned prior to its input to the main part of the (usually minicomputer-controlled) ATE system. A section of the book deals with data acquisition and conditioning systems.

In view of the importance of the knowledge of the performance characteristics of sensors, considerable emphasis will be placed on the factors bearing on this. Sensor calibration and testing, including static and dynamic calibration, operating environments, stability, durability, and reliability will be addressed in some detail. The assessment of sensor errors completes this approach which can help select the proper sensor, calibrate and test it realistically, and obtain a measure of the quality of its performance.

To further aid in the process, the handbook contains sections which list pertinent sensor standards documents and sensor resources. The latter includes a listing of sensor laboratories located in government and private industry, as well as a listing of manufacturers of sensors. Finally, for those who desire additional, more detailed theoretical and practical information, an annotated bibliography of sensor-related publications is added, as well as an extensive list of references.

To keep the size of the handbook reasonable, most treatments are kept as concise as practicable by avoiding unnecessary duplication of existing and otherwise readily available information.

The major thrust of this handbook is to cope with the fact that sensors are not the simple, stable devices they appear to be, and are not necessarily easy to select and use in complex systems and military environments. Careful and realistic considerations of measurands, operating environments, ATE system requirements, calibration needs, and desired durability are absolutely essential to achieve ATE mission goals. The handbook attempts to provide the information needed to assure this achievement.

The reader might well bear in mind the old quotation which states "for the want of a nail.... etc.!"

2. AUTOMATIC TEST EQUIPMENT AND SENSORS

As the number of components in a system increases, reliability tends to decrease. Hence increasingly complex electronic systems with many circuit elements, including large-scale integrated microcircuits, make it increasingly difficult to assure continuing proper functioning of all system elements. The incorporation of microcomputers and microprocessors, of increasing complexity themselves, in these systems, however, made possible greater levels of self-testing of the electronic system or its components. This was the genesis of ATE.

The field of ATE encompasses a broad spectrum of scientific/engineering disciplines and hardware/software technologies. ATE systems generally consist of a digital computer with its attendant software operating system, application programs and peripheral storage, and input/output (I/O) equipment, programmable stimulus and measurement instrumentation, and a network of sophisticated interfacing, switching, signal-conditioning, and routing interconnections. Essential to the operation and functions of any ATE system is the reliable performance of a variety of active and passive electrical/electronic modules, devices, and components.

Considerable efforts are expended on the design and development of automatic test equipment for electronic systems. The initial approach was the addition of automatic test functions to existing, or about-to-be-developed, equipment. Subsequently, the ATE functions were incorporated into the original design of the equipment. The success of the ATE concept has made possible tremendous advances in the capabilities and functions of electronic equipment (for communication, measurement, and control) while assuring continuing reliability of operation.

The military has long had an interest in the strategic importance of ATE. The increased electronic complexity of prime weapons systems requires better and more automatic means of testing the operational readiness of avionics, missiles, tanks, and shipboard electronic assemblies. A high turnover of personnel and a more limited training budget have compounded the military's test and support problems. To make matters worse, ATE bought by the services lacks the standard packaging and modularity (hardware and software) requisite for logistic support economics.

Automatic testing of <u>non-electronic</u> systems, such as machinery-monitoring instrumentation, is a logical extension of the state-of-the-art ATE for electronic systems. Military hardware, such as ordnance, automotive vehicles, ships, aircraft, and missiles, requires large amounts of spare parts and efficient repair of defective components. Maintenance time and costs naturally increase with the size and complexity of the equipment involved. A major contributor is the high cost of staffing, combined with difficulties of acquiring and retaining the skilled personnel needed. Automation provides the opportunity of reducing maintenance time and costs.

Ultimately, automation will control much, if not most, military machinery. To achieve this, it will be necessary to develop machinery performance monitoring systems to provide information on operation status as well as maintenance requirements. In the case of naval vessels, machinery performance monitoring will make it possible to attain the benefits of ship automation, reduction of human operations, and improved continuity of operation. The same considerations apply to military land vehicles, aircraft, missiles, and other weapons systems.

The performance monitoring of large, basically mechanical systems with the use of ATE requires the use of sensors (often called transducers) as the interfaces between the system to be monitored and the electronic ATE. A variety of performance monitoring and failure prediction approaches exists. They are based on the sensing of certain parameters, and a comparison between the measured values and those thought to establish limits of acceptable performance, whether singly or in combination. Any operating component has a mechanical, electromagnetic, or chemical "signature." Any change in this signature may indicate incipient failure before any other external indications exist. Physical parameters sensed include: vibration and motion, pressure, temperature, flow, force, torque, strain, etc. Thermal signals, chemical signatures, and electromagnetic signals are also used. Many approaches are under investigation.

A fundamental consideration for the ATE system and its interfaces, such as sensors, is that the ATE system must itself perform properly, otherwise, its output is worthless. Purely electronic systems are achieving a very high degree of reliability and predictability of operation. With the extension of ATE applications to non-electronic systems, the role of the necessary sensor interface between the system to be tested and the electronic ATE becomes critically important. Figure 1 shows a generalized concept of the sensor-ATE system matrix and the factors which influence sensor selection and operation. These sensors which provide an electrical output signal in response to a physical (or chemical) input are potentially the weakest link in the measurement chain essential to the proper functioning of the entire ATE system. This is often due to inherent limits in the performance of the sensors and/or because of limited knowledge concerning their performance. Two factors may exist: a lack of information by the sensor designer of the sensor performance needed by the user, and/or a lack of adequate information on sensor performance to guide system designers. Information on sensor performance in adverse environments, over long periods of operating time and to measure rapidly varying quantities, is not readily available. Users frequently have been forced to devise and carry out laboratory tests of their own to supplement the often meager information supplied by manufacturers, or to check the manufacturer's claim on performance. Methods and equipment for such tests, particularly for determining performance under dynamic conditions, have not always been available. Existing test methods may not be standardized adequately, leading to different results when used in different laboratories. Sensor test method development and standardization has been scattered among government agencies and private industry and the information on them is hard to uncover. To the author's knowledge, only one comprehensive, long-term program on transducers (sensors) was carried on: the "InterAgency Transducer Project" at the National Bureau of Standards from 1951 to 1979. Its major objectives were: investigating the performance characteristics of transducers required for making meaningful measurements of physical quantities, and the development of techniques and apparatus for the determination of those characteristics [1].[1]

The purpose of this handbook then is to present, in one volume, pertinent information on sensors and their performance. This information is aimed at sensors used in, or in conjunction with, automatic test equipment of military systems. However, much of the information is also pertinent to other sensor application, including machinery monitoring and process control.

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[1] Numbers in brackets refer to the literature references listed in section 9.

SENSOR - ATE SYSTEM MATRIX
FOR
SENSOR SELECTION

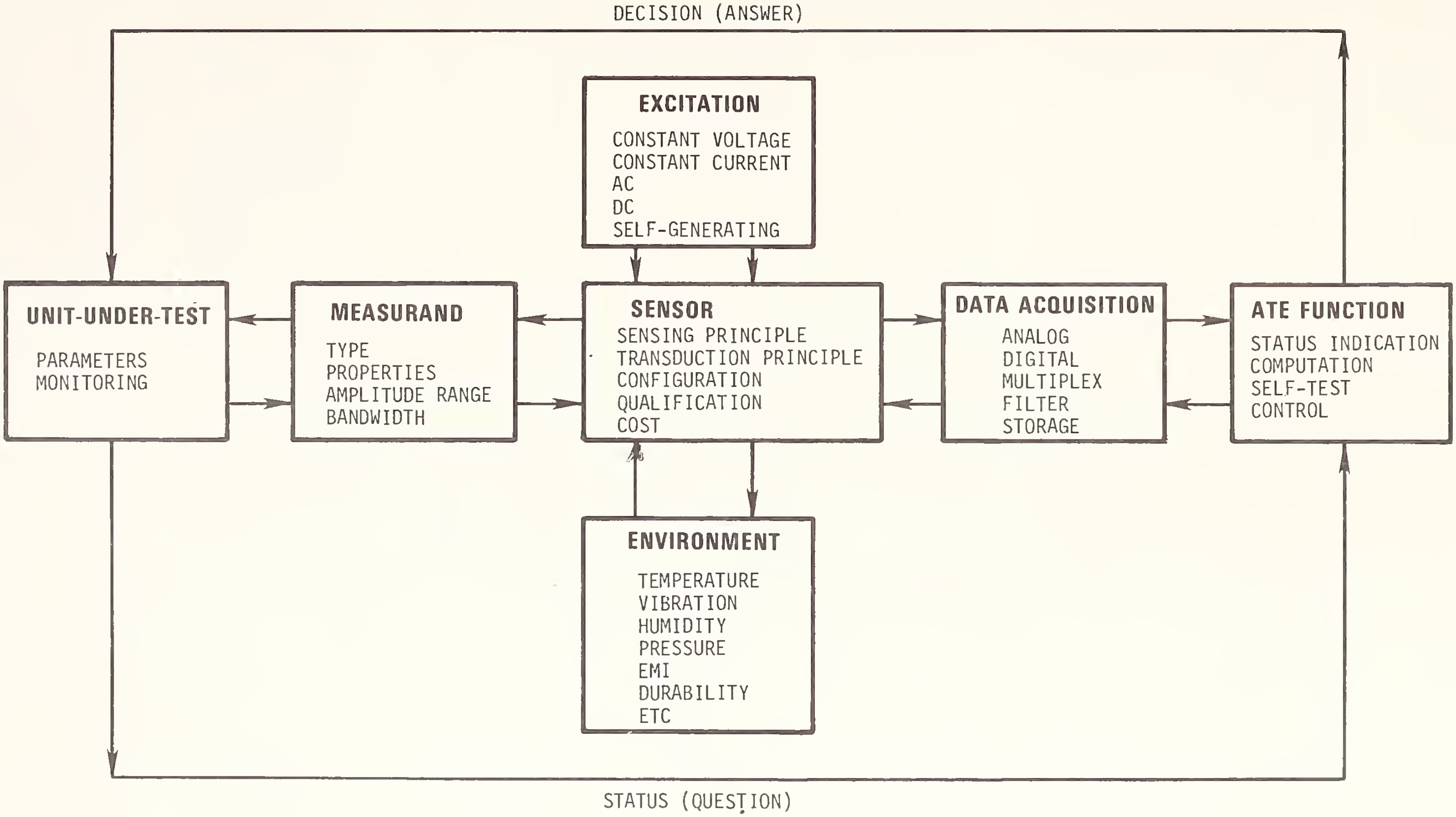

Figure 1 SENSOR-ATE SYSTEM MATRIX

3. SENSORS

3.1 Introduction

A sensor is a device that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, or motion) and transmits a resulting signal (for measurement or control). The term "sensor" is a general term commonly used to mean one, or some combination of, sensing element and transduction element. The term "transducer" is often used interchangeably with "sensor" (although it has a more specialized meaning in fields such as acoustics and electrical machinery: a device which converts energy from one form to another). In the field of measurements, a transducer can be defined as a device which converts information from one form to another, a generalization which includes the above definition of sensor. The term "transmitter" is frequently used to describe the sensor or transducer which is used in process control applications.

In this handbook, the term "sensor" will be used and its meaning will be restricted to devices which transmit a signal in the form of an electrical quantity, either by means of a change in a passive parameter like resistance, inductance, or capacitance or by the generation of an active output like voltage, current, or charge.

As indicated above, the sensor consists of two parts: the sensing element, which responds directly to the physical stimulus (measurand), and the transduction element, which converts the sensing element response to the electrical signal suitable for transmission and/or measurement. It should be noted that sometimes the two parts are combined and are not separable: a thermocouple which converts temperature differences directly to voltage is one example. See figure 2 for a schematic of a sensor.

The terminology used and most definitions in this handbook are based on a very comprehensive ANSI standard, originally developed by the Instrument Society of America: ANSI/ISA S37.1 "Electrical Transducer Nomenclature and Terminology" [2]. A selection of sensor terms is contained in the glossary, section 10. It should be noted that it is always better to give detailed descriptions rather than to rely on imperfect (or imperfectly understood) definitions.

The most common sensing elements for the measurement of physical quantities convert these measurands into mechanical force, or by use of an intermediate elastic element into mechanical displacement. The latter, in turn, acts on the transduction element to produce the electrical signal. Exceptions are thermocouples or resistance temperature sensors, radiation detectors, certain types of flowmeters, humidity and conductivity sensors, sensors of chemical composition, and a few others.

Sensors are usually analog devices, i.e., the electrical output is a continuous function of the measurand input. Certain quasi-digital devices exist in which the output is a frequency which is a function of the measurand. Since frequency is the measure of the input, by stipulating a time interval during which the frequency is measured, the output is "digitized." An example of a fully digital output is provided by an optically encoded shaft position sensor which produces an unambiguous digital code for any angle of rotation.

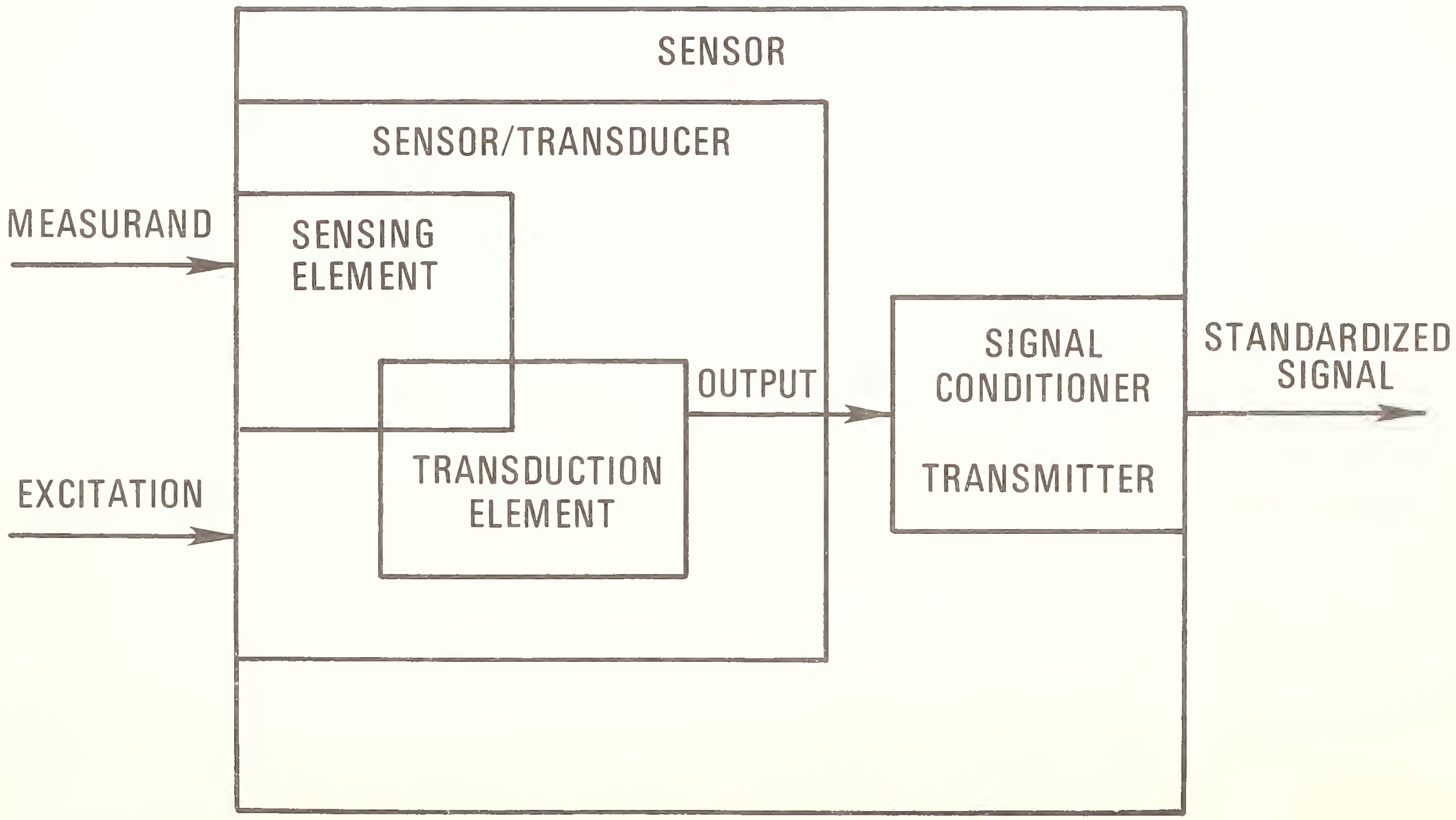

Figure 2 SCHEMATIC OF A SENSOR

It is also possible to convert the electrical analog output of a sensor to digital form by means of an electrical analog-to-digital (a-d) converter.

The "performance characteristics" of a sensor contain the information needed to assess the quality of the measurements made by the sensor. Later sections will describe in detail methods for establishing these characteristics. Sensor manufacturers generally supply performance information but this information may not be complete or up-to-date. It is highly desirable, and recommended, to be able to independently establish these characteristics upon acceptance or during later re-calibrations. It is particularly important to retest the sensor periodically, preferably as a part of the ATE system, to be assured of continuing quality of performance. The concept of "end-to-end" calibration requires a known, actual, or simulated measurand input to the sensor and a measurement of the system output. Repeating this at prescribed re-calibration intervals is an important "self test" feature of operational ATE systems. This will be discussed later.

A number of factors need to be considered in the selection of sensors to meet the requirements of a particular system. These factors are discussed briefly in the following parts of this section. Factors of particular importance are covered in greater detail in separate sections of this handbook.

3.2 Sensor Selection Factors

The selection of sensors requires the consideration and weighing of a variety of factors. External system constraints may make it impossible to select a sensor which is optimum for all factors. It is highly likely that compromises will be needed. Here are some of the items of importance:

The measurand which is to be sensed, the quality which is required of the measurements, and the particular type of sensor (principle of sensing) constitute major factors. These are discussed in detail in other sections of this handbook (section 4, Measurands and Principles of Measurements, and section 6, Sensor Calibration).

Selecting the right sensor to obtain data from a measurement requires an understanding of sensor performance characteristics and a clear idea of the effects which occur within the measurand before, during, and after the measurement. Successful specification of sensors may not require a comprehensive investigation of the measurement problems, but certainly the user will want to guard against pitfalls and surprises. In the case of ATE systems, the requirements posed by the rest of the system are of great importance to insure the compatibility needed for reliable functioning of the entire system. Excitation supplies, physical location, data format requirements, and accessibility of sensors must be considered.

Measurement objectives often dictate "impossible" locations for the placement of sensors. Available sensor size and operating environments are major considerations. Selection of a sensor which can be placed within minimum space envelopes may lead to performance compromises. Success in using sensors with limited accuracy for such installations requires the test engineer to fully understand the selected sensor's characteristics within the operating environment. Data analysis, with allowances for individual sensor performance as installed and used, can provide adequate information from sensors which could not otherwise be used for the measurement. The subject of "accuracy" is not only important but so frequently misunderstood that it deserves discussion in a section of its own: section 3.3.

Pressure sensors must be placed very close to the pressure sensing point to obtain wide band dynamic data. Vibration sensor mass may affect the vibration characteristics of the object under investigation. Regardless of sensor size, proper sensor installation is often the key to making accurate measurements.

Attention must be paid to installation torque or force and mounting position. Most sensors exhibit some sensitivity to deformation or torque on the exterior case. Often, zero shifts in the electrical output result from torque applied to pressure fittings or bolting fixtures. Recommended installation torque requirements should be obtained from the manufacturer. Zero shifts should be checked in a post-installation calibration.

Temperature also may cause subsequent tension or compression within an installation, resulting in output shifts beyond those anticipated in manufacturers' temperature error specifications. Temperature effects due to sensor installation can be reduced by selecting materials of similar coefficients of expansion and by allowing for physical dimension changes of the attachments.

Some sensors exhibit different performance characteristics with respect to gravity or acceleration in various positions. Mounting position information is usually included in manufacturers' specifications.

Operating and storage environments can have very large effects on sensor performance and are treated in more detail later. Here are some things to consider: Operating temperatures may be more restrictive than storage or nonoperating temperatures. Materials used in sensors may show temperature hysteresis which can influence measurement accuracies. The shutdown of equipment being tested may produce high "temperature soak" conditions which result in sensor calibration shifts.

Thermal lag between the test media and sensing elements has been worked out successfully for many applications. For example, baffles and multipath pressure ports with high thermal conductivity materials are used for hot gas pressure measurements. Water-cooled jackets are successfully employed in high temperature environments for both transient and steady temperature problems.

Transient temperature changes may cause errors quite different from manufacturers' specified temperature errors. The specified temperature errors usually are based on testing sensors within ovens which stabilize sensors at a given temperature before determining temperature effects on the output. When a transient temperature problem is known to exist, transducer case designs often are altered to accommodate the situation.

Vibration and shock during measurements will add uncertainty to the data. Persistence of such environments in excess of manufacturers' specifications may lead to sensor damage and ultimate failure. Shock mounting may provide protection against shock but may, in turn, cause other problems like thermal lag. Other environmental factors include humidity, electromagnetic and nuclear radiation. The subjects of environments and durability are treated in greater detail later on. Corrosion and erosion are factors which can greatly affect sensor durability. The compatibility of the sensor materials with the measurand and with the operating environment must be considered carefully. Section 3.4 will address this in more detail.

The characteristics of the electrical output of the sensor must also be considered with care. High level versus low level sensor output signals must be considered for many measurement installations. Local noise, cable length effects, and grounding considerations for power supplies, sensors, signal conditioning amplifiers, and record/display devices have been treated in the literature in some detail [9].

While detailed recommendations in all these areas are beyond the scope of this endeavor, certain basic choices in proper selection of a sensor are offered. In the case of strain gage sensors, full-scale outputs may range from 0-20 mV to 0-5 V, depending on the type of sensing element employed. Integral amplifiers are used to obtain outputs of 0-1 V or greater. Sensors for process control applications, commonly called transmitters, usually provide full-scale output signals of 4-20 mA in two-wire systems.

With the good, stable amplifiers available today, there is little significant difference in use of sensor output levels over the range of 0-20 mV to 0-100 mV. System compatibility with existing equipment may or may not be a consideration. Selection of a sensor with an integral amplifier to provide a high level output is generally made because of either severe operating noise or limited installation space available for amplifiers. Knowledge of electrical noise at the sensor location is important, since signals from a low level sensor operating at the low end of its range may be masked by electrical interference. One must remember, however, that integral semiconductor electronics may be more sensitive to harsh environments than the sensor itself.

Another factor, often overlooked, involves handling and mounting. From the time a sensor is disconnected after a test at the maker's plant until data is taken during an actual test by the customer, careless handling and lack of protection against environmental exposure may have changed some sensor characteristics. Proper practices in handling and packing of sensors for shipment must be used.

Different levels of protection against handling shock, vibration, and temperature are required for various sensor types. Engineering and test personnel installing and using the sensor must fully understand the sensors and their limitations. Installation of a sensor can be relatively simple, yet care in handling is required to ensure that the expected performance accuracy is achieved.

Cost is a factor, different in kind from the other factors discussed in this section, but of sufficient importance to be treated in section 3.4 in detail. In summary, the selection of a sensor for a particular function in a particular ATE system requires the weighing of many factors. The most important of these are discussed in this handbook. User experience, an intangible, may be more important than any other factor, but no handbook can provide this!

3.3 Sensor "Accuracy"

It seems logical that sensor accuracy should be one of the primary factors governing sensor selection. Yet the concept of accuracy is frequently misunderstood, often misapplied, and never simple. It deserves discussion.

"Accuracy" basically means the degree with which a measured quantity approaches the "true" value (which may be defined by a "national standard"). Since the "true" value is unknowable, accuracy is often taken as a measure of the deviation of measured values from the calibration values as referred to (or "traceable" to) national standards. Purists prefer the term "uncertainty," since it involves no direct reference to "true" values, but is an estimate of the error bounds of the measured quantity.

Nevertheless, "accuracy" is loosely used to try to convey an idea of quality in a quantitative manner. One major cause of confusion is the fact that a device like a sensor cannot really be "accurate." "Accuracy" in its proper interpretation can only apply to the act of measurement. This immediately shows that such "accuracy" (uncertainty is really a better term to use so as to eliminate confusion) is a function of many factors. These include the characteristics of the sensor, the signal conditioning system, environmental factors, the type of measurement process (steady-state or dynamic), and others.

Error assessment of a measurement system is a lengthy, complicated process, detailed in section 7 of this handbook. It is, however, the essential and only way to establish the quality and validity of the measurements. Many factors need to be considered and the basic laboratory performance of the sensor is only one. Laboratory performance, usually based on one or more static calibrations, is the basis of a manufacturer's claim of specified "accuracy" for the sensor.

A sensor with less deviation from linearity, smaller hysteresis, and better repeatability, in theory, can produce better measurements. However, it must be emphasized that those values are usually based on careful static calibrations at laboratory ambient conditions. Those values alone are not sufficient to indicate actual measurement quality in a real-world situation. Hence sensor "accuracy" is a misleading term and subsequent tables showing comparisons of sensing and transduction principles and systems do not specifically indicate "accuracy."

A major factor bearing on "accuracy" is the proper selection of the range of the sensor. Almost all uncertainty figures for sensors or systems from manufacturers or users are referred to the "Full-Scale Range" (FSR) or "Full-Scale Output" (FSO). This means that such figures apply only when the sensor measures measurand amplitudes at, or very close to, full-scale values. What one is really interested in, however, is the actual uncertainty of a reading anywhere within the sensor's range. If the sensor system has, for example, an uncertainty of ±1 percent of full-scale range, but senses a measurand value of 10 percent of full scale, the uncertainty of that particular measurement is ±10 percent of the actual reading.

Thus, to achieve optimum quality of measurement, the sensor's range must be selected to just slightly exceed the maximum expected values of the measurand. Improper range selection or incomplete knowledge of anticipated measurand values can seriously degrade the quality of the measurements. Continuing "accuracy" of measurement is another factor often taken for granted. As the sensor system is used, subjected to measurand variations and varied environmental conditions, its performance will change. This is covered in detail under "Stability and Durability" in section 6.4. It can be stated briefly that sensor performance generally deteriorates with time, increasing the uncertainty of the measurements.

The best way to be assured of continuing adequate measurement performance is by the use of periodic, in-place, sensor-system re-calibrations. Self-calibrating sensors would be highly desirable, but none appears to be commercially available now. Other ways must be found to assess, at regular intervals, the quality of the measurements. Section 6.4 has more details on field calibrations. This is another area where considerable research and development efforts appear desirable.

The reader should develop an appreciation for the many factors which need consideration to assure good measurements with sensors. The reader is urged to study section 7 carefully to become familiar with the essentials of error analysis.

3.4 Sensor Cost Considerations

Finally, there are cost considerations, although, generally speaking, the cost of the measurement is far greater than the cost of the individual sensor. If one tries to evaluate the effect, or cost, of an incorrect measurement on the Unit-Under-Test (UUT), the sensor cost may not be significant. However, costs need to be considered, at least initially, and in conjunction with costs of auxiliary equipment (signal conditioners, power supplies) which a particular sensor type may require.

Sensor performance specifications include a margin for yield which often influences the price. There are variables in materials which go undetected until late in the manufacturing or test sequences. Tight control on processes and close inspection of materials used cannot eliminate all variations in performance characteristics. The cumulative effects may cancel and result in sensors with outstanding performance; at other times, performance may be below permitted specifications. This "good," "better," "best" yield deserves to be recognized and large volume manufacturers can price performance accordingly.

A review of the manufacturing processes and material costs for each of the various sensor principles establishes many common costs. Although sensor designs and materials vary greatly, the labor to assemble and range an instrument involves much of the same effort.

Factory calibration against a known measurand and temperature testing takes about the same length of time, regardless of the method of transduction. Temperature compensation is accomplished by environmental testing, the addition of components, and retest. Tight specifications are met by repeated adjustment and verification of performance. Such practices cost nearly the same regardless of the type of sensing element employed. Therefore, selection of a sensor by preference of sensor type, in general, cannot be made on price alone.

It cannot be emphasized too strongly that the initial cost of the sensor itself may only be a small part of the cost of the entire installation-calibration-measurement-decision continuum; "life-cycle costs" must also be taken into account. While sensor cost is a selection factor, in the author's opinion, it should not be allowed to adversely affect quality of measurements.

3.5 Sensor Materials Compatibility

The compatibility of the sensor materials with the measurand and with the operating environment has a great effect on the durability of the sensor. Measurands like fluid pressure and flow may cause corrosion and erosion of sensor materials in contact with the measurand. This, in turn, may lead to changes in sensor performance and the reduction of sensor life.

The sensor design engineer may have only a limited selection of materials available if the sensor has to have certain performance characteristics. Temperature coefficients must be carefully matched for minimum temperature effects and for good mechanical repeatability and hysteresis. Sensing elements must be made from metals which exhibit very stable characteristics and long life.

The user must also determine media effects in the selection of a sensor. An investigation into the materials exposed to the measurand and ambient environment exposure of the external sensor case may be needed. Materials used in the construction of sensors are usually listed in the literature or such information is available from the manufacturer. For example, pressure sensors may be made from one or more of the materials listed below.

- Sensing elements may use various types of stainless steels, copper, and nickel alloys. Those may be generic types with published characteristics or proprietary ones. In the latter case, it may be more difficult to learn their limitations.

- Sensor cases may be made from a wide variety of steels, aluminum alloys, or even plastics.

- Sensor gaskets and seals may be metallic or nonmetallic ranging from copper, aluminum, and stainless steels through rubber compounds to a large variety of polymers.

- Transduction elements and integral amplifiers may be affected by corrosive elements in the environment, even if those components are not in contact with the measurand.

The ambient environment may affect other exposed portions of the sensor. Adhesives, lead-tin solder, and various potting compounds are employed to assemble electrical connectors and wires into cables. Wire insulation compatibility must also be considered.

Corrosion of materials in contact with the media and the external environment is a concern. The effects go beyond cosmetics. Corrosion of the pressure-sensing diaphragm will cause calibration shifts and changes in sensitivity. Structural strength of both the diaphragm and sensor case, including pressure fittings, can be affected.

Unfortunately, materials suitable for good sensor performance characteristics are not the most compatible with some media. Careful selection of sensor materials satisfies many installation requirements.

Isolation of the sensing elements is practical in many applications and is often done by using oil or water in the case of liquid media. Vacuum filling of the pressure cavity and plumbing is often employed to insure that no air is trapped which can cause an apparent reduction in frequency response of the measurements.

Even with considerable care, such isolation practices are limited in application, owing to the effects of gas diffusion or level change and temperature effects for liquid isolators. Media isolation using bellows or a diaphragm between the corrosive media and a liquid-filled sensor is successfully employed by some manufacturers. Even high-line low-differential pressure measurements are possible.

A major problem with pressure isolation systems is their ability to accommodate all expansion and contraction as temperature changes. The nonlinearity and hysteresis of media isolators under such conditions also may add error to the measurement.

Another problem posed by media isolators, including particle screen and diaphragm coatings, is the resultant reduction of quality of dynamic measurements. The latter must be assessed experimentally to assure that system requirements can still be met.

Sensor manufacturers offer configurations for differential pressure measurement which differ in their ability to accept conductive or corrosive media. A fully isolated sensor is often described as acceptable for wet-wet service. A differential sensor which exposes the sensing element's electrical circuits to the media on one side of the differential pressure is often described as acceptable only for wet-dry service. The user must protect this second pressure port connection so that no conductive or corrosive media reaches the sensor interior [3].

Quite similar considerations apply to temperature sensors like thermocouples. This is particularly true of measurements in hot gases, which may have oxidizing or reducing effects on the sensor materials. This may result in incorrect measurements and lead to complete deterioration of the sensor itself.

Flowmeters may show corrosion and erosion if used in streams of corrosive or particulate-laden fluids. If the flow measurement depends on the stability of dimensions of an orifice, measurement errors may increase with time.

3.6 Future Trends in Sensors

Sensor technology developed rather slowly during the 1940's and 1950's until it was spurred on by space age requirements in the 1960's. At that time, semiconductor technology began the development of silicon sensors fabricated using integrated-circuit batch-processing, high volume methods. Taken with advances in large-scale integration (LSI) fabrication techniques, the development held the promise that a family of sensors for a variety of parameters could be fabricated in silicon at extremely low cost. Some of the devices fabricated include: temperature sensors, Hall-effect devices, differential and absolute pressure sensors, thermal conductivity sensors, specific gas detectors, and others. The automotive industry, with its need for inexpensive engine control systems, is playing a leading role in this area as outlined in an excellent paper, "Sensor Development in the Microcomputer Age" [4]. In the automotive field, cost considerations are a prime concern, with durability and reliability of somewhat less importance. Thus other sensing approaches have not been discarded if they are cost effective. A major disadvantage of silicon sensors is that they operate only between -100 °C and 200 °C. Fabrication problems exist as well: aluminum wire bonding is not always suitable for rugged environments; methods must be developed for protecting sensors in applications where the chip must be "naked," as in measuring gas flow; and the integration of sensors and signal processing circuits on the same chip may lead to undesirable feedback effects [5].

Silicon is known to be a highly effective material for transducing many physical effects, including light levels, force, and temperature. The use of microcomputers has changed the emphasis in sensor design away from requirements for sensor output to be a simple function of the measurand. This, in the past, has required a linear output and minimum sensitivity to environments such as temperature. With the advent of the microcomputer, the emphasis has shifted to predictability and stability. Nonlinearity and sensitivity to other variables can be corrected by the processor, as long as the secondary variables can be independently measured. Thus one can expect the development of sensing systems incorporating single or multiple groups containing several sensors and the associated signal processing and correcting circuitry. Sensors are being designed from the start to work with microcomputers to achieve the best in overall system performance. Two-way communication between the sensor and the microcomputer will offer the possibilities of remote testing, auto calibration, and multiparameter measurements [4,5].

Thus it is likely that the future trend in sensor development will be toward "smart" sensors with integral signal processing. The two references cited, [4] and [5], give a very comprehensive overview of this field.

Two points must be emphasized, however. One, the developments cited can be described as "near future"; i.e., current efforts which should lead to viable, commercially available devices in the "near" future. They are not available now, certainly not in quantity, to the ATE system designer. Two, there is almost no information given in either survey on the performance of these devices. There is no mention of tests or test methods required to establish their performance characteristics.

Great caution must be used when incorporating new and promising developments into military systems. There is no doubt that new systems (including ATE) are apt to be more reliable if they retain those components of old systems which have proved reliable in the past. Newness is no guarantee of durability or reliability!

4. MEASURANDS AND PRINCIPLES OF MEASUREMENTS

4.1 General Considerations

Previous sections have shown the importance of good sensor performance on the proper functioning of measurement systems in general, and ATE systems in particular. Section 3 discusses the subject of sensors, in general, and outlines some of the factors which should influence sensor selection. Those factors can, then, have considerable influence on sensor performance.

The sensor selection process is, of necessity, an iterative one if one expects optimum system performance, and should take into account the factors outlined above which are detailed in this handbook.

The primary selection (and classification factor) is the measurand. This section of the handbook presents a discussion of sensors arranged by measurands. It should be noted that in the selection of sensors for a specific measurand, two important factors must be considered: the effect of the measurand on the sensor and the effect of the sensor on the measurand.

For example, in the case of a pressure measurement, it is important to know whether the pressure is that of a liquid or gaseous medium, as well as the exact nature of the medium. Certain media are corrosive and incompatible with the materials of certain sensors; others may be abrasive. A pressure sensor designed for gaseous media may have totally different dynamic characteristics when used with a liquid medium. If it is an active sensor and dissipates heat, its long-term stability may be different with different media.

Temperature sensors will have different time constants when used with different media. Temperature sensors may also conduct heat away from the medium, thus producing erroneous readings. Flowmeters may reduce pressure and flow in a system because they introduce obstructions to the flow. There are many other situations in which it is important to consider carefully the mutual effects of measurand and sensor in the selection process. It is generally true that the introduction of any sensor into any system will disturb the system and produce uncertainties in the data. It is equally true that any measurand will ultimately have a degrading effect on the sensor. It is almost always possible, however, with knowledge and judgment, to select a sensor which can approach the optimum desired for a given system.

4.2 Specific Measurands

Sensor principles and considerations appear in the sections below arranged by measurand. The order is based on the author's experience and indicates his assessment of the relative importance of the measurands listed. In a number of cases, the same transduction principle may be used for a variety of measurands; such principles will be covered in detail only once, and then referenced.

4.2.1 Pressure

4.2.1.1 Introduction

A large fraction of all mechanical measurements is concerned with pressure, particularly in propulsion systems, process control systems, and ordnance systems. Pressure is the actual quantity required in many instances; however, in other cases the desired parameter is inferred from pressure measurements. Thus flow may be measured in terms of the differential pressure across a deliberate flow obstruction or in terms of the force exerted against a deflection plate.

As indicated before, the concept of pressure as measurand refers to a fluid medium (pressure in a solid medium as a measurand is commonly referred to as "force" or "stress"). Fluid media can be either liquid or gaseous (a mixture of the two can usually be classified, for pressure measurements, as either of the above depending on the location of the sensing end of the sensor). The selection of pressure sensors is influenced by the type of medium, primarily in regard to compatibility of materials and dynamic characteristics of the sensor. Much of the material in the following sections has been excerpted, with permission of the CEC Division of Bell and Howell, from their "Pressure Transducer Handbook" [3].

4.2.1.2 Pressure References

All pressure measurements are made with reference to a specified datum pressure and the range of the sensor (and the pressure units used) is normally expressed to reflect this.

There are four possible cases:

ABSOLUTE PRESSURE. The reference is to a vacuum. Typically, the interior of the sensor case is evacuated and sealed. Some absolute transducers are referenced to a sealed bellows or capsule, the exterior of which is acted upon by the active measurand.

GAGE PRESSURE. The reference is to ambient atmospheric pressure. The sensor uses essentially the same configuration as an absolute pressure sensor with the case vented to atmosphere rather than evacuated.

SEALED GAGE PRESSURE. Sealed reference pressure is offered in sensor designs to prevent ambient media from entering the sensor case. Usually these instruments are of such range that atmospheric pressure change does not affect the measurement. This configuration is usually built with a partial atmosphere of helium or nitrogen sealed within the instrument, following practices applied to absolute pressure sensor construction.

DIFFERENTIAL PRESSURE. Two pressure ports are incorporated in this design to permit application of pressure to both sides of the pressure sensing element. This permits measurement of small pressure differences even at high line pressures with accuracies superior to those obtainable by measuring each pressure independently.

Ranges for differential pressure measurement include bidirectional and unidirectional pressure sensing capability. A bidirectional or plus/minus pressure measuring sensor offers additional flexibility for monitoring pressure changes in which prior identification of the higher of the two pressures is unknown or changing. The bidirectional pressure sensor is offered in two basic configurations depending on the application. Based on which of the pressure ports is to be exposed to the liquid medium, the sensor may be classed as wet-dry and wet-wet media acceptance. The considerations in regard to corrosive pressure media were discussed above in section 3.5.

4.2.1.3 Units of Pressure

In technological applications, the units of pressure customarily used are different for different portions of the pressure domain. Absolute pressures less than atmospheric may be expressed in millimeters of mercury, or torr, or inches of water, or pounds per square inch absolute, or dynes per square centimeters. Pressures above atmospheric are commonly expressed as pounds per square inch (absolute, gage, or differential, as outlined in section 4.2.1.2) or pascals, bars or atmospheres, and torr.

Despite efforts at unification and standardization, it is likely that this profusion of pressure units will continue. The Eleventh General Conference on Weights and Measures (CGPM) in 1960 formally promulgated a rationalized selection of units from the metric system known as the International System of Units, abbreviated "SI," based on the four MKSA units (meter-kilogram-second-ampere) plus the kelvin as the unit of temperature and the candela as the unit of luminous intensity. This system includes a unit of force (the newton) which was introduced in place of the kilogram-force to indicate by its name that it is a unit of force and not of mass. The preferred metric SI unit of pressure is the pascal (newton per square meter).

A brief table of conversion factors appears below, extracted from ANSI Standards Z210.1 "Standards for Metric Practices" [6]. The current edition of this document should always be consulted prior to any conversion calculations requiring great accuracy.

1 pound per square inch (psi) = 6894.76 pascals (Pa)
1 kilo pascal (kPa) = 0.145048 pounds per square inch
1 millimeter of mercury (mm Hg)(0°C) = 133.322 Pa
1 bar = 100 kPa
1 inch of water (in H_2O)(39.2°F) = 249.082 Pa
1 atmosphere (Standard) = 101.325 kPa
1 torr (mm Hg) (°0C) = 133.322 Pa

4.2.1.4 Pressure Ranges

Practical pressure measurements cover approximately 18 orders of magnitude. For example, measurements of pressure may be higher than 10^6 pounds per square inch (about 10^8 millimeters of mercury) in studies of the properties of materials and geology. Vacuum metallurgy, on the other hand, may involve measurements as low as 10^{-10} millimeters of mercury. This vast domain of pressures can be divided into two major sectors, vacuum and pressure. For most practical applications, the sectors can be further subdivided into convenient classes as follows:

Pressure

A) 0 to 100 psi
B) 100 to 1000 psi
C) 1000 to 10 000 psi
D) >10 000 psi

Vacuum

E) $<10^{-6}$ mmHg
F) 10^{-3} to 10^{-6} mmHg
G) 10^{-1} to 10^{-3} mmHg

4.2.1.5 Pressure Sensing Technologies

Pressure measuring systems probably vary over a greater range of complexity than any other type of measuring system, extending from simple manometers to the very complex systems used in vacuum measurements. The majority of pressure measuring instruments with electrical output, however, are devices operating on the principle that the deflection or deformation of a sensing element may be used as a measure of pressure.

Major types of elastic sensing elements are: diaphragms, Bourdon tubes, capsules, and bellows. One or more of these are useful over most of the pressure ranges cited, as well as for low vacuum. In order to produce an electrical output, the elastic element must act in conjunction with electrical transduction elements, which will exhibit a change in some electrical parameter in response to the deflection or deformation of the elastic element. Sometimes the two functions are combined as in the piezoelectric pressure sensor.

Commonly used electrical transduction elements include metallic and semiconductor strain gages, potentiometers, piezoelectric elements, variable capacitance and variable inductance devices, and differential transformers. A few transducers employ more esoteric principles: vibrating wire, magnetostriction, ionization, photoelectricity, and electrokinetic potential. Devices employing these principles are generally used only in highly specialized applications and may not be suitable for ATE systems.

For the measurement of high pressure, above 10^5 psi, the mechanical element may be dispensed with and the pressure applied directly to a resistance wire. The wire will undergo an elastic size change and a corresponding change in resistivity and will produce a measurable resistance change in response to the change in hydrostatic pressure. Manganin wire is frequently used for this purpose, as is an alloy of gold and chromium. Similarly, dynamic pressures may be sensed by the direct application of the pressure to a hydrostatically sensitive material like lithium sulfate or barium titanate. Such materials generate an electrical charge in response to a change in pressure.

Very low pressure (vacuum) may be measured by systems which infer the pressure from the density and other characteristics of the gases present. The temperature of a heated wire depends on the power supplied to it and the amount of heat lost through radiation and conduction of the medium surrounding it. The conduction heat loss is a function of the density of the gas and its composition. At a known temperature, the density of the gas is a measure of its pressure. The temperature of the wire may be determined by means of an attached thermocouple or inferred from its resistance, as in a "Pirani" gage. Such thermal conductivity devices generally use a second sealed compensating element to minimize variations caused by ambient temperature changes.

For extremely low pressures, less than 10^{-3} torr, Bayard-Alpert-type ionization gages are used. This device is similar to an electronic vacuum tube. It uses a heated filament emitting electrons which ionize some of the molecules of the gas whose pressure is to be measured. The ionized molecules are attracted to the plate of the tube causing a current flow in the external circuit which is a measure of the number of molecules present (the density), and therefore a function of the pressure.

To aid the user of this handbook, several tables are provided in the appendix which summarize the pertinent properties of some current commercial sensors. It is to be noted that this sampling is not complete and is intended only to illustrate the kinds of devices on the market and their performance trade-offs.

The inclusion of particular devices does not constitute endorsement by the author, nor does omission show disapproval. The user who wants to procure pressure sensors should contact sensor manufacturers to get the latest information on these devices.

4.2.1.6 Pressure Sensing Elements

As previously mentioned, a pressure sensor consists basically of the pressure sensing element which converts the pressure to a force or displacement and the transduction element which converts the force or displacement to an electrical signal. Although these are usually two separate elements, there are exceptions.

The most common pressure sensing force-summing element is the diaphragm. This is generally a planar metallic component which, when subjected to pressure, deflects predictably and thereby activates the transduction element. Many variations to the basic diaphragm exist. Diaphragms may be flat or convoluted, stretched, or slack. A capsule consists of two corrugated diaphragms. A bellows is essentially a series of capsules. Metals used in the fabrication of diaphragms include copper and nickel alloys and a variety of stainless steels. In modern semiconductor sensors, the diaphragm may be silicon. Diaphragms may be welded to their supports to minimize hysteresis. Sensors machined from solid blanks of metal also show low hysteresis, but are difficult to produce and are expensive.

Bourdon tubes are basically curved or twisted tubes whose ends rotate when pressure is applied to the inside of the tube. Straight tubes change body dimension when subjected to internal or external pressure. Bourdon tubes are made of the same alloys as diaphragms. They can be made with thick walls to withstand high pressures.

These are the major types of pressure sensing elements used in sensors with electrical output signals. General advantages and disadvantages of these elements are tabulated in table 1. It should be noted that some of those are relative and design compromises are possible.

Finally, as indicated in section 4.2.1.5, there are those elements which combine sensing and transduction functions due to bulk properties of their materials. They will be discussed in more detail below.

4.2.1.7 Transduction Elements

There are a variety of approaches to convert the pressure-derived force or displacement into an electrical signal. They are discussed in some detail below. Advantages and disadvantages of these approaches are presented in tables 2 and 3 in section 4. Again proper design, engineering, and trade-offs can reduce or eliminate some disadvantages to emphasize the advantages of particular types. Table 4 in section 4 shows approximate ratings in a number of categories for commonly used transduction elements. This table can be used as a general guide, but should not be used for absolute choices between two adjacent items in a column.

(1) Strain Gage Sensing Elements

It is interesting to note that engineering test measurements are taken with strain gage sensors more frequently than with any other type of pressure sensor. There are several general reasons for this: They include the need for high accuracy, capability for flat frequency response from steady state to several thousand cycles, reliable operation over extended periods of time, known performance characteristics, ready commercial availability, and standardization of data signal conditioning and power supplies. Within the strain gage sensor family, there are several types of transduction elements. They are divided into two major classes: metallic and semiconductor gages, each with a variety of configurations.

Force or diaphragm displacement causes a change in position or change in length of the sensing element. In the unbonded strain gage sensing element, a short length of wire is stressed by pulling on one end of the wire or deflecting the position of its mounting posts. Bonded strain gages are attached to the diaphragm or bending beam by means of an adhesive. Thin film sensors are a special example of the bonded strain gage. They generally employ a metal substrate and vacuum deposited layers of insulation and circuit elements. The diffused semiconductor gage consists of a single silicon chip into which an impurity, such as boron, has been diffused to produce piezoresistive elements.

Strain or shear is induced by the sensing element upon the wire or crystalline strain gage element. Each active element exhibits a resistance change, which can be measured by a Wheatstone bridge circuit.

The resistance change, compared to the unstrained element resistance, is often referred to as gage factor. It is a measure of the electrical sensitivity of the gage to mechanical strain.

Gage factor is expressed as

$$GF = \frac{\Delta R/R}{\Delta L/L}$$

where ΔR is change in resistance
R is unstrained element resistance
ΔL is change in element length
L is unstrained element length.

Different types of gages exhibit different gage factors. Gage factor is an important element in proper design of the sensors, since it defines the requirements for the signal conditioning of the sensor output. High amplitude output signals are desirable provided other performance characteristics such as temperature sensitivity are acceptable to the measurement.

Typical gage factors of the various types of strain gages are compared below:

Type of Sensor Gage	Gage Factor (Approximate)
Unbonded wire	4
Bonded foil	2
Thin film	2
Diffused semiconductor	80-150
Bonded bar semiconductor	80-150

Characteristics of the different types of strain gages are discussed below. The gage factor determines output level and sensitivity of the sensor, but variances from unit to unit can be adjusted to a nominal value with resistors placed in series with the gages. Gage factor is not normally specified in any sensor performance characteristics since it is "internal" to the sensor.

By proper adjustments, manufacturers can set the sensor output to achieve some or all of the following: changes in zero output level, in full-scale level (sensitivity or span), temperature effects on zero, temperature effects on full scale (sensitivity or span), and in input or output impedance matching.

Effects of temperature change and the time required for the transducer output to restabilize after a temperature transient are important design and use considerations. Good design practices incorporate low thermal resistance paths among sensor elements and compensation resistors to quickly restabilize errors due to transient temperature changes. The effects of transient temperature changes and tests to establish them will be discussed in a later section.

It seems proper to discuss in more detail the different types of strain gages now.

The unbonded wire gage consists of metallic wire, usually 0.3 mils to 0.5 mils in diameter, wrapped around nonconductive posts. In some designs, the tension in one winding is increased while tension in a second winding is decreased as positive pressure is applied. The two windings have precise adjustments of tension to insure that optimum sensitivity and balanced characteristics are obtained. Some designs cause only one element to move, resulting in one-half the output sensitivity of a four-active arm Wheatstone bridge. A rod transmits the force from the pressure sensing diaphragm to the flexure or bending platform on which the strain wire is mounted. Both unidirectional and bidirectional pressure measurements can be taken with properly designed unbonded gages. This design can accommodate stops to prevent mechanical over-travel for over-pressure protection in both the positive and negative directions. Table 2 shows the advantages and disadvantages of the unbonded strain gage as a transduction element.

The bonded strain gage consists of metallic wire, foil, or ribbon coated with a thin layer of insulation and cemented to the rear of the diaphragm or cantilever beam which is deflected by changes in the pressure sensing diaphragm.

Strain sensing elements, similar in composition to the unbonded gage, are laid out in special patterns to be sensitive in a single axis of deformation. They are mounted directly to the pressure sensing diaphragm in medium and high pressure range sensors. Low pressure range designs may incorporate a rod to transmit the force between the pressure sensing diaphragm and a beam to which the strain gages are bonded. In bonded gage designs, greater force is required than for the unbonded gages to deflect the material on which the gages are mounted. For this reason, foil gage sensors are limited to a 0-10 psi minimum range. To obtain more sensitivity at low pressures, larger diaphragms or bellows are required. The trade-offs between sensitivity and environmental effects on accuracy (vibration, acceleration, temperature) set the lower practical range limit for their pressure sensitivity.

The bonded gage exhibits a characteristic related to the bonding to the diaphragm or beam which is not present in the thin film and diffused semiconductor gages. The adhesive between the gage and the surface to which it is attached may plastically deform, resulting in slight shifts or repositioning of the gage at elevated temperatures; this characteristic can be minimized to achieve good repeatability and stability specifications.

The rugged construction of bonded strain gage sensors permits considerable abuse in handling and use where transient over-pressure might destroy other types of sensors. After rough handling and use, the sensors may require re-calibration, however, as zero and sensitivity shifts will occur. Temperature compensation and shunt calibration techniques are similar to those employed in unbonded gages. Table 2 lists advantages and disadvantages of the bonded strain gage sensors.

Vapor deposition (sputtering) of insulation and strain gages results in a thin film strain sensor with improved performance. The good features of unbonded and bonded strain gage sensors are combined. However, this method of transduction does not solve all application problems. To construct such a sensor, a metal substrate, which can be either the sensing diaphragm or bending beam, is polished to a mirror finish. The substrate forms are placed in a high vacuum chamber for deposition either by vacuum deposition or the sputtering process.

First, an electrical insulator such as silicon monoxide is deposited over the substrate. Next, the metal employed for strain gage elements is deposited on the insulator using sputtering or vacuum deposition. Multi-step operations are required to mask and deposit gages and electrical terminals. The fabrication of thin film devices requires careful control of cleaning, polishing, and etching to build satisfactory gages. Although the same processes are used to make IC's, etc., performance requirements of pressure sensors are unique and require special care.

The geometric patterns of strain gages are defined in one of two ways. The first uses a punched mask placed between the source of evaporant and the substrate to shadow the substrate in those regions where deposition is not required. The second method uses a photosensitive polymer, or photomask, to protect those areas where the pattern is desired. The unwanted deposit is then chemically etched. Laser trimming of the strain gage pattern is employed to precisely adjust the resistance of each element. Once a gage is built and tested, it can be installed within a sensor case following practices employed with other kinds of bonded strain gages.

The thin film gage exhibits little creep or set. Effects of linearity, hysteresis, repeatability, and stability are almost all limited by materials employed in the sensor case, diaphragm, and any beams or flexures to which the gage is attached. The best gage offers no better performance than the materials from which it is assembled. Also temperature hysteresis and case distortion due to torque, etc., may cause errors much greater than those developed within the gage itself.

The gage and other sensor components must be considered carefully to properly design a sensor which exhibits good stability during temperature changes. It is possible to closely match the temperature coefficients of the gage elements and the pressure sensing diaphragm through proper selection of materials. Sensor specifications for thin film gages list thermal sensitivity shifts of 0.005 percent FS/°F, which is typical of a good unbonded strain gage. However, less temperature compensation is required due to better coefficient match between gage and the sensing diaphragm.

The thin film processes used in microcircuitry and pressure sensors employ, as the name suggests, thin films of both conductors and insulators. For operating conditions within the manufacturer's specifications, such elements are quite satisfactory. However, excessive voltages can cause the insulation to break down.

Transient voltages in adjacent circuits or radio frequency interference may cause voltages greater than the dielectric layer between gage elements and their mounting surfaces can withstand. The resulting punchthrough from the elements to diaphragm or beam usually produces a permanent path of low resistance, rendering the unit worthless. The voltage at which this occurs poses no problem in most installations. Unbonded or bonded strain gages can withstand much higher voltage than thin film types. As transistor and integrated circuit technology improves, thin film strain gages will be developed with higher dielectric strengths. It is good practice to review the installation requirements for potential failure due to dielectric overstress.

Thin film gage sensors offer the promise of good long-term stability and uniformity of characteristics. As with all other metallic strain gages, their voltage output is relatively low.

The latter disadvantages have been overcome with the introduction of the <u>semiconductor strain gage.</u>

The technologies developed for manufacture of transistors and integrated circuits are now applied to pressure sensors. Integrated circuit manufacturing techniques can be employed to build, calibrate, and test pressure sensors. These techniques can be used to produce high accuracy, stable pressure sensors in high volume at very low costs.

Within the <u>semiconductor</u> or piezoresistive family of <u>strain gages</u>, two types of sensors are employed: the bar gage and the diffused gage. The bar gage sensor is nearly identical in concept to the bonded foil strain sensor. Bars of silicon are individually bonded with epoxy to a mechanical structure, such as a beam or diaphragm, to act as transduction elements. The diffused gage sensor uses a silicon element, but the active region of the gage is diffused into the silicon.

In the bar gage, an impurity such as boron is introduced into the silicon crystal as it is grown. In a bar gage, the entire piece of silicon is an active gage. The individual gages are then electrically matched, as nearly as possible, and the four legs of a bridge circuit are cemented to the pressure sensor (either a diaphragm or bending beam). Although the four-gage elements made from silicon-based semiconductors exhibit high gage factor levels (20 mV/V), they suffer the inherent limitations associated with other bonded gages: zero shift and creep from variations in elasticity and differing expansion coefficients of bonding cement and sensor materials. Although the bar gages are somewhat easier to produce, considerable assembly labor and element matching is required to produce a good sensor.

The diffused semiconductor strain gage employs a multi-step process of polishing and cleaning of the sensor surface, and the application of photoresist, the masking and diffusion of this active area, electrical terminal deposition, and lead attachment. Automation of gage manufacturing process provides consistent results at relatively low cost. If the pressure diaphragm and sensor are properly designed, excellent performance characteristics are obtainable.

The diffused semiconductor gage offers excellent long-term stability. The diffused gage is integral to the silicon crystal and therefore exhibits no creep or set relative to the silicon base material. Relatively high gage factors may be attained resulting in large electrical signals with a given strain. Thus the stress level within the pressure sensing element or diaphragm can be lower than in other strain gage sensors. This results in improved hysteresis, linearity, repeatability, and long-term stability provided good sensor case design practices are followed. However, achieving a stable bond between the silicon base material and the case structure requires specialized techniques. Unfortunately, commercial designs do not always achieve the levels of stability and performance which are theoretically possible in a diffused element system.

In theory, a zero temperature coefficient should be attained for a four-arm diffused gage. That is, with equal temperature coefficients and equal element resistance characteristics, a diffused four-gage element should exhibit equal changes in each bridge leg, thereby canceling resistance changes due to temperature variations. In practice, however, minor differences in geometries, etching, depositing, and lead attachment resistance result in some residual zero unbalance within the bridge. However, very good temperature coefficients can be achieved with minor amounts of additional compensation.

Temperature sensitivity (change in full-scale output with change in temperature) can be compensated by including temperature sensitive voltage or current regulation in the strain gage excitation. Typically, thermistors, zener diodes, or transistors may be employed. Recently developed compensation networks incorporate hybrid circuits which can be trimmed to required values with a laser beam. Temperature compensation elements are usually located near the pressure sensing element within the sensor case. A possible thermal lag between step-temperature changes at the pressure port and the location of compensation must be considered.

The stability of recent amplifier designs and incorporation of complete circuits on a single chip makes it practical to manufacture sensors providing high level dc output. These units offer excellent performance at low costs in volume production.

Utilization of the semiconductor pressure sensor is generally limited to applications where temperature does not exceed 125 °C. Short exposure to higher temperatures (150 °C) is permissible in some designs, but rapid deterioration in performance and permanent damage can be expected. With proper design, the semiconductor gage can be successfully used in cryogenic temperature applications down to -270 °C (liquid helium).

Apart from temperature-imposed limitations and some sensitivity to nuclear and electromagnetic radiation, semiconductor strain gage sensors offer the greatest potential for inexpensive high quality sensors.

(2) Potentiometer Elements

The potentiometer is one of the earliest transduction elements used for a variety of sensors. Typically, a force-summing pressure bellows or Bourdon tube is linked to a potentiometer wiper which travels across a multi-turn wire coil or deposited resistor. Usually some mechanical amplification is employed between the force-summing element and the wiper which tracks across the resistance element to increase resolution. Balancing masses may be employed to minimize acceleration error. Friction between the wiper and resistance element plus pivot bearing friction and wobble result in considerable hysteresis for measurements taken in a vibration-free environment. A taut band movement shows less hysteresis. Vibration and pressure fluctuations cause dither of the wiper resulting in fast wear of the resistor. For short-term measurements where moderate accuracy is adequate, the potentiometric sensor offers several advantages. The resistor can be shaped to provide specialized output linearities such as linear, sine, cosine, and exponential transfer characteristics. Since potentiometers are basically used as voltage ratio devices, close regulation of the excitation voltage is not required. High level output is inherent in the potentiometer concept, but output load impedance must be kept high to limit loading effects.

Potentiometer-type pressure sensors can be produced inexpensively, but their short life expectancy makes them an expensive selection for repeated or medium duration test measurements.

(3) Variable Reluctance and Inductance Elements

Variable reluctance or variable inductance transducers indicate pressure changes by changes in output impedance. One approach uses a pair of coils that changes their magnetic coupling by means of a pressure-driven armature which displaces, or rotates, between the two coils. When the coils are excited by a carrier frequency, changes in the ratio of reluctance of the two coils can produce output levels of the order of 40 mV per volt of carrier voltage. Thus a 25 V signal can produce output levels of one volt with no amplification. Some designs include dc-to-ac inverters to supply the carrier output amplifiers and demodulators for direct operation from unregulated 28 V dc supplies to produce an output of 0-5 V-dc. Two basic designs have been developed using the variable reluctance principle. One type uses a Bourdon-tube-driven armature which rotates above a single "E" core with two coils or a pressure-displaced diaphragm positioned between two "E" cores which alters the effective inductance of each coil on the "E" core. The armature-driven system is massive and is primarily used in secondary standard stationary applications.

The other type of variable-reluctance sensor uses a diaphragm configuration with a high natural frequency; it is extremely rugged. Because the diaphragm itself is part of the inductive loop, a compromise is made between good mechanical linearity and magnetic sensitivity. Among the trade-offs to be considered in choosing reluctance transducers are high output, the requirement for ac excitation, ruggedness, vibration sensitivity, and sensitivity to external magnetic fields.

(4) Linear Variable Differential Transformers

Somewhat similar to reluctive sensors in their requirement for ac excitation and demodulating circuitry are linear variable differential transformers (often abbreviated LVDT). For these transduction elements the force-summing device is often a diaphragm. Bellows and Bourdon tube designs are used where applications do not require exposure to high levels of shock or vibration. In most designs, a push rod or linkage displaces a magnetic core within a three-coil transformer to produce unbalance within two secondary windings. AC excitation of the transformer primary can be as low as 50-60 Hz from the power line. Aircraft applications may require operation at 400 Hz. Moreover, an excitation frequency of 10 kHz or higher is frequently employed to reduce the size and mass of sensor components and permit higher frequency dynamic measurements. The sensitivity of the transduction elements is a design trade-off between the displacement of the transformer core and the transformer turns ratio. Due to the relative large core displacement required, this type of sensor is not employed where acceleration or vibration is present or where high frequency response is needed. Servo-type force-balance sensors discussed below often employ this type of transduction element.

(5) Variable Capacitance Elements

Variable capacitance transduction elements can have a very simple geometry, and therefore more readily predictable mechanical characteristics. One design has a stretched flat diaphragm positioned between two fixed plates; its deflection causes a capacitance change in two circuits. In some sensor designs only a single capacitance element is employed. The change in capacitance can be used to vary the frequency of oscillators or null a capacitance bridge. If the dielectric of the capacitor is stable with temperature and time or compensated for its variations, a very repeatable sensor is achieved. The small displacements of the capacitor-diaphragm system result in low hysteresis, good linearity, and good response to high frequencies.

The dual element concept can be employed to drive two oscillators: one increases, the other decreases in frequency as pressure increases. The difference signal from a mixer fed by the two oscillators is highly linear. Capacitance-type sensors are ideally suited for pressure sensor ranges up to 100 psi and down to the medium vacuum region. Capacitance sensors require signal processing circuitry with short leads from the high impedance output of the sensor. This may cause mechanical configuration problems in some applications.

(6) Force Balance Elements

Force balancing (servo) sensors produce a signal in response to the sensing element's deflection, which generates the force needed to oppose that deflection exactly. By balancing the force caused by the applied pressure and restoring the sensing element to its original position, hysteresis and nonlinearity are practically eliminated.

Two types of transduction elements (capacitive or differential transformers) are usually employed within these sensors. However, the force-summing element diaphragm or capsule can be coupled to any of the various types of sensors compatible with properly designed electronics to produce a restoring force which returns the system to a null condition.

The force-restoring element typically consists of an electromagnetic coil or servo motor, which produces the necessary null displacement or balancing torque. Leverage is often incorporated into a balance beam to amplify the restoring force applied to the force-summing pressure sensing element.

The magnitude of power required to restore the force balance to null condition is usually measured as the voltage across a series dropping resistor in the servo loop. Various resistor values can be selected to change sensitivity or adjust output levels to correspond to engineering units as read on a dc voltmeter. A high level output of 0-10 volts (or even higher) makes possible a high resolution system for secondary standard applications.

The massive element and balance beam construction drastically reduce the frequency response. In fact, the bandwidth of the electronics is intentionally limited from dc to approximately 5 Hz. Despite their potentially superior accuracy, force balance devices are usually too large, delicate, and expensive for other than laboratory applications.

While there are no true digital pressure sensors, two approaches to obtain digital pressure data do exist. The most common is the use of an electronic A-D converter to change the analog output of the above described sensors into digital form. This will be more widely used in the future in order to meet the needs of computerized ATE systems. Section 5 on Data Acquisition will discuss this approach in more detail.

The other approach makes use of a digital position encoder linked to the sensing element. Such an approach commonly uses a sectored disk to generate a digital code that describes its angular position with respect to a reference point. Such encoders are described in more detail later. However, such digital encoders have relatively poor resolution and large mass of moving parts. Both factors severely curtail the dynamic measurement capability of such devices.

(7) Vibrating Wire or Cylinder Elements

There are also quasi-digital transduction systems based on the vibrating wire or cylinder principles which are described below.

A force-summing diaphragm causes a change in tension of a fine wire or cylindrically configured element. The wire, or cylinder, is excited by a varying magnetic field and is in resonance. As tension changes in the wire or tube, the resonant frequency changes. The frequency deviation can be counted with digital circuitry or handled as an analog signal with discriminator circuits. The low-mass vibrating system has good frequency response and is quite insensitive to steady acceleration. However, it is very sensitive to shock and vibration which tend to modulate the vibrating element's natural frequency. Unlike the dual element capacitive gage which employs two oscillators, this "single element" design generates a variable frequency from a mechanical system which is very sensitive to temperature change and requires a long time to stabilize after temperature changes.

(8) Piezoelectric Elements

The piezoelectric system is based on the principle that strain applied to asymmetrical crystalline materials generates an electrical charge. The piezoelectric effect has been used in a variety of instruments. The most common crystals employed include barium titanate, quartz, Rochelle salt, and tourmaline. Special ceramics polymers and other salts have been developed for special applications by various sensor manufacturers, but the basic principles are observed. Piezoelectric sensors produce an electric charge in response to changes in pressure (force) with respect to time and cannot respond to static pressures or forces.

A pressure sensing diaphragm is coupled to a selected axis surface of the crystal to induce strain. The high impedance output of piezoelectric devices requires a voltage or charge amplifier to match the sensor output with signal conditioning before transmission beyond a few feet from the sensor.

Dynamic pressure measurement with flat frequency response from below 10 Hz to over 50 kHz can be obtained from well-designed sensors. High frequency data and dynamic calibration of other kinds of pressure sensors are dependent upon these sensors.

Piezoelectric sensors have two major advantages: They are self-generating, requiring no external electrical excitation, and they are capable of response to very high frequencies. They also have great drawbacks: Piezoelectric sensors have no steady-state response and therefore can only be calibrated dynamically. They are frequently temperature-sensitive (quartz is relatively immune to this, but has low sensitivity). Such sensors are also high impedance devices, requiring appropriate signal conditioning.

Other Transduction Elements. The above described elements are those which are being used in commercially available pressure sensors. At various times other transduction elements have been introduced, but have proved less viable because their disadvantages outweigh their advantages, technically or economically. They include electro-kinetic, photoelectric, and nuclear radiation elements, to name a few. Undoubtedly other new principles will be introduced in the near future and one or more may prove superior to existing ones. Section 4.2.1.9 discusses new developments and looks at future trends in this area. Until new developments have thoroughly proved themselves, it is likely that the above described major transduction principles will be the ones used.

4.2.1.8 Vacuum Sensors

Although vacuum is, theoretically, a space devoid of matter, the term is used in the field of pressure measurements to denote, generally, pressures below one standard atmosphere. Conventional pressure sensors of the absolute type can be used to measure such pressures provided the absolute pressure is a substantial fraction of an atmosphere, perhaps 1 psia or greater, in order to achieve reasonable output signals.

When it is necessary to measure much lower pressures, different types of sensors must be used. It is customary to refer to vacuum sensors when pressures below one torr (1/760 of standard atmosphere) are involved. Vacuum sensors do not use pressure sensing elements distinct from the transduction elements. Instead they generally sense properties other than pressure of the gaseous medium whose pressure (vacuum) is to be measured.

Vacuum sensors as a class are more delicate than most conventional pressure sensors and are not often used for field measurements. Several different types exist which are briefly described below based on information in the "Handbook of Transducers for Electronic Sensors" [7].

(1) Thermoconductive Vacuum Sensors

Thermoconductive vacuum sensors measure pressure as a function of heat transfer by a gas. They are of two basic forms as discussed below. Heat flow originates at the surface of an electrically heated wire (filament) and is transferred by a gas in an enclosed vessel to the inside wall surface of this vessel. The quantity of heat transferred is proportional to the number of gas molecules and, hence, to the pressure in the vessel. A decrease in pressure causes the filament to get hotter, because fewer gas molecules transfer less heat away from the filament and to the wall of the vessel. At low pressures the heat conductivity of a gas decreases linearly as pressure decreases. The actual conductivity depends on the composition of the gas.

Thermoconductive vacuum sensors require a well-regulated filament supply for their excitation. The filament is typically of tungsten or platinum wire. The filament and its end supports must be carefully designed to minimize heat losses from radiation from its surface and from conduction through the vessel, preferably down to cryogenic temperatures. The normal measuring range of these sensors is from 10^{-3} to 1 torr.

The first type of thermoconductive vacuum sensor is the resistive thermoconductive vacuum sensor. This type of sensor is characterized by a filament that changes resistance due to heating. The temperature of the filament is determined, in turn, by gas pressure. An increase in filament temperature causes an increase in filament resistance. The sensor is usually connected so that the hot filament forms one arm of a Wheatstone bridge. A second sensor of the same configuration, but sealed so as not to respond to any pressure changes, is often connected as a second arm of the bridge. This can compensate for changes in the temperature of the vessel or chamber.

This type of sensor is commonly referred to as the "Pirani" gage. It operates from a constant-voltage filament supply. The filament is normally heated to a temperature of about 400 °C at the lower end of the measuring range. A design variation (operating at lower temperature, but higher sensitivity) uses a thermistor instead of a filament.

The second type of instrument is the thermoelectric thermoconductive vacuum sensor sometimes called the thermocouple gage, which uses a thermocouple as transduction element. The thermocouple's sensing junction is welded to the center portion of the filament and measures the filament temperature. The sensor operates from a constant-current filament supply. It is somewhat less accurate than the resistive type. Design variations use a thermopile or multiple thermocouples connected in series instead of a single thermocouple for increased output voltage. One design uses a center-tapped thermopile both as heat source and as transduction element.

(2) Ionizing Vacuum Sensors

The ionizing vacuum sensor measures pressure as a function of gas density by measuring ion current. The ion current results from positive ions which are collected at a negatively charged electrode when the gas is ionized by a stream of electrons or other particles. The ion current is proportional to gas density (molecular density) and, hence, proportional to pressure. This is true only when the number of electrons and their average path length are constant and all ions are collected. Because these sensors measure density, however, their calibrations are different for different gases. Nitrogen is most frequently used as reference gas.

The thermionic ionizing vacuum sensor often referred to as the ion gage or ionization gage resembles a triode-type radio tube and differs from it primarily by having an opening in the bulb. In a typical design the filamentary cathode is surrounded by a helical grid around which a cylindrical anode is placed. Positive ions are collected at the grid, which is kept at a low negative voltage with respect to the filament; the anode collects the secondary electrons.

Tungsten or iridium filaments are used in most designs. Thoriated tungsten is used in some designs to allow operation at low temperatures and to prolong filament life. The pressure port for tubing connection (the tubulation) is kept short and of relatively large (typically 0.75 in) diameter. To further reduce tubing effects, some thermionic ionizing vacuum sensors are furnished without glass envelopes, for direct installation in vacuum vessels.

The normal measuring range of the triode-type sensor is from 10^{-8} to 10^{-3} torr. At pressures higher than this the space charge effect and the recombination of ions due to a reduction in the mean free path of the ions cause extreme nonlinearity; this tends to limit the range to that given. A variation, the Shulz-Phelps ion gage, is designed to minimize space charge effects and yields a usable range from 10^{-5} to 1 torr.

Radioactive ionizing vacuum sensors use particles other than electrons to ionize gas. One example is an alpha-particle ionizing vacuum sensor, the "Alphatron." The radioactive-particle source is a small thin plaque usually containing radium, tritium, polonium, or a similar radioactive material which is in equilibrium with its daughter products. In a typical design a radioactive source of Ra^{226} with a strength of 200 microcuries is used to provide a relatively constant alpha-particle flux. When the average path length is fixed, the average energy is constant, and all ions which are formed are collected. The ion-current-vs-pressure relationship is linear up to about 50 torr. One design variation contains an auxiliary, smaller, ionization chamber for use at higher pressures. Although this sensor is most commonly used over the range from 10^{-1} to 100 torr, its range capability is from 10^{-5} to 1000 torr. When the higher range is available on a given design, the ambient atmospheric pressure level can be used as a convenient calibration checkpoint. Ion current can be amplified and read out in terms of voltage, current, or pulse frequency. Output readings can differ for different gases or gas compositions which have different ionization cross sections for alpha particles. It should be noted, however, that calibrations for different gases are closer to each other for this type of sensor than for any other type of ionizing vacuum sensor.

There are other types of vacuum sensors primarily intended for even lower pressures than the above [8], not likely to be of concern for ATE applications and not discussed in this handbook. Of interest in validational troubleshooting may be devices like partial pressure analyzers which are useful in detecting leaks.

4.2.1.9 Current Problems and Future Trends

While section 3.6 addresses future trends in the field of sensors in a general way, some remarks on pressure sensors and pressure measurements follow.

It is highly likely that increased emphasis will be placed on sensors with digital output signals, particularly for use in ATE equipment. Practical problems of data transmittal in the presence of extraneous noise require true conversion to digital form as close to the sensor as possible. Sensors are being developed with integral digital encoders in the body of the sensor. Developments of this kind may be expected to increase greatly as the use of electronics in the sensor may impose more stringent limits on the sensor's operating environments than would apply to the sensing element alone.

In pressure sensors, insufficient output and large size may have a considerable effect on measurement quality. The former makes the effects of system noise more critical and requires additional signal conditioning which increases the complexity of the system. The size of the sensing element may have a considerable effect on the pressure which can be measured and on the dynamic fidelity with which pressure variations can be sensed. The whole area of the fidelity of dynamic pressure measurement is one which has not been fully explored and needs further investigation. The durability of sensors operating for extended periods of time and in harsh environments is another area requiring additional work. One area of considerable potential trouble is the lack of agreement among manufacturers and users on performance characteristics, test methods, and data interpretation regarding pressure (and other) sensors. Continuing efforts by the entire sensor community are necessary to correct this situation.

The most important advance in the last decade in pressure sensors was undoubtedly the introduction of the semiconductor strain gage, which resulted in signal levels greater by at least one order of magnitude than previously known. Clever temperature compensation schemes, combined with artificial cooling, permit operation of pressure sensors at very high temperatures. The operation of sensors at high temperatures, however, has only partially been solved, as has the need for improved materials compatible with some of the exotic fluids whose pressures are to be measured.

Miniaturization of components, rapid advances in silicon sensor technology, and wideband, stable microcircuitry begin to show the way to better and cheaper sensors for measurement of dynamic pressure. Better evaluation techniques and equipment are needed to attain a better understanding of the capabilities of these sensors as parts of measurement systems.

Future trends, as far as can be discerned, will be essentially extensions of present efforts. Increased knowledge of material characteristics and increased use of microcircuitry should lead to smaller, cheaper, and better sensors. Based on silicon technology, new principles or designs will appear at times, but their long-range success will depend on their being significantly better than existing devices. The advantages of fiber-optics (immunity to electrical noise and small size) encourage the development of sensors based on variable light intensity as a measure of deflection of a surface (such as a diaphragm). The optics must be compensated for changes in light source intensity.

Information on trends can be gathered from annual articles in technical journals. A very informative article on silicon sensors, in general, appeared in the November 6, 1980 issue of Electronics [59].

TABLE 1

Pressure Sensors
Comparison of Pressure Sensing Elements

Type	Advantages	Disadvantages
Diaphragm	Variety of materials available to suit conditions Flush mount possible May be field replaceable High natural frequency Variety of electrical sensing mechanisms Diffused silicon for direct electrical conversion	Sensitive to overpressure Displacement limited for linear responses Sensitive to thermal Corrosion prone
Capsule (combination of diaphragms)	Greater displacement than diaphragm for given pressure Can be sealed to provide absolute reference Variety of materials Variety of electrical sensing mechanisms	Lower natural frequency than diaphragm More sensitive to vibration than diaphragm Larger volume than diaphragm type sensing elements
Bellows	Large linear displacement Variety of materials Variety of electrical sensing mechanisms	Larger sensing element volume Low natural frequency Vibration sensitive
Bourdon tube	Variety of shapes for angular or helical displacement Highest pressure range capability Variety of materials	Poorer linearity than above elements Large sensor volume Vibration sensitive Low natural frequency
Vibrating wire Vibrating cylinder	Direct conversion to digital output Capable of high repeatability and accuracy	Shock sensitive Temperature hysteresis Large sensing element volume

TABLE 2

Pressure Sensors
Comparison of Transduction Elements

Type	Advantages	Disadvantages
Metallic Strain gages unbonded	Static and dynamic response Continuous resolution High frequency response	Low output Temperature sensitive Delicate
Bonded	Static and dynamic response Continuous resolution High frequency response ac or dc excitation More rugged than bonded	Low output Bonding adhesive may creep
Thin film (sputtered)	Static and dynamic response Continuous resolution High frequency response ac or dc excitation Rugged Very good stability	Low output Limited high voltage capability
Semiconductor Strain Gages Bar gage	High output Static and dynamic response Continuous resolution High frequency response ac or dc excitation	Temperature sensitive Radiation sensitive (electromagnetic, nuclear) Bonding adhesive may creep Shock sensitive
Diffused	High output Static and dynamic response Continuous resolution High frequency response ac or dc excitation Low hysteresis Can be made very small Inexpensive in quantity	Temperature sensitive Radiation sensitive (electromagnetic, nuclear)
Potentiometric	High output ac or dc excitation Special shapes of output curves available Static and dynamic response Inexpensive	Poor resolution Friction, large hysteresis Limited life Vibration sensitive Wiper contact noise

TABLE 3

Comparison of Transduction Elements

Type	Advantages	Disadvantages
Reluctive	High output Continuous resolution Static and dynamic response Direct conversion to digital possible	ac excitation only Frequency response limited by excitation frequency Sensitive to magnetic fields Vibration and shock sensitive may require demodulator
Linear variable differential transformer	High output Continuous resolution Static and dynamic response	ac excitation only Low frequency response Vibration and shock sensitive may require demodulator
Capacitive	Very high sensitivity High output Continuous resolution Low hysteresis Good linearity	Temperature sensitive Requires short leads High impedance output Requires additional electronics
Force-balance (servo)	High output Very high accuracy Excellent linearity Very low hysteresis High stability	Large size Vibration and shock sensitive Low frequency response Requires additional electronics
Vibrating wire Vibrating cylinder	High resolution High repeatability Direct conversion to digital output possible	Temperature hysteresis Nonlinear Vibration and shock sensitive Requires additional electronics Expensive
Piezoelectric	Self-generating output Very high frequency response Large dynamic range Can be made very small	No static response Temperature sensitive Radiation sensitive Shock sensitive High impedance output Sensitive to cable noise

TABLE 4

Quality Ratings of Transduction Elements In Order of Decreasing Quality (Approximate)

utput evel	Static accuracy	Stability	Frequency response	Vibration immunity	Small size	Low Cost quantity	High Temperature operation, °F	
FB	VW	VW	PE	PE	PE	SD	C	850
PO	FB	VC	SD	SD	SD	SB	U	600
VC	VC	TF	TF	VC	U	U	VR	600
VW	TF	SD	VC	TF	SB	PO	TF	525
DT	SD	SB	U	BF	TF	DT	PE	400
VR	U	BF	SB	U	VR	TF	PO	300
PE	SB	U	BF	SB	BF	VR	DT	300
SD	BF	VR	VR	VR	PO	PE	BF	300
SB	VR	DT	VW	VW	VC	SB	SD	250
U	DT	PE	DT	DT	DT	VC	SB	250
TF	PE	PO	PO	PO	VW	VW	VW	200
BF	PO	FB	FB	FB	FB	FB	FB	165

BF	Bonded foil strain gage
DT	Differential transformer
FB	Force balance
PE	Piezoelectric
PO	Potentiometer
SB	Semiconductor bar strain gage
SD	Semiconductor diffusor strain gage
TF	Thin film strain gage
U	Unbonded strain gage
VC	Variable capacitance
VR	Variable reluctance
VW	Vibration wire/tube

4.2.2 Motion

4.2.2.1 Introduction

Measurements need to be made either of the motion of objects in inertial space or of the motion of certain parts of objects with respect to other parts. The type of measurement, the amplitude and frequency response requirements, as well as certain environmental considerations usually dictate the particular aspect of motion sensed and the type of sensor used. Motion can also be considered equivalent to position as a function of time.

Much of the following discussion is taken, with permission, from material in the ISA Transducer Symposium [8].

Motion sensors discussed in this section convert linear and angular displacement, and their time derivatives: velocity, acceleration, and jerk, to electrical signals. Each of the motion parameters may be directly sensed and converted in one or more steps to the desired electrical signal, or the desired signal may be derived by differentiation or integration from a signal transduced from one of the related motion parameters.

Motion may be measured relative to a reference point on a material object or with respect to inertial space. In the latter case the measurement is sometimes referred to as "absolute." Absolute displacement and absolute velocity cannot be measured directly, independent of reference objects, but only by integration of acceleration. The integration is often accomplished electrically or mechanically without explicit recognition or disclosure of the process.

"Absolute" measurement of acceleration is based on Newton's second law for constant mass:

$$F = m \frac{dv}{dt} = m\alpha$$

To measure acceleration by application of the second law, one measures the force required to impress upon a "known" mass (the mass may be inferred by calibration) motion identical to the motion to be measured. The most commonly used method is elastic deformation as embodied in a spring-mass system. To measure acceleration by this method, the motion to be measured is transmitted to the known mass through a spring of known stiffness. The displacement representing compression of the spring is, by Hooke's law, a measure of the force exerted by the spring on the mass. Figure 3 shows a schematic of such a system.

The measurement of motion is basically one of displacement and tables 5 and 6 summarize the advantages and disadvantages of various transduction elements which may be used for this. These tables are quite similar to tables 2, 3, and 4 for pressure sensors. Unlike the latter, motion sensing does not involve a variety of force-summing elements, except in the case of piezoelectric sensors. In this case the piezoelectric crystal serves both as the sensing (force-summing element) and the transduction element.

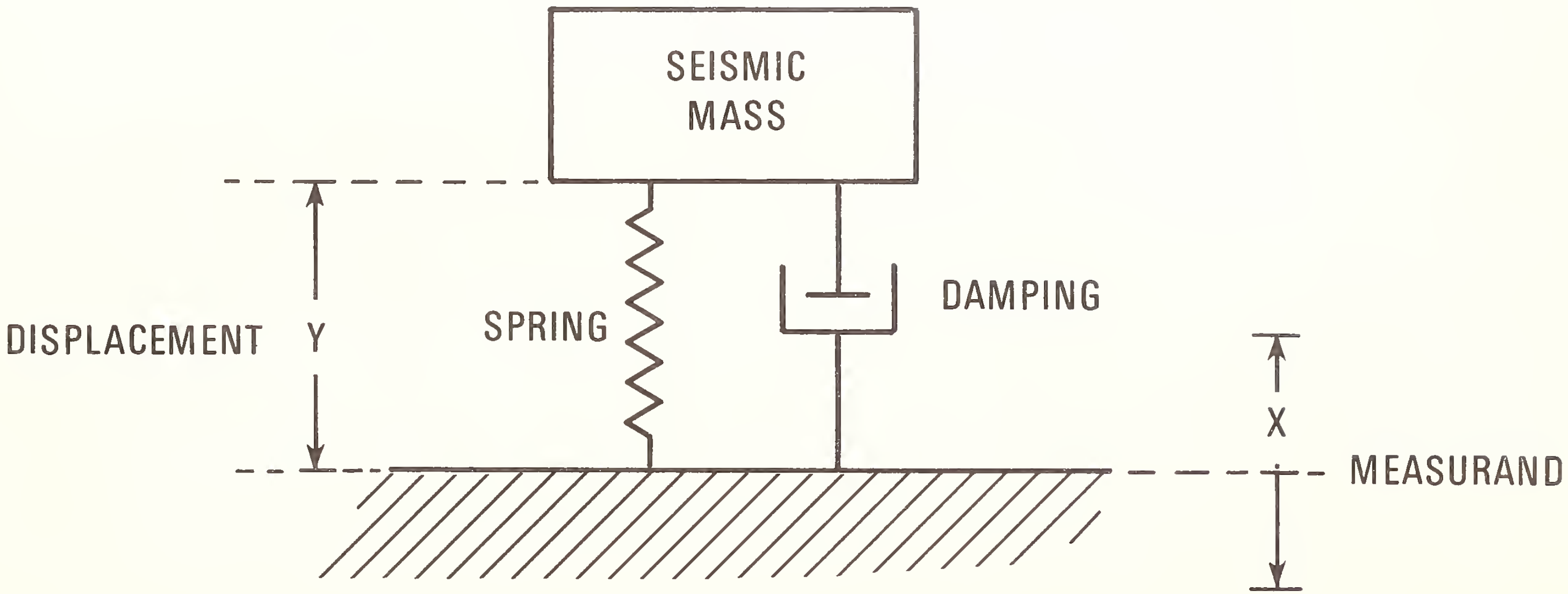

Figure 3 SCHEMATIC OF SPRING-MASS MOTION SENSOR WITH DAMPING

The measurement of acceleration and its time integrals is more complex than the measurement of displacement. For example, two conflicting requirements are apparent when changing accelerations are to be measured: On the one hand the spring must be stiff in order to faithfully transmit the measurand motion to the mass. On the other hand, the deformation of the spring must be sufficient to be susceptible to accurate, noise-free transduction to an electrical signal. In practice, the capability for transducing rapidly changing accelerations is limited by the stiffness of available "spring" materials and by the need to sense very small relative displacements. Application of other force fields is strictly analogous to the spring-mass system.

If the measurand is motion relative to a reference point, displacement and velocity can be transduced directly to an electrical magnitude. For example, the proportionality of induced voltage to velocity and the frequency modulation provided by the Doppler effect are often used. A wide variety of relationships between electrical phenomena and displacement are utilized, to determine displacement including piezoelectricity and piezoresistivity, dependence of electromagnetic induction upon proximity, change of resistance with length of conducting path, change of capacitance with electrode separation, and change of illumination with distance. Transduction of relative displacement to an electrical signal is commonly the final step of the transduction chain leading from other measurands to an electrical signal. (See tables 5 and 6.)

Periodic motion is measured by the same means as other displacements, within the limits of dynamic response capabilities of the sensors.

In the foregoing discussion, the measurement of motion has been discussed in terms of change of position with time. The general relationship between position and time can be expressed as the sum of sinusoidal components described by specifying their frequency, amplitude, and phase. These data in the frequency domain contain all of the information required to describe the motion in the time domain. For some purposes such as observation of vibration, not all of the frequency domain parameters are of interest. It may sometimes be desired to know only the frequency of the vibration; more often, frequency and amplitude are required with phase omitted. Vibration sensors that make these more limited measurements are included within the scope of this section although, in a strict sense, they do not transduce motion as such. Also included are sensors for either time domain or frequency domain that indicate only peak values of the measurand occurring during the interval of interest.

In general, the reaction of the sensor upon the measurand object must be considered in applying sensors. In the measurement of acceleration with spring-mass system sensors, for example, the force required to move the accelerometer comes from the measurand structure and, hence, the sensor mass reacts upon the structure. Since the measurand structure is neither perfectly rigid nor infinitely massive, the measurand motion may be modified appreciably by reaction of the sensor. Sensors that must measure rapidly changing accelerations must therefore be of small mass and their attachment to the measurand surface must be rigid.

4.2.2.2 Materials and Environmental Factors

Considerations discussed in sections 3.5 and 6.3 apply to motion sensors insofar as environmental factors are concerned. There is generally no effect of the measurand itself, in this regard. The exception might be an accelerometer designed to measure extremely small accelerations, whose sensing element might acquire a permanent deformation when subjected to very large acceleration. An example might be a navigational acceleration sensor subjected to high-g launch accelerations.

4.2.2.3 Displacement

It should be recognized that sensors for a variety of measurands convert that measurand, such as pressure, into a displacement. In those cases, displacement is an intermediate step. In this chapter, motion (or displacement) is the primary quantity to be sensed. There is then a certain amount of overlap (and duplication) in the discussions on transduction considerations for displacement in several chapters of this handbook. The author believes, however, that the approach chosen is more useful for the reader. Tables 2, 3, and 4 summarize transduction principles and should be consulted. Additional ones are covered in table 5.

Changes of resistance, inductance, and capacitance are prominent among the large number of physical effects used to sense displacement in commercially available displacement sensors.

For motions that take place very slowly or in steps with long stationary periods potentiometric devices have the advantages of large electrical output, availability at any desired displacement range, generally low cost, and simple associated instrumentation.

For the measurement of strain displacement, there are commercial strain gages made of fine wire or foil, with refinements such as noninductive windings, compensation for use with particular materials under conditions of changing temperature, and special mounting materials and techniques to allow the measurement of strain in the plastic range up to a strain of several percent. Dimensions of strain gages range from 1/16 to 6 in. (1.6 mm to 0.15 m) long, and 1/16 to 1/2 in. (1.6 to 12.7 mm) wide. These gages are generally mounted in pairs such that tension acts on one gage and compression on the other. The two gages are connected in adjacent arms of a resistance bridge for better temperature compensation and somewhat increased output.

An increase in sensitivity by almost two orders of magnitude may be attained by piezoresistive (semiconductor) strain gages which have become commercially available in the past few years. At the present time, these are made of silicon with various amounts of impurity doping to improve the temperature characteristics. Strains up to three parts per thousand (and, for selected devices, somewhat more) can be sensed. For larger strains, adaptors are available which reduce the strain at the element.

"Absolute" displacement measurements can be made with spring-mass systems for motions whose frequency components are sufficiently far above the resonant frequency of the spring-mass system. In effect, the spring-mass system under these circumstances performs a double integration of acceleration. In making such measurements, as in seismometers, an extremely low resonant frequency is required and the mechanical spring may be further weakened by electrical feedback. Since these systems have extremely small restitution forces, a non-contacting electrical sensing system must be used to obtain the best low-frequency characteristics.

The advantage of little or no friction is characteristic of sensors based either on optical principles or on change in self-inductance, mutual inductance, electrical coupling, or capacitance.

Other transduction elements include linear variable differential transformers having ranges from a few hundredths of an inch to several feet (from tenths of a mm to several meters). Excitation may be directly from the 60 Hz, 120 V line or, for better frequency response, from carriers having frequencies from a few hundred to several thousand hertz. The linearity generally depends upon the excitation frequency, and both are usually specified by the manufacturer.

Capacitive devices are available that offer high displacement sensitivity, but these often require somewhat more complicated associated instrumentation. Thus cylindrical capacitors with a small cylindrical air gap may be used over considerable ranges with good linearity, while parallel-plate capacitors with a spacing of 0.001 in. (0.025 mm) or less have been used to measure full-scale displacements of the order of 10^{-7} in. (approx. 2.5×10^{-9} m) or less.

Piezoelectric devices can be used to measure displacement in situations where high reactive forces can be tolerated. A piezoelectric crystal or ceramic generates a charge that is very nearly proportional to a rapidly occurring compressional bending or shear strain. If it is not required that very-low-frequency components of motion be reproduced accurately, then this charge may be measured with the help of a charge amplifier or a high input impedance amplifier such as a cathode follower or emitter follower. Piezoelectric devices have comparatively large outputs and very high resonant frequencies. Their major disadvantage is the fact that they have <u>no response at zero frequency</u> and <u>cannot be calibrated statically</u>.

Another class of sensors which measure motion in terms of position and provide a digital output are usually referred to as "encoders." They can be applied to either linear or angular motion (position). These devices use graphic digital codes patterned on discs, plates, drums, or wheels. The position of the moving plate or disc is detected either mechanically (brushes on conductive elements of the coded surface), optically (photo cells sensing light transmitted through, or reflected from, the coded surface) or through inductive or capacitive coupling. The major advantage of "encoders" is the direct digital output; major disadvantages are size, vulnerability to vibration and shock, and limited high frequency response. The latter is due to the comparatively large mass of the moving components and the limits of optical resolution of the coded disc which may necessitate significant disc or plate motion.

Optical displacement sensors are available which measure displacement in terms of light intensity reflected from a moving surface. Such sensors are linear over only small displacement ranges and require close control of light source intensity [60].

Quite recently, a class of semiconductor photoelectric position (displacement) sensors have become available. They sense the location or movement of a spot of light on the sensitive surface. With displacement ranges up to several centimeters and frequency responses of kilohertz, they offer interesting design possibilities, although their environmental performance may be limited.

A resistive displacement transducer based on the conductivity of an electrolyte has been used commercially for phonograph pickups, as well as in horizontal-sensing angular-displacement transducers. The motion changes the cross-sectional area available to the flow of current through the electrolyte, generally increasing the area in one path and decreasing it in the other. Two other devices having large outputs and, in addition, the ability to follow extremely low frequencies are the electronic displacement gage and the capacitive "ionization transducer." In the electronic displacement gage, an element of a vacuum tube is moved relative to the other elements by means of a linkage extending through the shell. In the capacitive ionization transducer, the position of the plasma surrounding two electrodes in a gas tube is affected by the displacement of metallic rings or plates external to the tube. The environmental vulnerability of the last three devices may outweigh their potential usefulness except in special applications.

In certain applications where a direct measurement is not advantageous, an output that is proportional to displacement may be obtained by performing an electrical integration of the velocity output. This integration is readily performed by means of a simple resistor-capacitor circuit, providing the available velocity signal is sufficiently large. This approach has inherent frequency limitations which must be carefully considered in its use.
A thorough survey of displacement sensing principles, their advantages and disadvantages, applications, and other considerations can be found in reference [61].

In general, a simple, well-proven principle of sensing is almost always to be preferred to a more exotic one which may exhibit unanticipated deficiencies.

4.2.2.4 Linear Velocity

Measurement of velocity is most readily made by means of a sensor that follows the motion and whose output system has a response proportional to the first time-derivative of the displacement, i.e., to the velocity. The most commonly used electrical devices use the relative motion of a coil with respect to a magnetic field so that the magnetic flux linking the coil changes as a result of the motion. This may be accomplished either by having a small coil move in a very concentrated magnetic field or by moving a magnet past a stationary coil. In either case, nonlinearity effects will occur unless the displacement range is limited such as by mechanical stops.

A mass isolated from accelerating forces can be used as a reference against which to measure changes in velocity, since the velocity of such a mass will remain constant. Such an isolated mass may be approximated by a spring-mass system whose undamped natural frequency is well below the frequencies associated with the rate of velocity change of interest. The velocity of the base of the sensor relative to the "stationary" mass may be transduced to a proportional electrical signal by electromagnetic induction as indicated above. Devices of this type are commonly used for vibration and shock measurement. The low-frequency limit of such a sensor is set by the natural frequency of the spring-mass system. As frequency increases, the reaction forces of electromagnetic induction (including eddy currents) increase, thus imposing an upper frequency limit on the sensor. In applications involving large displacements, such as in the shipboard measurements of shock caused by waves or enemy action, the design of instruments within these limits leads to devices that are quite bulky and heavy.

It is possible to overcome some of these difficulties by means of a different type of velocity-measuring system involving electrical integration of the output of a piezoelectric accelerometer. The range limitation becomes trivial (cable length effects can be eliminated by using charge amplifiers) with such a system and the low-frequency response is readily extended to frequencies of the order of one hertz or less with an amplifier of proper design. To achieve integration with a reasonable signal-to-noise ratio, a relatively large mass is required to load the piezoelectric element and to produce a sufficiently large signal. Such a device is likely to be bulky.

Quite different approaches are used in the determination of rotary speed. The discussion which follows describes some of the methods used for this type of measurement.

4.2.2.5 Angular Velocity (Tachometer)

Rotary speed sensors may be classified into analog and digital types [9]. In analog types, the amplitude of the intelligence signal is a function of rotary speed (usually linearly proportional over the useful speed range). In digital types, the frequency or the time interval between peaks of the signal are proportional to the rotary speed. Many conventional tachometer systems are highly developed analog types.

For many industrial applications, conventional analog tachometer systems are adequate and have many desirable features, including long development and service histories, and a minimum of auxiliary circuitry. Needs arose for improved techniques for measurement of shaft speed, particularly for operation in severe temperature and nuclear radiation environments, operation over wider speed ranges, and with greater accuracy requirements. Digital tachometer sensors which are much less sensitive to environmental variations are meeting these needs.

Rotary speed analog sensors include the ac induction tachometer, which is essentially a variable coupling transformer in which the coupling coefficient is proportional to rotary speed. One winding of the transformer is excited by an ac voltage at either the line- or a carrier-frequency. An ac voltage at excitation frequency, and proportional in amplitude to the rotary speed, is obtained at the output phase winding. Rotation of the shaft of a rugged squirrel-cage or drag-cup rotor produces the shift in flux distribution which is the principle of operation of this device. This tachometer type requires a source of excitation voltage that is stable in amplitude and frequency.

DC tachometer generators are similar to the ac types but these devices can be excited by a small permanent magnet, or separately excited from a dc source. One of the chief advantages of the dc tachometer is its high sensitivity (10 to 20 V per 1000 rpm) in a very small size. One of the main disadvantages is that a commutator and brushes are required. The brushes vibrate and arc creating electromagnetic interference, and associated maintenance problems of deposits from the brushes on the commutator, and brush and commutator wear.

For applications where the direction of shaft rotation must be determined, the dc tachometer generator is useful since its output polarity is dependent upon rotational direction. The output voltage of the permanent-magnet type may be calibrated to provide an accuracy of 0.25 percent to 0.1 percent of the full-scale range.

Another analog device for measuring rotary velocity is the permanent-magnet alternator. This rotary speed sensor is similar to a constant-field synchronous generator and produces a linear output voltage proportional in amplitude and frequency to shaft speed. Performance tends to be poor at low speeds. With an auxiliary rectifier circuit on the output, a dc voltage proportional to speed over a wide range can be obtained without the disadvantages of brushes or sliding contacts. However, these devices are not suitable for measuring very low angular velocities.

The frequency characteristic of the alternator output provides a more accurate measurement of rotational speed. It is essentially unaffected by loading, temperature variations resulting from ambient conditions and self-heating, and armature misalignment caused by shock and vibration. Through the use of signal conditioning circuits, the frequency may be converted to a proportional dc voltage.

With the greater use of digital converters and signal processing, the desirability of using sensors with digital outputs has increased. This is true in the area of rotary speed measurements.

The units of measurement of shaft speed are events per unit time, most often expressed as revolutions per minute (rpm). Digital measurement of shaft speed is facilitated by using electronic counting circuits and precise time-interval measurement. If a reference mark in a readily measurable form is placed on a rotating shaft, the number of passages of the reference mark past a sensing element per unit time will provide a measure of shaft speed. If a number of reference marks are placed uniformly around the periphery of the shaft, fractions of a revolution can be detected and counted.

An ideal digital tachometer system would consist of a sensor that produces one pulse each time a shaft discontinuity passed the fixed sensor element, with signal amplitude constant and independent of shaft speed and circuit variables. If signals are nearly constant in amplitude, the pulse recognition circuits can be much simpler in design than if the signals vary widely in amplitude. Appropriate optional circuits are available to count and display, to encode, or to convert the signal repetition rate to an analog voltage amplitude.

The signal amplitude may vary due to factors such as environmental changes. The system will remain operative and accurate as long as the signal amplitude does not drop below the level of system noise or below the threshold of the recognition circuits, and as long as the signal amplitude does not increase to the point where amplifiers are overloaded. A digital tachometer system inherently has a wider range of operating conditions than has an analog tachometer system. In addition, feedback techniques may sometimes be employed to extend the operating range by adjusting sensor excitation or signal preamplifier gain to maintain a constant signal level.

Important criteria for digital shaft speed sensors are the signal-to-noise ratio and amplitude difference between the two states of the signal (pulse and no-pulse, or maximum and minimum values of alternating signals). As long as the auxiliary circuits can distinguish between the two states, shaft revolutions or sub-intervals of a revolution can be counted per unit time. Therefore, the accuracy, resolution, and dynamic range of the tachometer system will depend to a greater extent on the characteristics of the auxiliary circuits rather than those of the sensor. Although the sensor may be subjected to environmental extremes, the auxiliary circuit can be located in a more moderate and controlled environment. Degradation of signals due to losses in the transmission of the pulses between sensor and circuits will not affect performance as long as the degradation is not so extreme as to mask the signals entirely.

There are a number of ways of producing digital electrical signals proportional to speed. Two techniques can be used to produce capacitance variation as a function of shaft position: The relative position of a pair of capacitor plates can be varied or, alternately, the dielectric constant between the stationary plates can be varied.

A commonly used configuration has a capacitor formed by a metallic stator plate and a rotor attached to the shaft the speed of which is to be sensed. The capacitance rotor consists of a modification of a portion of the shaft. Since shafts may have smaller diameters, lower electrical conductivity, or higher interfering magnetic permeability than desired for the sensor, a geometry modification can be obtained by attaching a disc of appropriate shape and material to the shaft.

A variable dielectric-constant sensor operates on the principle of a rotor of variable dielectric constant moving between the fixed plates. In this case, the effective dielectric constant is a function of rotor position, and the capacitance varies cyclically for every revolution or fraction of a revolution. These types of sensors are more affected by changes in environment than are those based on moving capacitor plates.

Another system uses variations in magnetic permeability for the sensing of rotary speed. This is generally referred to as a variable reluctance sensor. A gear-type chopper (driven by the shaft) may act in the air gap of a variable reluctance sensor to change the inductance of a passive circuit element or the induced voltage for an active circuit. A form of magnetic sensor consists of a cylindrical permanent magnet and, extending from it, a pole piece surrounded by a pickup coil of copper magnet wire. The sensor generates a voltage whenever the permanent magnet field around it is disturbed. When a piece of magnetic material is brought near the head of the sensor, the lines of magnetic force shift and, in doing so, cut across the pickup coil and generate a voltage in it.

The output voltage depends upon the rate of change of the magnetic field. This, in turn, is dependent on three factors: (1) the amount of clearance between the sensor and actuating element, (2) the rate of movement of the latter, and (3), the size of the element. Output voltage tends to be inversely proportional to the clearance between the head of the sensor and the actuating element. For a given clearance and rate of interruption, sensor output is linear with the surface speed of the magnetic actuator.

The sensor can be actuated by the teeth of a gear, the blades of a turbine, spokes of a wheel, or a steel part, such as a screw, mounted on a moving nonmagnetic material. The most common application is the measurement of rotary speed from the teeth of a gear. Small-tooth gears (20-pitch or higher) produce an output that is approximately a sine wave. Coarser teeth produce a more distorted output, but the peak-to-peak voltage values are higher. The outputs for single activating masses produce waveforms similar to the coarse-tooth gear. Peak-to-peak voltages are roughly proportional to the width of the single tooth.

It is preferable to actuate a magnetic sensor with a protrusion from a metallic surface rather than with a keyway or slot in the surface. In the latter case, the sensor is closer to the entire mass of the exciting material, and consequently more vulnerable to unwanted background signal due to varying density or eccentricity of the material. On the other hand, when excitation is from a protrusion, the sensor is at a relatively greater distance from the exciting material and less likely to pick up stray signals between excitation periods. With any given speed and clearance conditions, maximum power and output results when the field of the sensor is filled with what amounts to an infinite mass of magnetic material at one instant and a complete absence of such material at the next.

It is possible to excite magnetic sensors through thin sections of a nonmagnetic substance. Such a barrier may be needed when the exciting means is in hot or corrosive environments or when it is necessary to provide a seal against pressure. With nonmagnetic separators, the output of the sensor is affected only by the increased clearance due to the separator thickness.

Metallic separators between the sensor and the actuating device reduce the output appreciably. This is due to a shortened-turn effect, since eddy currents are induced in the metallic separator. Loss of output increases with output frequency and becomes prohibitive at about 5 kHz.

Another type of sensor operates on the eddy current principle. The parameters of interest in eddy-current sensors are the inductance and resistance of air-core coil sensors. A highly conductive element attached to, or part of, a rotating shift causes parameter variations with shaft rotation. The electromagnetic field created by the sensor coil induces eddy currents in the conductive element as it passes near the coil. The eddy currents, in turn, create a magnetic field which opposes the original field. The superposition of the two fields reduces the effective inductance of the coil. For an element with finite conductivity, there is a power loss due to the eddy currents. As a result of this power loss, the effective resistance of the coil is increased.

In common with other magnetic sensors, the Hall effect permits the transduction of mechanical quantities to an electrical output without physical contact. When a magnetic field is applied perpendicularly to the current in a conductor, the moving charges which constitute the current are deflected by the Lorentz force in a direction perpendicular to both the current and the applied magnetic field. This deflection results in a potential gradient within the conductor, and a voltage appears between the two edges of the semiconductor parallel to the current direction. This voltage is proportional to the vector cross-product of the magnetic flux density and the current. It is independent of the rate of change of flux, at least for changes occurring in time intervals greater than 10 ns. A semiconductor device employing the Hall effect can be used to sense the change of position of mechanical assemblies independent of their velocity.

Where it is undesirable to connect a tachometer mechanically to a device because of the small energy (torque) available, or when the measurand speed is very high, an optical tachometer pickup may be used. Such devices are capable of measuring speeds from a few rpm to 300 000 rpm (5000 rps) or even higher. A typical device includes a light source which illuminates the rotating part provided with alternate reflecting and absorbing surfaces and a phototube which converts the reflected light into electrical pulses. Alternate opaque and translucent surfaces can also be used.

While incandescent lamps and phototubes can be used as sources of light and light detectors, recent developments in solid state light sources (LED, lasers) and solid state light sensors make these preferred components. Solid state components can be physically small, rugged, use little energy, and are relatively inexpensive. They may, however, be more vulnerable to environmental conditions such as high temperature, humidity and nuclear radiation.

The most current manufacturers literature should be consulted prior to the selection of the components for any optical tachometer system to determine their environmental degradation.

4.2.2.6 Acceleration

The measurement of acceleration is of great importance in many technologies. In general, acceleration is measured by means of a spring-mass system, with the spring fixed to the case of the instrument which is in turn attached to the structure to be tested as shown in figure 3. It is readily shown that, for frequencies which are low with respect to the undamped natural frequency of the system, the displacement of the mass with respect to the frame of the instrument is proportional to the acceleration imparted to this frame.

As the frequency is increased, the displacement per unit acceleration, and hence the sensitivity of the accelerometer, changes in a manner which depends on the damping of the spring-mass system. The theoretical relationships are sufficiently important to warrant the following detailed treatment.

The relative displacement, x, in such a system is given by a second-order differential equation with constant coefficients, $\ddot{m}x + cx + kx = F$, where m, c, and k are the mass, damping coefficient, and spring constant, respectively, and F is the external force applied to the system. (The dot denotes differentiation with respect to time.) The following terms are commonly used as a measure of the degree of damping:

Damping Coefficient (c): The damping force per unit velocity, in the above differential equation.

Damping Constant (a): The Napierian logarithm (base e = 2.718...) of the ratio of the first to the second of two values, separated by unit time, of an exponentially decreasing quantity; $a = c/2m$.

Logarithmic Decrement (δ): The Napierian logarithm of the ratio of two successive peak amplitudes in the same direction;

$$\delta = 2\pi c / \sqrt{4mk - c^2}.$$

Damping Ratio (c/c_c): The ratio of the damping force per unit velocity, c, to the value $c_c = 2\sqrt{mk}$ of this force which would make the system critically damped. This ratio is often expressed as "percent of critical damping."

Damping Factor (e-et): The ratio of the first to the second of two values separated by time t, of an exponentially decreasing quantity having a damping constant a.

(Q): A measure of the sharpness of resonance, by analogy with electrical systems. For small damping, Q is nearly equal to the magnification at resonance. At the undamped natural frequency, $Q = (2c/c_c)^{-1}$.

A measurement of acceleration by a spring-mass system is thus converted to a measurement of relative displacement, and the methods available include in principle all the methods discussed in connection with displacement measurements. The most commonly used transduction principles include potentiometers, bonded and unbonded strain gages, devices based on changes in self-inductance, linear variable differential transformers, vibrating wires, capacitive, piezoresistive, and piezoelectric devices.

Tables 2, 3, 4, and 5 outline the advantages and disadvantages of these transduction elements.

Acceleration is usually measured in terms of g -units (where g is the acceleration of gravity: approximately 32.2 F/s^2 or 0.81 m/s^2). In case of high accuracy measurements, the actual local gravitational acceleration value which g represents must be specified.

It is well to think in terms of two types of acceleration measurements: slowly changing, or quasi-static, accelerations such as are encountered in moving vehicles of all types; and vibratory and shock accelerations associated with machinery and explosions, and also with certain biomedical phenomena. In some tests, the two types of acceleration occur simultaneously and the demands on the instrumentation may become quite severe.

Measurements of slowly changing acceleration are often related to guidance or other high-accuracy functions and hence require sensors and associated instrumentation of the highest accuracy. Force-balance or servo types are well suited to this application. Accuracy is attained, however, at the expense of high-frequency response and ability to withstand large shocks.

On the other hand, measurements of vibration and shock often do not require accuracy better than 5, 10, or even 20 percent. In view of the large range of vibration and shock amplitudes at different points of a structure or vehicle, particularly for frequency components above several hundred hertz, high accuracy at a single point may have little value. The requirements for accelerometers suitable for vibration and shock measurements generally include a high resonant frequency, extremely rugged construction free of subsidiary resonances, very low response to accelerations at right angles to the sensitive axis, a mass that is negligible in its reaction upon the structure to be tested, small temperature effects, small sensitivity to sound and to ambient pressure changes, and low electrical noise generation by motion of the connecting cable. These characteristics may be achieved in a number of designs of piezoelectric accelerometers but always at the expense of the ability to follow very-low-frequency acceleration changes.

Measurement requirements for the two types of acceleration are fundamentally incompatible. Considerable compromise of performance in the fundamental requirements would have to be made to use a single instrument for both types of measurements. Thus it is a common practice in missile technology, for example, to use separate devices for the two types of acceleration measurements. Since these devices generally have different masses and cannot be mounted at the same position, the records may not agree in the range of frequencies in which both devices measure correctly. Considerable effort has been made to develop accelerometers having compromise specifications that make them suitable for low-frequency accelerations and for vibration and shock applications. These include strain-gage types having resonant frequencies above 1500 Hz and capacitive devices with frequency-response characteristics controlled by air damping.

4.2.2.7 Sensing Technologies

The discussion above pointed out that acceleration sensors produce output signals in response to displacements or forces due to the acceleration. The transduction principles used are then the same as those discussed in the chapters on pressure and displacement and summarized in tables 2, 3, 4, and 5.

Nevertheless, it is useful to discuss in more detail some transduction principles as they apply specifically to acceleration sensors. It has already been pointed out that piezoelectric sensors essentially combine to force acting on the piezoelectric crystals. The geometry of the sensors is relatively simple, involving in each case a seismic mass acting on the piezoelectric transduction element. Three principal designs are used: compression design (excellent temperature characteristics, high sensitivity), shear design (insensitive to base bending), and bender design (high sensitivity with small mass).

As pointed out earlier, piezoelectric sensors are self-generating and require no external excitation. On the other hand, they have no output for a constant acceleration and therefore cannot be calibrated statically. This can be a distinct handicap when accurate calibrations are required. The high frequency capabilities of piezoelectric sensors make them useful for the measurement of environmental vibration and shock. Such measurements do not require high accuracies because other factors cause measurement uncertainties which are often much greater than the errors associated with the sensor itself. They include effects of the sensor on the system to be measured uncertainties of high frequency dynamic calibrations, lack of inherent damping, and non-homogeneities of materials.

Damping of an accelerometer is an important subject. Most sensors are basically single or multiple spring-mass systems with little damping. Consequently, their amplitude response increases as the resonant frequency is approached. It is necessary to have a flat amplitude-frequency response and constant (or linear) phase-frequency response in order to measure transient accelerations without distortion. If the lowest resonant frequency of the system is far above the frequency range of interest, as is usually the case with piezoelectric acceleration sensors, there is not much of a problem. If, on the other hand, the frequencies of interest extend close to, or even beyond, the resonant frequency of the sensor, damping must be provided.

The most common approach to damping is the use of a liquid to provide (viscous) shear damping between the moving seismic mass and the enclosure of the acceleration sensor. Silicone oils are frequently used because of their stability, chemical inertness, and small temperature coefficient of viscosity. It can be shown that damping ratio is directly proportional to the viscosity. Thus as viscosity decreases (with rising temperatures) damping decreases as well. This results in changes in the dynamic characteristics with changes in temperature, a factor which cannot be overlooked in evaluating the dynamic performance of accelerometers. For shear damping to be effective, significant movement between seismic mass and case is required, consequently, it can only be applied to low frequency accelerometers. Piezoelectric sensors cannot be effectively damped.

One other type of acceleration sensor deserves mention: namely, the servo (or force balance) accelerometer. In operation, a linear or pendulum acceleration-sensitive element feeds a servo amplifier that provides a torque or force balance to the input. Motion of the acceleration sensing element generates an error signal which is amplified to generate the electromagnetic restoring force which counteracts the motion and restores the sensing element to its undisturbed position. The output signal is thus proportional to the restoration force and is a measure of the applied acceleration. Electrical damping is inherent to servo systems and can be varied to suit the requirement. This type of damping is not dependent on temperature.

Servo accelerometers can be highly accurate, stable, and sensitive, and often serve as secondary standards. They also tend to be large, delicate, expensive, and have a limited frequency range.

4.2.2.8 Angular Acceleration

The previous discussion has been generally applicable to both linear and angular acceleration measurements. Angular acceleration is more difficult to measure primarily because such accelerometers are more difficult to design and calibrate. Generally, the calibration of angular motion sensors is more difficult since they are also sensitive to linear motions in certain planes. Angular accelerometers tend to be large devices, with low natural frequencies.

One design uses a balanced beam, able to rotate about a center suspension. Springs keep the beam in a fixed position normally. The beam deflects when angular acceleration acts on it and thus deflection (displacement) produces an output signal. Liquid damping is provided between beam and enclosure. In another design, liquid in a ring-shaped enclosure, in response to angular acceleration, provides a reaction force on a fixed "paddle." The deflection of this paddle is sensed electrically.

Very few calibration methods have been developed for angular accelerometers. In some cases, it is possible to sense angular motions with the aid of two linear accelerometers mounted equidistant from the axis of rotation about which motion is to be measured.

The general subject of the measurement of angular acceleration (torsional vibration) is covered in detail in reference [62].

4.2.2.9 Jerk

The characteristic of motion which is of interest under conditions of rapidly changing forces is sometimes the rate of change of acceleration, or jerk. As indicated by the above definition, jerk is expressed in g -units per second, meters per second^3, or feet per second^3. The major applications for jerk measurements have been in connection with physiological measurements, where it appears that discomfort and injuries from transient motions correlate well with the measured jerk. Ballistocardiographic measurements render additional detail by time differentiation of the more usual velocity or acceleration traces.

An output proportional to jerk is readily obtained by electrical differentiation of the output of an accelerometer. This process is particularly simple for piezoelectric accelerometers, because these devices represent capacitive sources that require only a resistive load to perform the required differentiation.

4.2.2.10 Current Problems and Future Trends

Current problems in the measurement of motion (particularly acceleration) are reflected in the desires to have smaller and cheaper sensors, producing greater output signals and showing greater tolerance to adverse environmental conditions. This is a common desire in the transducer community.

In response to these desires, one would expect continuation of the following: the use of new piezoelectric and semiconductor materials with greater sensitivity and lower temperature effects and the increasing use of integral microelectronic signal conditioners in the sensor body.

The use of integral adaptive filters, self-calibration features, integral digitizing, and the use of fiber optics as a data link between the motion sensor and its associated signal conditioning circuitry appear as possibilities in the more distant future.

TABLE 5

(Motion) Displacement Sensors
Comparison of Transduction Elements
Additional to Those Covered in Tables 2, 3, and 4

Type	Advantages	Disadvantages
Eddy current	High output Continuous resolution Static and dynamic response Direct conversion to digital possible	ac excitation only Frequency response limited by excitation frequency Sensitive to magnetic fields Vibration sensitive
Digital encoder optical	Digital output Good resolution for large range	Light source vibration sensitive Detector radiation sensitive Poor resolution at small displacements
magnetic	Digital output Good resolution for large range	Sensitive to magnetic fields Poor resolution at small displacements
inductive	Digital output Good resolution for large range	Sensitive to magnetic fields Poor resolution at small displacements
Permanent magnet[a]	Self-generating output	Output frequency dependent Magnet temperature sensitive Massive

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[a] This principle is used primarily for velocity sensing.

4.2.3 Flow

4.2.3.1 Introduction

Fluid flow measurements are of great importance in propulsion systems and vehicles, chemical process industries, and in the transfer of certain types of goods. The flowing media may be liquid, gaseous, a granular solid, or a combination of these. The flow may be laminar or turbulent, steady-state or transient.

Flow measurement methods may be categorized into two basic methods. The first method uses devices to measure quantity of fluid such as weight or volume tanks or positive displacement meters. This method is frequently used as a means of calibrating flow rate devices, or in applications involving relatively steady flow and the need for direct output indication. Examples are gasoline pumps and home gas meters. Flowmeters using this method are unlikely to be used in conjunction with ATE systems and are not discussed further in this section.

The second method uses devices such as obstruction meters, velocity probes, and certain other special methods. Brief descriptions of common types of these flowmeters follow in later sections.

Rate meters may be defined as those in which the fluid stream continuously passes through the meter without being interrupted or broken up into discrete quantities and counted. The flow rate is inferred because of some action of the fluid on the primary metering element; hence, these meters are sometimes referred to as inferential meters. Established laws of fluid behavior and, in some cases, empirical data form the basis for predicting the flow rate from the measured action.

It is conventional to consider a flow sensor as divided into two parts, a primary element and a secondary element. The primary element is that portion which is in contact with the fluid stream and upon which the steam acts. The secondary element is the device that measures the action. For example, an orifice plate is the primary element in an orifice type meter and the differential pressure sensor which measures the flow-induced pressure drop across the orifice plate is the secondary element. In the measurement of gas pressure, the static line pressure sensor is also part of the secondary element. Thus a complete flow sensor may consist of more than one actual sensor.

Other meters have only one secondary element as the flow sensor. For example, a transverse-momentum mass flowmeter's primary element, a turbine, is acted upon by the steam to produce a force that is directly proportional to the mass rate of flow. The secondary element must detect the magnitude of the force and provide an output signal.

4.2.3.2 Material Compatibility Factors

The same considerations which were discussed in section 3.5 for pressure sensors also apply to flowmeters. In addition, abrasion becomes an important factor in the selection of materials of construction for flowmeters. Additionally, the presence of particles in the fluid may deposit debris at pressure taps or interfere with the rotation of turbine impellers. Thus the selection of a flow sensor should take into account possible long-term deleterious effects of the measurand fluid on the performance of the sensor.

4.2.3.3 Units of Flow

Fluid flow, or more correctly rate of flow, is measured and expressed in two different ways: as volumetric flow rate or as mass flow rate. The choice depends partly on the use made of the measurement and partly on the type of sensor.

Volumetric flow rate is most commonly expressed in gallons per minute for liquids and in cubic feet per minute, or cubic feet per second for gases. In the SI system, volumetric flow rate units are cubic meters per second. The term liter (cubic decimeter) as applied to the volume of liquids and gases is permitted by the SI system; hence, volumetric flow rate could also be given in terms of liters per minute or second.

To facilitate conversion of units, the following conversion table is given for volumetric flow rates [5]:

1 gallon per minute (gpm) = 3.78541 liters per minute (lpm)
1 liter per minute (lpm) = 0.264172 gallons per minute (gpm)
1 cubic foot per minute (ft^3/min) = 28.317 liters per minute (lpm)
1 liter per minute (lpm) = 0.035314 cubic foot per minute (ft^3/min)
100 000 gallons per minute (gpm) = 6.30902 cubic meters per second (m^3/s)
1 cubic meter per second (m^3/s) = 15 850.3 gallons per minute (gpm)

Mass flow rate is usually expressed in terms of pounds (mass) per minute or kilograms per second in the SI system. In the case of gases, mass flow rate may be expressed as equivalent volume flow at "standard" conditions (20 °C and 14.7 psia) in "standard" units as standard cubic feet per minute or standard cubic centimeters per minute.

A brief conversion table for mass flow rate follows:

1 pound per minute (lb/min) = 0.00755987 kilograms per second (kg/s)
1 kilogram per second (kg/s) = 132.277 pounds per minute (lb/min)
1 standard cubic foot per minute (ft^3/min) = 28 316.9 standard cubic centimeters per minute (cm^3/min)
100 000 standard cubic centimeters per minute (cm^3/min) = 3.53146 standard cubic feet per minute (ft^3/min).

4.2.3.4 Range Considerations

It is difficult to classify flow sensors into specific ranges, since most flow measuring principles can be applied to most ranges. Generally, restrictive (orifice) type sensors can be used in very large diameter pipes for the measurement of very large flow rates. Variable area and vortex-shedding sensors are normally used at intermediate flow rates and pipe diameters.

Turbine meters can be used in very small diameter pipes, however, a minimum flow rate is required for proper operation of the turbine. Manufacturers literature should be consulted for specific information.

4.2.3.5 Sensing Techniques in General

The sensing elements which respond directly to the flow rate of a fluid fall into three general categories:

(a) A section of a pipe or duct with a restriction of some sort which produces a differential pressure proportional to flow rate. This differential pressure can then be measured by a pressure sensor.

(b) A freely moving, or elastically restrained, mechanical member which responds to the moving fluid either by rotating (such as a turbine impeller), by deflecting (such as a cantilevered or drag body), or by a vertical displacement in a tapered tube (such as a float in a variable-area flowmeter).

(c) The fluid itself, with one of its physical characteristics interacting with the transduction element (such as the cooling of a heated wire by the fluid).

A flow rate measurement may be required in terms of mass flow rate when volumetric flow is actually measured. However, if the fluid density is known, the mass flow rate can be computed from the volumetric flow rate.

The description of flow sensors which follows is based largely on the chapter "Flow" by R.L. Galley in the ISA Transducer Compendium [8]. Additional information can be found in two other publications dealing with flowmeters [10,11].

Table 6 presents a comparison of some of the advantages and disadvantages of the most common types of flow sensors. These are also discussed in the following sections.

4.2.3.6 Differential Pressure Flow Sensors

Classified as obstruction meters, the orifice plate, the flow nozzle, and the venturi all operate on the principle of an obstacle placed in the path of the flowing fluid, causing localized changes in the velocity of flow. Concurrently with the velocity change, there will be a pressure change in accordance with Bernoulli's law. At points of maximum restriction, hence maximum velocity, minimum pressures are found. From the measurement of the pressures at fixed locations on either side of the obstruction, the flow rate can be calculated. A certain amount of pressure is lost by the fluid when passing through any obstruction meter.

(1) Thin-Plate Orifice Meters

The thin-plate orifice meter consists of a thin, flat plate with a circular hole (orifice) bored through and mounted in the flow conduit perpendicular to the flow. Most often, the plate is held in place between pipe flanges.

This is the most widely used flow rate sensor. Calibration factors (discharge factors) are widely known and have contributed to a relatively high degree of accuracy for concentric orifices in a wide variety of flow line sizes, from 2 inches through 42 inches.

As previously mentioned, the orifice is usually mounted concentric with the bore of the pipe because (1) this configuration is easiest to manufacture; and (2) the empirical factors are most exactly known. However, in some cases, eccentric or segmental orifice plates may be useful. They are usually recommended where solid matter in the fluid stream might collect in front of a concentric plate, resulting in inaccurate metering.

Pressure taps are precisely located in the conduit. The standard location of the taps may vary from one industry to another or even within an industry. Some of the more common terms used to describe tap locations are flange taps, pipe taps, vena contracta taps, and corner taps. Each set of standard tap locations is associated with a particular set of discharge coefficients. The most extensive data are available for flange or pipe tap locations. The use of either of these standardized sets of coefficients will facilitate computation because of existing step-by-step calculation tables.

For accurate measurements, a method must be applied to assure laminar flow of the fluid. This is commonly done with a long, straight length of pipe upstream of the orifice plate, sometimes aided by straigtening vanes. A shorter length of straight pipe downstream of the plate is provided to reduce the effect of downstream disturbances.

The pressure drop or differential head across the orifice plate must be measured. This is performed with instruments ranging from ordinary manometers to more sophisticated differential pressure sensors of various types. The "dry-type" differential pressure sensors are gaining in popularity, since the fluid does not contact the sensor and they reduce corrosion problems of the pressure sensor. A variety of pressure sensors are used for the differential pressure measurements required for flow sensing. Section 4.2.1 gives detailed information on pressure sensors and their characteristics.

The basic orifice meter is not inherently a wide-range meter because the flow rate is directly proportional to the square root of the differential pressure. Therefore, if the differential pressure sensor has an effective sensing range of twenty to one, the orifice flow sensor as a whole will have a range of the square root of twenty or only about four and one-half to one. Various techniques and methods have been developed to increase the range.

One of the standard techniques is that of multiple meter runs. As the flow changes, by-pass pipes (meter runs) are either opened or closed automatically to keep the flow and hence the pressure differential within the necessary range for accurate metering. Major suppliers specializing in orifice meters can provide such equipment.

Another method automatically changes the size of the orifice plate. This method, traditionally done manually, has been mechanized such that the orifice assemblies will be substituted from a selection of plates automatically. These assemblies are made in several ranges and sizes and for various working pressures; therefore, they may prove to be quite popular.

The detailed calculations necessary to obtain useful information regarding flow rate or total flow have often caused the engineer to use some type of automatic method to provide direct readings of flow. A variety of analog electronic circuits now exist which can perform the desired functions; some are integral with the flow sensor. The use of electronic digital computers has introduced digital methods for calculating flow from pressure differentials.

(2) Flow Nozzles

The flow nozzle operates on the same theory as the orifice, the principal distinction being that the entrance is streamlined. This tends to produce discharge coefficients much nearer to unity than those of an orifice meter. It has been suggested that this is an advantage, because higher flow rates can be measured.

The International Standards Organization (ISO) has done a great deal to standardize the flow nozzle. Another standard configuration includes the ASME long-radius flow nozzle. It differs from the ISO flow nozzle in that the ASME inlet shape is a quadrant of an ellipse, while the ISO nozzle shape is composed of sections of two arcs. The ISO nozzle is also shorter. As with orifice meters, various tap locations have been proposed and offered. These include pipewall taps, throat taps, and corner taps.

Any secondary elements that are applied to orifice meters are also suited to most flow nozzle applications. One exception to the rule comes from the fact that many flow nozzles are employed for free discharge to the atmosphere, while thin-plate orifices are not usually used in this manner. The effect of entrance conditions is much the same for a flow nozzle as for a thin-plate orifice meter.

(3) Venturi Meters

The venturi meter has both the entrance and the exit streamlined. Its purpose is to provide a measurable change in static pressure between the entrance and the throat; however, it must create a minimum of disturbance in order that a significant portion of the energy of the stream may be recovered, i.e., to minimize permanent pressure losses.

Simplified, the convergent entrance may have an included angle of about 20 to 25 degrees, followed by a straight throat and a divergent exit (diffuser) with an included angle of from 5 to 15 degrees. Normally either six or seven degrees of divergence will provide excellent recovery. Wider angles are used primarily to shorten the total length of the venturi, but at some expense in lost energy.

Various modifications of the venturi have been employed. In all cases, however, the venturi depends upon the diffuser to recover kinetic energy as pressure. Contrary to some beliefs, venturis are not more accurate than orifices or nozzles. Again, secondary sensors are similar to those used for orifice plates or flow nozzles.

Although the basic form of the venturi has not changed radically in over 50 years, it is still widely used in various water and steam applications; its design is not likely to undergo drastic change in the future.

Relative merits of the three obstruction devices can be briefly summarized as follows:

Orifice meters

Advantages:	Disadvantages
Inexpensive	Poor pressure recovery
Low space requirements	Inaccuracy due to wear
Moderate cost	Prone to damage by transients

Flow nozzle meter

Advantages:	Disadvantages:
High accuracy	More expensive than orifice
Moderate pressure recovery	Difficult to install properly
Low space requirements	

Venturi meter

Advantages:	Disadvantages:
High accuracy	More expensive than others
Good pressure accuracy	High space requirements
Resistance to abrasion	

(4) Pitot Tubes and Pitot-Static Tubes

The pitot tube consists, in its simplest form, of a small, open-ended tube that is parallel to the line of flow. The impact of the flowing stream produces a change in pressure, above static pressures, that is proportional to the kinetic energy of the stream.

This holds true for subsonic flow, for example, mach numbers below 0.4 where the mach number is the ratio of flow velocity to the velocity of sound in the fluid. As sonic velocity is approached and exceeded, other, more complex laws apply. They are predictable, however, and are routinely employed in all phases of wind tunnel testing, in-flight tests, etc.

The pitot tube is a valuable research tool, but it has not been widely applied as an industrial flow transducer. This is simply because the conventional forms are intended to measure the fluid velocity at a particular point. Some specialized designs have been adapted to infer total stream flow by individual calibration.

Specialized forms of pitot tubes have been adapted to determine the direction, as well as the magnitude of the flow. Again, these are very useful in research work.

(5) Linear Resistance Flowmeters

All previously discussed flow sensors were based on Bernoulli's theorem and are basically nonlinear devices. The linear resistance flowmeter (sometimes referred to as friction meter) has a very different characteristic. In it, the pressure differential across the primary element is linearly related to the flow rate. This is due to the fact that the flow is maintained in the laminar flow range. Capillary tubes and porous plugs form the primary elements and their small passages and low velocities result in low Reynolds numbers, or laminar flow.

Linear resistance flowmeters are most useful at low flow rates. They are commonly used in laboratory work where clean fluids are being metered. Particles in the fluid may cause the primary element to act as a filter and thereby cause a change in the linear relationship with flow.

The linear resistance meters are usually calibrated for each particular application, a procedure necessitated in part by the fact that pressure differential is also related to the fluid viscosity.

(6) Critical Flow Nozzles

These are similar to flow nozzles in appearance. They are used only in gas flow applications. Critical flow nozzles may be defined as those that have a sufficiently low pressure ratio between the throat static pressure and the upstream total pressure to produce a stream velocity at the throat that is equal to the sonic velocity (at throat conditions). The critical pressure ratio for a given gas is determined by the ratio of specific heats, usually somewhere between 0.5 and 0.6 for most gases. At any pressure ratio below the critical value, the sonic velocity exists at the throat.

Suppose that the upstream pressure is maintained constant and the downstream pressure is gradually reduced. The flow rate will increase until the critical pressure ratio is attained, but no further increase in mass flow will be obtained by decreasing the downstream pressure to pressure ratios that are below the critical value. On the other hand, suppose that the downstream pressure is maintained constant and the upstream pressure is gradually increased. In this case the flow rate will increase as well. Below the critical pressure ratio, the velocity at the throat increases with increasing pressure. This causes the flow rate (either mass flow rate or "standard" volume) to increase. This point is commonly misinterpreted by those who are not familiar with critical flow nozzles.

Critical flow nozzles have been employed to calibrate large and remotely located gas meters. They have been used for years in steam work, or in any other place where an expansion exists to the extent that the critical pressure ratio is obtained. Steam tables list the sonic velocity at various conditions. A recent survey of pressure and velocity head flowmeters appears in reference [63].

4.2.3.7 Fluid Velocity and Mass Responding Sensors

The second major group of flow sensors is based on the force exerted by the flowing fluid on some fixed or moving member, the deflection or movement of which is an indication of the flow rate. A recent survey discusses some of these [63].

1. Area Meters

Area meters may be defined as fluid meters that have a constant pressure differential and in which the area is changed with varying flow rate. The area change is usually brought about by a change in level of a float in the fluid conduit.

There are two types of area meters: (1) the tapered tube and float type (rotameter); and (2) the cylinder and piston type. Because of the wider acceptance of the tapered tube and float, only that type will be discussed.

2. Tapered Tube and Float Meters

This meter consists of a float (or bob) suspended in a tapered tube. The flow is upward, causing the float to assume a particular position for a specific flow rate. The position of the float is also a function of the fluid density and viscosity. This consideration is most important in gas metering.

The tube is made of a wide variety of materials, including glass, plastic, and metals. Glass tubes provide a simple method of visually observing the position of the float and therefore the relative flow rate. Opaque materials require a more elaborate secondary element. A common approach is to detect the float position with a magnetic follower. Plastic or resin-coated tubes may be used for applications involving corrosive materials. Metal tubes may be used where high pressures are encountered. Different ranges can be achieved in the same tube by using floats of different densities.

Much of the art of designing a satisfactory float and tapered tube meter has been associated with the material and shape of the float. Manufacturers are able to provide special designs for various applications.

3. Force Meters

Force meters are available for both open-channel flow (hydraulic pendulum used to determine velocity of liquids) and closed-channel flow. Those used in closed-channel flow depend upon some force being exerted on the primary element by a change in the momentum of the stream. This discussion will be limited to closed-channel flow. There are various types.

4. Drag (or Lift) Meters

These may be defined as meters that are acted upon by the stream to generate a force, which is measured and from which the flow rate can be inferred. In practice, the configuration is such that the force is directly proportional to the kinetic energy of the fluid stream and therefore to the square of the flow velocity. Hence the output is nonlinear.

The principle underlying this type of meter is very old, but has not been widely used except in hydraulics. This could possibly be attributed to the past lack of good force sensors. The principle employed in this primary element is also commonly used as a method for detecting flow in "off-on" type switch systems.

5. Velocity Meters

Velocity meters are fluid meters whose primary element is driven at a constant rotational speed by the fluid stream, but which does not break the stream into nominally discrete segments (as in quantity meters). The secondary elements may be similar to those used on quantity meters, because either rotor speed (for flow rate sensing) or cyclometers (for totalized flow) may be used.

This classification includes at least two types for open flow, the cup anemometer (for measuring wind velocity) and propeller meter, neither of which has great industrial significance.

6. Turbine Meters

The sensing element is a rotor with blades (usually helical) which is mounted in the flowing stream with its center of rotation corresponding with the centerline of the pipe. When freely suspended, the rotor will turn at a speed directly proportional to the velocity of the stream. Special designs that tend to minimize bearing drag or friction are available. The transducing element is usually a magnetic pickup of some type, e.g., a magnet in the tip of each rotor blade may energize a coil in the pickup at the wall of the conduit. These meters are available in a wide range of sizes, from laboratory sizes to very large pipeline sizes. Generally, they are employed in liquid measurement; however, gas models are also available.

7. Mass Flowmeters

A mass flowmeter represents another classification of force-sensing flow devices and may be defined as a flow-measuring device in which the action upon the primary element by the fluid stream is nominally proportional to the mass rate of flow. In the three main categories, which collectively may be called "transverse-momentum mass flowmeters," a force or torque is produced that is linearly related to the mass flow rate. To fulfill this requirement, fluid stream properties such as density, pressure, temperature, viscosity, and Reynolds number (which determines whether flow is laminar or turbulent) should have a negligible effect upon the meter within its design operating range.

Transverse-momentum mass flowmeters all operate on some momentum or inertia principle. Newton's second law of motion (force being proportional to the product of mass and acceleration) is universal to all head meters. The principle of these meters makes them true mass flowmeters. They all require power to drive some part of the meter.

8. Axial Flowmeter

This meter is composed of two parts, a turbine and an impeller, that comprise the primary (sensing) element. The impeller is driven by a motor at a constant speed, imparting an angular momentum to the stream. The turbine is stationary, and it extracts angular momentum. This causes a torque on the turbine shaft that is directly proportional to the mass rate of flow.

These meters were originally developed about 1950 for military applications. Since then, they have been applied to many industrial applications over wide flow and pressure ranges for both gases and liquids.

9. Gyroscopic Mass Flowmeter

In this type of meter, the liquid measurand is made to flow around a circular loop of pipe which is in a plane perpendicular to the input line. Following one pass around the loop, the fluid is returned to the input axis. During the rotation, the fluid develops angular momentum. When the loop is vibrated through a small angle about an axis in the plane of the loop, an alternating gyro-coupled torque is developed. The peak amplitude of this torque is directly proportional to the mass flow rate. By measuring the torque or converting it into a measurable displacement, mass flow rate can be sensed.

Such directly sensing mass flow rate sensors tend to be more complicated, delicate, and expensive devices than the other types discussed above.

Another approach to mass flow measurements is discussed below.

10. Inferential Mass Flowmeters

This type of mass flowmeter consists of two or more sensor sections that may be combined in a prescribed manner to provide an output that is a function of the mass flow rate.

For example, a velocity meter output may be multiplied by the output of a density sensor. When properly calibrated, this combination will give a single output linearly related to the mass flow rate. Other types of inferential mass flowmeters exist.

There is a great deal of interest in these schemes at present. Suitable secondary elements may be connected to existing primary elements (such as orifice plates) to provide an indication of mass flow rate or to measure total flow. Computing circuits or mechanisms are an inherent part of these meter types.

4.2.3.8 Flow Sensors Based on Physical Characteristics of the Fluid

1. Electromagnetic Meters

These are based on the principle that an electromotive force is generated when a conductor is moved through a magnetic field so as to cut the magnetic flux lines. The fluid stream acts as the conductor and the magnetic field is maintained electrically. The electromotive force is directly proportional to the velocity of the conducting fluid stream and is measured with the aid of two electrodes across the conduit.

This type of meter is now widely accepted. It is necessary that the fluid be a conductor of electricity, and this has limited its application. One of its more interesting applications is for slurry measurements, a difficult task for most meters. By the use of plastic coatings, this meter can be rendered very resistant to corrosion.

2. Acoustic (Sonic/Ultrasonic) Flowmeters

In the acoustic flowmeter, sound waves are propagated downstream and upstream. The time interval required for the waves to move known distances is measured. The velocity of the stream may be computed by using the time interval, the distance, and the velocity of sound in the fluid. This computation is usually performed electronically.

They are good for corrosive fluids, slurries, and other difficult metering problems. Acoustic flowmeters have the important advantage of being able to be clamped on the outside of the pipe carrying the flow to be measured without altering the structure in any way except to clean the outside surface.

Acoustic flowmeters using Doppler principles and others which use electronic cross-correlation to measure fluid-transit time are in various stages of development.

3. Tracer Type Meters

These introduce a foreign substance into the fluid stream and measure the time required for the substance to travel a known distance. The distance traveled, divided by the elapsed time, is the average velocity of the fluid stream.

Salt is the foreign substance commonly used in water measurements and detection is achieved with conductivity measuring devices. In petroleum pipeline work, a ball or "pig" may be introduced and its passage detected mechanically. This basic method is used in "pipe-type" meter provers for quantity meters in petroleum applications. It is an acceptable secondary standard.

In gas and liquid measurement, radioactive material may be introduced and its passage detected by radiation detectors.

4. Thermal Flowmeters

Thermal flowmeters are of two types. The first type is known as the hot-wire anemometer. It operates on the principle of the fluid cooling a heated temperature sensor. It is used to determine fluid velocities in experimental work. It is especially sensitive to small velocity changes. Hot-wire anemometers must be calibrated if good accuracy is to be achieved. They are somewhat delicate and are not widely used in commercial applications.

The second type of thermal flowmeter uses the transport of heat by the fluid over a known distance as a measure of the fluid velocity.

5. Magnetic Resonance Meter

Flowmeters using nuclear magnetic resonance are commercially available. They have produced excellent results for applications in petroleum products, pipelines, chemical processing plants, in the measurement of jet and rocket propellants, and liquid hydrogen.

Using nuclear magnetization imparted to the fluid, the flow measurement is made from outside the pipe wall; no electrical, mechanical or optical contact with the fluid is required although the pipe wall must be nonconductive. This results in a straight through, nothing-in-the-stream design and a flowmeter that has the appearance of a thick-walled pipe spool. The direction of the nuclear magnetization in the fluid is modulated at one point and a component of the magnetization is detected downstream at a distance equal to one diameter. The frequency of the modulating signal is controlled in order to maintain a fixed phase difference between the modulation signal and the detected signal by means of an external, phase-locked, solid-state, servo loop. The modulating frequency is, therefore, proportional to the flow velocity and is read out on an electronic counter for totalization.

6. Laser-Operated Meter

The Doppler shift of laser light scattered from a moving fluid is a precise measure of the velocity of the fluid. The Doppler shift is detected by optical mixing (heterodyning) of the scattered beam with a reference beam from the same laser. The difference or "beat" frequency is equal to the Doppler shift and is detected with conventional electronic gear. Velocities down to 10^{-3} cm/sec may be measured in volume elements as small as 10^{-3} cm in diameter.

7. Vortex-Shedding and Swirl Meters

A more recent development in flow measuring instruments is based on a natural phenomenon known as vortex shedding. When a fluid flows past an obstruction, boundary layers of slow-moving viscous fluid are forced along the outer surfaces. If the obstruction is a bluff body, the flow cannot follow the obstacle contours on the downstream side; the boundary layers become detached and develop into vortexes which are shed from alternate sides of the body. The frequency at which they are shed are directly proportional to fluid velocity. As this vortex sheds from the bluff body, the pressure distribution also changes at that point. It is possible then to sense vortex generation through the sensing of pressures on sections of the bluff body or by means of a microphone which senses the passage of the vortexes downstream from the obstruction [10]. A somewhat similar principle is used in the swirl meter in which an obstruction causes rotating helium vortexes. The velocity of their passage is sensed by heated thermistors or microphones to yield a measure of flow rate. The principal advantage of these devices is their relative ruggedness due to a lack of moving parts.

8. Corona Discharge Mass Flow Sensor

Somewhat similar to acoustic flowmeters, the corona discharge flow sensor uses the time of a passage (or distance from its source to its detection) or ionized particles in the fluid. It's a relatively recent development [64].

There are probably more schemes for measuring fluid flow than for any other measurand. It should be kept in mind that many of the schemes are somewhat experimental, not fully proven and may not have the dependability and predictability required of components of military ATE systems. Advantages and disadvantages of the common flow measuring systems are summarized in tables 6 and 7.

4.2.3.9 Current Problems and Future Trends

There are areas of fluid metering that pose special problems. One of these is pulsating flow. Although pulsating-flow theory has been advanced by research in recent years, no ideally suited meter is yet available. Within certain ranges of pulsation amplitude and frequency, meters such as turbine meters and certain mass flowmeters may be applied. Hot-wire anemometers have been used in some area of pulsation research.

Another problem area is two-phase flow. There are many applications in chemical, petroleum, and petrochemical industries in which the fluid exists in both the gas and the liquid phase. For processes involving chemical reactions, it is very desirable to know the total fluid rate (the most useful form would be either mass or weight per unit time).

Slurry measurement still poses problems in many cases. There are flow transducers available for certain slurries, but all of the problems are not yet solved.

Flow Sensors
Comparison of Common Operating Principles

Type	Advantages	Disadvantages
Differential pressure	No moving components Available in many sizes Suitable for most gases and liquids Orifice need not be flow calibrated Widely established	Square root pressure/flow relationship Usable flow range limited to 4:1 Accuracy deteriorates with wear Accuracy affected by density, viscosity, and flow profile Unrecoverable pressure drop
Turbine	High accuracy and repeatability Linear output 10:1 flow range Suitable over wide pressure and temperature conditions Fast response High reliability	Not suitable for high viscosity fluids Calibration required Subject to wear of moving component Can be damaged by overspeeding or gassing
Variable area	Low cost Linear output 10:1 flow range Constant low pressure loss Suitable for very low flow rates	Must be mounted vertically Bulky Limited flow and pressure capability Suitable for clean fluids only
Electromagnetic sensor	No moving parts Unobstructed Linear output Suitable for slurries and abrasive liquids Unaffected by viscosity Pressure, temperature, or density	Liquid must be electrically conductive Not suitable for gas Calibration required Expensive Sensitive to asymetric flow profile Electrodes must be kept clean

TABLE 7

Flow Sensors
Comparison of Common Operating Principles

Types	Advantages	Disadvantages
Vortex shedding	Good accuracy and repeatability Calibration not required Suitable for gas or liquid Digital or analog output Wide flow range No moving parts	Not suitable for dirty or abrasive fluids Not suitable for viscous liquids Limited maximum pressure and temperature Limited resolution
Hot wire anemometer	No moving parts Negligible head loss Simple installation	Delicate Damaged by corrosive gases Requires constant gas composition Requires complex signal conditioning circuitry
Deflecting vane drag body	Sensitive Suitable for bidirectional flow Rugged No rotating parts Good resolution Fast response	Square force/flow relationship Sensitive to viscosity Some obstruction of flow
Mass flow rate gyroscopic angular momentum	Direct mass flow rate output Accurate	Complicated Expensive Need for external power input Sensitive to vibration
Acoustic	Mountable on outside of pipe Rugged	Sensitive to temperature Sensitive to changes in flow profile Requires complex signal conditioning circuitry

At ordinary process temperature and pressures, certain gases depart dramatically from the ideal gas laws. The departures are not always well known or predictable. This makes computations from quantity, inferential, and volumetric meters extremely difficult and of doubtful accuracy.

The more commonly encountered problems of extremely low temperatures (cryogenic) or high fluid and/or ambient temperatures and the problem of developing corrosion-resistant meter bodies depend largely upon advances in construction materials rather than advances in the science of fluid flow measurement itself. Certainly the increasing use of microcomputers as integral parts of sensing devices will be applied to flow sensors. In view of the fact that flow rate, in the case of a number of the described sensing principles, is inferred rather than directly measured, signal processing and computation within the sensor appears a logical aim.

As in other areas of sensing, the environment in which such combined mechanical and electronic systems are forced to operate will have a critical effect on the overall performance and durability of flow sensors. It is likely that sensors without moving parts (such as acoustic, electromagnetic, and vortex-shedding types) will be used increasingly because of their greater ruggedness.

4.2.4 Temperature

4.2.4.1 Introduction

Temperature is among the most widely measured parameters. It is also probably that physical quantity which has been measured for the longest span in the history of technology. Liquid-in-glass thermometers, bimetallic elements, thermocouples, and resistance thermometers are widely used and of great importance to the monitoring of industrial processes, machinery, and the health of human beings.

Apart from the specific application considerations, which will be discussed later, the most important factor about temperature measurements is that a temperature sensor can only measure its own temperature. To some extent, the introduction of any sensor into a measurand system will disturb that system and modify the measured parameter. This is particularly true in the case of temperature measurements.

The temperature of the measurand must be inferred from the output of the sensor by carefully considering all the factors which may influence the sensor's ability to measure correctly, as the following example indicates.

A thermocouple in a hot gas stream will report an apparent temperature which will have an additional impact energy (stagnation) component, modified by radiation loss from the tip of the couple and conduction loss along the thermocouple wire. In addition, both chemical and physical, time-related processes will change the thermoelectric voltage generated as a function of time. The use of a protective thermal well will further modify the measurements made by the thermocouple.

Careful consideration of the sensors and measurement system is necessary to assure continuing and meaningful measurement. In this handbook, discussion will be restricted to temperature sensors with an electrical output. These include thermocouples, metallic resistance thermometers (RTD), metal-oxide resistance temperature sensors (thermistors), and semiconductor temperature sensors.

Table 10 shows some of the advantages and disadvantages of different sensing-transduction elements.

4.2.4.2 Materials Compatibility

Materials compatibility is of particular importance in the case of temperature sensors with electrical outputs. High temperature measurands can affect the materials of a thermocouple (particularly) of other temperature sensors by causing changes in physical and electrochemical characteristics. These result in changes in the temperature-sensitivity characteristics, resulting in measurement errors. A more subtle effect, investigated at NBS, concerns the catalytic action of some thermocouple materials in hot gas streams, resulting in increased temperatures at the thermocouple due to catalyst-enhanced oxidation [12].

The selection of temperature sensor materials to insure compatibility with the measurement environment can be critical. Often thermal wells or protective sheaths are used to avoid the effects discussed. In these cases, however, the temperature sensor may no longer indicate the desired measurand temperature and its response time may be degraded as well.

4.2.4.3 Units of Measurement

Units of temperature are probably better known than for any other measurand. The most common units are degrees Celsius (1.8 degrees Fahrenheit) and degrees Fahrenheit (0.5555 degrees Celsius). Some equivalent references follow:

0 degrees Celsius (C) = 32 degrees Fahrenheit (F)
0 degrees Celsius (C) = 273.15 degrees kelvin (K)
0 degrees Fahrenheit (F) = 459.67 degrees Rankine (R)

It seems desirable to discuss briefly temperature scales based on the section on temperature in the "ISA Transducer Compendium" [8].

The experimental basis for the concept of temperature is the zeroth Law of Thermodynamics: Two systems in thermal equilibrium with a third are in thermal equilibrium with each other. To establish an empirical temperature scale, some system is selected arbitrarily as the basis for a standard thermometer and a set of arbitrary rules is adopted for assigning numbers (temperatures) to its isotherms. The number (temperature) assigned to any isotherm of the standard thermometer is also assigned to the corresponding isotherm for every other system. Then, for any two systems connected through a conducting wall, difference of temperature means that heat will flow and equality of temperature means thermal equilibrium.

The International Practical Temperature Scale is an operational procedure designed to solve the problem of referring measurements by actual instruments to the thermodynamic scale. The International Practical Temperature Scale is based on a series of fixed points (freezing and boiling points) to which specified values of temperature have been assigned, and on the use of specified means of interpolation and extrapolation. This scale, as adopted in 1968, is based on eleven fixed and reproducible equilibrium states to which are assigned numerical values according to their respective thermodynamic Celsius temperatures as follows:

TABLE 8

Fixed Points on International Practical Temperature Scale

	Fixed Point	Temperature (°C)
t.p.*	Hydrogen	-259.34
b.p.	Hydrogen (25/76 atm.)	-256.108
b.p.	Hydrogen	-252.87
b.p.	Neon	-246.048
t.p.	Oxygen	-218.789
b.p.	Oxygen	-182.962
t.p.	Water	+ 0.01
b.p.	Water	100
f.p.	Zinc	419.58
f.p.	Silver	961.93
f.p.	Gold	1064.43
	Secondary Fixed Points	
f.p.	Tin	231.9681
f.p.	Lead	327.502
b.p.	Sulfur	444.674
f.p.	Antimony	630.74
f.p.	Aluminum	660.37

* t.p. - triple point
b.p. - boiling point
f.p. - freezing point

The International Practical Temperature Scale is divided into four ranges using three different instruments for interpolation. The range from the triple point of hydrogen (-259.34 °C) to the freezing point of water (0 °C), is measured using a standard platinum resistance thermometer and the resistance value is corrected to temperature using a special equation with values of deviations from other fixed points in the range for relating temperature to resistance. The next higher temperature range from the freezing point of water (°C) to the freezing point of antimony (630.74 °C) also uses the standard platinum resistance thermometer, but the resistance is converted to temperature with a modified Callendar formula. For the third range of the scale, from the freezing point of antimony to the gold point (1064.45 °C), a standard platinum and platinum-rhodium thermocouple is used and parabolic formula relates temperature to electromotive force when one junction of the thermocouple is at the temperature being measured and the other is at 0 °C. The fourth part of the range is above the gold point where temperature measurements are made with a narrow-band radiation pyrometer. The Planck radiation formula is used.

The present lower limit of the International Practical Temperature Scale at the oxygen point leaves a region below this point of less than 14 Celsius degrees where there is no defined scale. The present International Practical Temperature Scale also has no upper limit and the use of a radiation pyrometer for modern high temperatures leaves much to be desired from a practical standpoint.

4.2.4.4 Temperature Sensors (Non-Electrical)

Instruments used to measure temperature are classed as either pyrometers or thermometers. Originally the term "pyrometer" was applied only to instruments that measured temperatures above the range of the mercury thermometer. Since some of these "pyrometers" have also been used to measure temperatures in the range of the mercury thermometer, the terms "thermometer" and "pyrometer" became somewhat interchangeable. Today different meanings are attached to the two terms. If the device for measuring temperature is inserted into or attached to the body or substance that is to be measured, the device is called a "thermometer." If the device is located some distance away from the temperature source, it is classified as a "pyrometer." This concept practically limits the term "pyrometer" to radiation and optical devices. The term "pyrometric" is often applied to paints, cones, etc., and other devices used to determine maximum or minimum temperatures sustained during a given time period.

Although temperature sensors with an electrical output are of primary importance of ATE application, other types will be briefly discussed since they are often used as reference standards for calibration purposes.

In a liquid-in-glass thermometer, the differential expansion of a liquid in a closed glass system is used to indicate the temperature. The device consists of a thin-walled glass bulb attached to a glass capillary system closed at the other end, with the bulb and a portion of the stem filled with an expansive liquid. Temperature is indicated by a scale marked on or attached to the capillary. Working range is from -165 to 620 °C, the upper fixed by glass properties. Other limits are dependent upon the liquid used as follows: organic liquids (typically -200 °C to +230 °C), mercury-thallium mixture (typically -60 °C to +120 °C), and mercury(from $-39^{o}C$ to $+620^{o}C$).

Accuracy attainable with these thermometers varies, but can be as good as ±0.01 °C, depending on precision of manufacturer, calibration, scale length, and range. Similar in nature are filled-system thermometers, all-metal assemblies of bulb, capillary tube, and a Bourdon tube pressure sensor. The latter is usually provided with a dual readout. The system is filled with a liquid which changes its state or phase with temperature. This is communicated through the capillary to the Bourdon tube which provides an indication of the temperature. Such system may be filled with various gases, vapors, or liquids. Mercury is also used. Temperatures sensed by such systems may extend from as low as -240 °C to as high as 815 °C, depending on system design and materials. They generally have uncertainties of about ±1 percent of the range.

Another type of mechanical thermometer is the bimetallic thermometer.

The operation of these thermometers depends on the difference in thermal expansion of two metals. The instruments consist of an indicating or recording device, a sensing element called a bimetallic thermometer bulb, and a means for operatively connecting the two. Bimetallic thermometers are available in ranges from -130 to 540 °C. For continuous operation an upper limit of 430 °C is more suitable. The industrial type has a nominal error of 1 percent and the laboratory type has an error of 0.5 percent of span.

4.2.4.5 Thermocouples

Among temperature sensors with electrical output, thermocouples are probably the most widely used and useful devices.

In these devices the electromotive force developed in a circuit comprised of two dissimilar metals is used to measure temperature. The voltage developed across a thermocouple junction is uniquely established by the materials of the junction of the two metals. The system consists of a sensing element (thermocouple), which produces the electromotive force, a device for measuring electromotive force, and electrical conductors for connecting the two. The range of these devices depends on the materials used in their construction as shown in table 9 which follows.

TABLE 9

Commonly Used Thermocouples [8]

ANSI Type	Thermocouple Material	Nominal Temperature Range (°C) Lower	Upper	Approximate Sensitivity mV/100 °C
B	PLATINUM, 30% RHODIUM-Platinum, 6% Rhodium	870	1650	0.45
E	CHROMEL-Constantan	0	870	7.6
J	IRON-Constantan	-185	760	5.6
K	CHROMEL-Alumel	0	1260	4.1
R	PLATINUM, 13% Rhodium-Platinum	0	1480	1.0
S	PLATINUM, 10% Rhodium-Platinum	0	1480	0.90
T	COPPER-Constantan	-185	370	4.7

*Positive material in capital letters

The accuracy of thermocouple wire (deviation of emf-temperature relationship from standard tables) depends on the material of the wires, the range, and the grade used. Two grades are available commercially, "standard" and "special." Special wire is that which has been selected from standard grade and matched to provide emf-temperature relationships that match the tabular values with a deviation about one-half that of the standard grade. The National Bureau of Standards has published extensive tables with these values [68]. For greater accuracy either grade of thermocouple wire may be calibrated.

The accuracy characteristics of commercial thermocouples appear in the following table.

TABLE 10

Accuracy Characteristics of Thermocouples From ANSI Standard MC96.1-1975 [13]

ANSI Type	Temperature Range, °F	Limits of Error	
		Standard	Special
J	32 to 530	±4 °F	±2 °F
	530 to 1400	±3/4%	±3/8%
K	32 to 530	±4 °F	±2 °F
	530 to 2300	±3/4%	±3/8%
	-300 to -75	± -	±1%
	-150 to -75	±2%	±1%
T	-75 to 200	±1-1/2 °F	±3/4 °F
	200 to 700	±3/4%	±3/8%
E	32 to 600	±3 °F	±2-1/4 °F
	600 to 1600	±1/2%	±3/8%
	32 to 1000	±2-1/2 °F	±2-1/2 °F
S,R	1000 to 2700	±1/4%	±1/4%
B	1600 to 3100	±1/2%	-----

Some of the characteristics of the different thermocouples are discussed in this section, extracted from the "1979 Temperature Measurement Handbook" by Omega Engineering [14].

(1) Iron-Constantan (ANSI Symbol J)

The Iron-Constantan "J" curve thermocouple with a positive iron wire and a negative constantan wire is recommended for reducing atmospheres. The operating range for this alloy combination is 1600 °F for the largest wire sizes. Smaller size wires should be used only at the lower temperatures because of the large surface-to-volume ratio; chemical effects due to temperature which can change thermocouple characteristics become apparent after shorter periods of time [65]. This is true of all types of thermocouples.

(2) Copper-Constantan (ANSI Symbol T)

The Copper-Constantan "T" curve thermocouple with a positive copper wire and a negative constantan wire is recommended for use in mildly oxidizing and reducing atmospheres up to 750 °F. It is suitable for applications where moisture is present. This alloy is recommended for low temperature work since the homogeneity of the component wires can be maintained better than other base metal wires. Therefore, errors due to inhomogeneity of wires in zones of temperature gradients are greatly reduced.

(3) Chromel-Alumel (ANSI Symbol K)

The Chromel-Constantan thermocouple may be used for temperatures up to 1600 °F in a vacuum or in an inert, mildly oxidizing or reducing atmosphere. At sub-zero temperatures, the thermocouple is not subject to corrosion. This thermocouple has the highest emf output of any standard metallic thermocouple.

(4) Platinum-Rhodium Alloys (ANSI Symbol S, R and B)

Three types of "noble-metal" thermocouples are in common use; they are: 1) a positive wire of 90% platinum and 10% rhodium used with a negative wire of pure platinum, 2) a positive wire of 87% platinum and 13% rhodium used with a negative wire of pure platinum, and 3) a positive wire of 70% platinum and 30% rhodium used with a negative wire of 94% platinum and 6% rhodium. All have a high resistance to oxidation and corrosion. However, hydrogen, carbon, and metal vapors contaminate a platinum-rhodium thermocouple. The recommended operating range for the platinum-rhodium alloys is up to 2800 °F, although temperatures as high as 3270° can be measured with the Pt-30% RH vs Pt-6% RH alloy combination.

(5) Tungsten-Rhenium Alloys

Three types of tungsten-rhenium thermocouples are in common use for measuring temperatures up to 5000 °F. These alloys have inherently poor oxidation resistance and should be used in vacuum, hydrogen, or inert atmospheres.

4.2.4.6 Resistance Thermometers

The basis for resistance thermometry is the fact that most metals and some semiconductors change resistivity with temperature in a known, reproducible manner. A resistance thermometer consists of a sensing element called a resistor, a resistance measuring instrument, and electrical conductors for connecting the two. A resistor may consist of a metallic sensing element, usually in wire form, having known reproducible and stable temperature-resistivity characteristics. More recently semiconductor devices have become available, which are basically variations of silicon transistors with special output current-temperature characteristics. They are small, inexpensive, with good linearity, but have a somewhat limited temperature range.

A thermistor is a special type of resistor (semiconductor) comprised of a mixture of metallic oxides. These are substances whose electrical conductivity at or near room temperature is less than that of metals but greater than that of typical insulators. Thermistors have a high negative temperature coefficient, in contrast with most metals, which have a positive coefficient. Their measurement range depends on the materials used in construction.

The most commonly used metallic resistance thermometer is made of platinum. Of all usable metals, platinum best meets the requirements of thermometry. It can be highly refined. It resists contamination. It is mechanically and electrically stable. The relationship between temperature and resistance is quite linear. Production units can be made closely interchangeable in calibration. Drift and error with age and use are negligible.

(1) Platinum Resistance Thermometers

Platinum resistance thermometers are used for temperature measurements in the range -220 to +600 °C (standard), to 750 °C (special order). The maximum temperature is determined by the type of insulation material used to enclose the platinum winding. The heart of the platinum resistance thermometer is the sensing element, made of high-purity platinum wire wound upon a ceramic core. The sensing element is carefully stress relieved and immobilized against strain or damage. It is normally protected by a stainless steel sheath.

Production units supplied by most manufacturers are closely interchangeable in calibration. To achieve stability of measurement, elements are artificially aged during fabrication, hence no further aging is observed with elements in glass up to 500 °C and ceramic up to 600 °C. Either glass or ceramic encapsulated resistances can be used up to 600 °C.

In its laboratory form the platinum resistance thermometer is the world standard for temperature measurement from -270 °C to +660 °C. In its industrial version, performance approaching that of laboratory standards can be achieved in instruments rugged enough to withstand difficult process environment.

Commercial thermometers are typically of reference grade platinum (99.999+% pure), strain free, with interchangeability between units of 0.25 °C at 0 °C, and long-term drift less than 0.050 °C up to about 500 °C. They are generally supplied with a nominal resistance of 100 ohms at 0 °C, although 50, 200, 400 and 500 ohms are also available. The temperature coefficient of resistance change ("Alpha") is 0.003902 ohms per ohm per degree C ("American" curve, used in the U.S.).

Precautions and compromises encountered in using other types of electrical temperature sensors are less important for platinum sensors. Connecting leads may be platinum, nickel, or copper depending on temperature environment and application. Since the calibration is absolute, cold junction compensation is not necessary. The linear response eliminates corrective networks and errors in interpretation. Freedom from drift makes frequent calibration unnecessary.

In the application of platinum resistance thermometers, attention must be paid to the time constant of the sensor-sheath system if rapidly changing temperatures are to be measured. Other factors to be considered include the self heating due to the current through the resistor and error signals due to electromagnetic induction.

(2) Thermistors

Another major class of resistance temperature sensors is represented by thermistors. Most of the following information is extracted from the "1979 Temperature Measurement Handbook" by Omega Engineering [14].

Thermistors are essentially metallic oxide semiconductors which behave as "thermal resistors"--that is, resistors with a high (usually negative) temperature coefficient of resistance. In some cases, for example, the resistance of a thermistor at room temperature may decrease by almost 6 percent for each degree C rise in temperature.

In use thermistors operate as either "self heated" or "externally heated" units. When externally heated they convert changes in ambient or contact temperatures directly to corresponding changes in voltage or current. They are well suited for precision temperature measurement, temperature control, and temperature compensation because of their very large change in resistance with temperature. This provides a degree of resolution, or of gain, not available with other sensors. Externally heated thermistors are widely used for such applications in the range of -100 °C to over 300 °C.

Self-heated units employ the heating effect of the current flowing through them to raise and control their temperature, and thus their resistance. Under normal operating conditions the temperature may rise 200 °C to 300 °C, and the resistance may be reduced to 0.001 of its value at low current. This operating mode is useful in such devices as voltage regulators, microwave power meters, gas analyzers, vacuum gauges, flowmeters, and automatic volume and power level controls, but not in temperature measurements.

Probably the most familiar property of the thermistor is the fact that, within certain limits, its electrical resistance is almost entirely a function of its temperature. More important, this temperature dependence is so great that, over the range of -100 °C to 400 °C, there may be a change of as much as 10 million to one in its resistance. The result is an extremely high sensitivity (many times greater than that of thermocouples and resistance bulbs, for example). This makes the thermistor an unusally effective sensor for temperature measurement, control, and compensation, particularly where accuracy and high resolution are important.

The temperature coefficient of resistance of a thermistor (which, unlike that of most materials, is negative) may be expressed as:

$$a = \frac{1}{R} \frac{\Delta R}{\Delta T} \quad \text{ohms/ohm/}^{\circ}\text{C, or \%/}^{\circ}\text{C}$$

The resistance-temperature behavior of individual thermistor types is usually specified by the ratio of the resistance at 0 °C to the resistance at 50 °C.

In temperature measurement applications the thermistor's relatively large resistance change per degree change in temperature provides good accuracy and resolution. A typical 2000-ohm thermistor with a temperature coefficient of 3.9%/C @25 °C will exhibit a resistance change of 178 ohms per degree C change in temperature, compared to only 7.2 ohms for a platinum resistance bulb with the same basic resistance. Connected in a simple bridge circuit with an indicating galvanometer, a thermistor will readily indicate a temperature change of as little as 0.0005 °C. It is a simple matter with such a circuit to obtain a 1 °C full-scale output. This high sensitivity, together with the relatively high thermistor resistance which may be selected, makes the thermistor ideal for remote measurements or control, since changes in contact, , resistance, or transmission line resistance, due to ambient temperature effects have a negligible effect on the measurements. For example, 400 ft of #18 AWG copper wire transmission line subjected to a 25 °C temperature change will affect the accuracy of measurement or control by less than 0.05 °C.

One of the drawbacks of thermistors is their nonlinear resistance-temperature characteristics. For narrow ranges of sensing this is less critical. For wider ranges of measurement thermistor linearizing networks can be designed in the form of resistance bridges. Current work is leading to thermistors with greater long-term stability, the ability to operate at higher temperatures, and thermistors with positive temperature coefficients of resistance [66].

(3) Semiconductor Temperature Sensors

A relatively new class of sensors makes use of the properties of semiconductors like silicon. These devices may be in the form of two terminal resistors of heavily doped p-type silicon with a positive temperature coefficient of 0.7 percent per degree C. This type of sensor is quite linear over its measuring range from -65 °C to about 200 °C without resort to any linearizing network.

Another type of semiconductor temperature sensor makes use of an actual transistor defect: junction instability. In this device the highly predictable correlation between temperature and transistor base-to-emitter voltage of a bipolar transistor, which is roughly 2 millivolts per degree C, is used to sense temperature. There are also integrated circuits which act as constant-current elements. The current through the circuit is dependent on temperature. Such circuits are capable of good linearity and a temperature range up to about 150 °C.

The field of semiconductor temperature sensors is rapidly changing and growing. Future trends appear to lead to such sensors of smaller size, faster response, better linearity and interchangeability, and lower cost [67].

4.2.4.7 Radiation Temperature and Heat Flux Sensors

All the temperature-measuring methods discussed so far require the temperature sensor to be in contact with the body whose temperature is to be measured. There are applications where it is not possible or desirable to have this direct contact. There are methods for inferring the temperature of an object from its thermal radiation. Such sensors are called radiometers, radiation pyrometers, or radiation thermometers. Another consideration is that there are measurement situations in which measurement of heat transfer rates (heat flux) are required. This is further complicated by the fact that heat transfer can be by radiation alone or by convection (in gas or liquid media) or by a combination of the two.

Radiation-temperature sensors operate on the principle that every body above absolute zero in temperature emits radiation dependent on its temperature. The radiant intensity varies with wavelength, with peaks of radiative power occurring at wavelengths inversely related to temperature. The total radiated power is directly proportional to the fourth power of the absolute temperature. In radiation thermometers, the radiation is focused on a detector which produces an electrical signal. Thermal detectors are blackened elements designed to absorb a maximum of incoming radiation at all wavelengths. The absorbed radiation causes the temperature of the detector to rise until equilibrium is reached with heat losses to the surroundings. Thermal detectors, such as resistance thermometers or thermocouples, measure this temperature. Photon detectors also are used to sense thermal radiation. They operate on the principle that incoming radiation (photons) frees electrons in the detector structure and thereby produces an electrical output. Through photoconductive or photovoltaic effects, proton detectors have a sensitivity that varies with wavelengths, and they must be taken into account in radiation measurements [69].

Heat flux measurements are somewhat similar in that one measures the temperature rise of a body, such as an insulated metallic slug of known mass or a thin foil. The rate of rise of temperature of the slug is proportional to the rate of heat transfer to the slug. The thin foil sensor is bonded at its periphery to a metallic body. Usually foil and body meterials are chosen so as to produce a thermocouple which measures the temperature difference between the center and the edge of the foil. This temperature difference is directly proportional to the rate of heat transfer to the foil. The section "Heat Flux" in the ISA Transducer Compendium [8] provides more detail.

Optical temperature measurements and heat flux measurements are quite complex. Disadvantages of the former are difficulty of correcting for emissivity in converting from measurements of emitted radiation to a measurement of temperature, the need for line of sight measurements, and difficulties with radiation-transmitting windows covering the sensor.

Heat flux measurements are also strongly influenced by knowledge of the emissivity of the sensing body by the heat leakage from the sensor to its surroundings and by the mode of heat transfer (radiative, convective, or a combination). There are also a number of other factors, some of them time-variant, discussed in the above-cited reference [8].

Calibration of optical and heat flux sensors is difficult as well, but essential to obtain an indication of the validity of the measurements. As indicated above, radiation temperature and heat flux measurements are usually resorted to only when it is not possible to make contacting temperature measurements.

4.2.4.8 Selection of Temperature Sensors

The many secondary phenomena associated with changes in temperature often tend to be confusing for engineers. Where the object is the measurement or control of temperature itself, however, the broad assortment of effects (and of sensors that detect them) is a decided advantage and the problem often becomes simply a matter of selecting the optimum sensing technique from among a number of possibilities.

Frequently, for industrial or military applications where continuous temperature ranges are to be monitored, the choice is limited by practical considerations to three familiar devices: thermistors, resistance thermometers, and thermocouples.

Some general considerations in the selection of sensors are discussed in section 3.2. In the case of temperature sensors, some additional factors need to be considered in their selection and are discussed below.

Type of Measurement - Resistance-temperature devices such as thermistors and resistance thermometers provide a direct indication of absolute temperature. Thermocouples, on the other hand, which measure the temperature differential between two junctions of dissimilar metals, provide a relative measure. For direct temperature indication, one thermocouple junction must be accurately maintained at, or compensated to, a known reference temperature.

Temperature Range - Thermistors are available for measuring temperatures from a few degrees above absolute zero to about 315 °C. They can be used at higher temperatures but tend to decrease in stability above 300 °C. Platinum resistance thermometers normally have a range of -183 °C to about 1100 °C, while platinum-irridium alloys can be used up to about 2200 °C. Nonlinearity of resistance change increases, of course, at temperature extremes.

Thermocouples are available for use up to more than 3300 °C. Accuracy at extremely high and low temperatures is usually limited.

Sensitivity - The sensitivity of resistance-temperature transducers is a function of the temperature coefficient of resistance or the change in resistance resulting from a unit change in temperature. A typical platinum resistance bulb will exhibit a change of less than 0.06 ohm/°C at room temperature. Thermistors, on the other hand, provide changes of from about 6 ohms to 6×10^4 ohms/°C under the same circumstances. (Between -100 °C and 400 °C the resistance of a thermistor may change by ten million to one, compared with a change of about four to one in the resistance of platinum over the same temperature range.)

Due to the large voltage outputs provided by a typical thermistor bridge or by a typical thermistor telemetering circuit, no amplification is required. The voltage output of a thermistor bridge at 25 °C will be 18 millivolts/°C using a 4000 ohm thermistor; 450 times greater than that of a Chromel/Alumel thermocouple whose output is only 0.040 millivolts/°C.

Thermistor control systems are inherently sensitive, stable, and fast acting, and require relatively simple circuitry. Neither polarity nor lead length is significant, and no reference temperature or cold junction compensation is required, as with thermocouples.

Accuracy - In general, thermistors and resistance thermometers provide relatively high absolute accuracies. Ordinary commercial-grade thermocouples are normally of specified accuracies of ±1 °C or less over the measurement range. Both thermistors and resistance bulbs will provide accuracies of ±0.01 °C or better. Repeatability of thermistor measurements is such that variations in repeated readings are within the overall accuracy of the measuring circuit.

Installation Effects - As indicated earlier a temperature sensor can only sense its own temperature. To what extent this value represents the temperature that is desired to be known depends on a number of factors.

The installed accuracy (indicated vs measurand temperature) is the result of complicated heat transfer effects produced by the measurand, sensor, protective housing, measurand vessel, environment, and steadiness of state. When the measurand is a moving gas or vapor, several temperatures exist simultaneously, and it is necessary to decide which should be or are being measured.

The indication of a calibrated sensor is thus subject to many influences from installation effects. In general, it is not good practice, nor are the necessary data usually available, to correct a poor installation by the use of computed "correction factors." Such factors can be in error by a greater amount than the magnitudes of the effects that they are attempting to rectify. In-place calibration, or checking by a known standard, will simply verify the correctness of the transfer function because the standard will indicate its own temperature as it too will be subject to installation effects. For realistic temperature measurement, it is necessary to make an analysis of each proposed installation, select a suitable sensor, and install it in such a manner that undesired heat transfer effects are minimized.

Sometimes the physical or chemical conditions of the measurand require that the sensor be housed in a protection device such as a tube or thermometer well. In such cases this housing becomes the "measurand" to the sensor. Since usually the true measurand temperature is the one whose measurement is desired, and since the two interact, in the discussions that follow, the term "probe" is used to mean both the sensor and its protective housing, if any. This approach considerably simplifies the discussion of some of the more common installation effects. Again, the intent is to present highlights as a reminder; for any work in depth, the references cited should be consulted.

The following discussion on factors influencing temperature measurements is extracted from the "ISA Transducer Compendium" [8].

Kinetic Energy

In a gas at rest, temperature is a measure of the random motion of the gas molecules. In a moving gas, the directed velocity may be appreciable compared with the mean velocity of random motion. In such cases two temperatures are of interest, the static or stream temperature T_s and the total or stagnation temperature T_t. For an ideal gas these two temperatures are related as follows:

$$T_t - T_s = V^2/2gJc_p$$

where V is the gas velocity, g is the acceleration due to gravity, J is the mechanical equivalent of heat, and c_p is the specific heat of the gas at constant pressure.

The attainment of T_s requires that the probe move with the same velocity as the gas; the attainment of T_t requires a probe that brings the gas to rest by isentropic compression. Neither probe can be physically constructed, so that stationary probes in fluid streams will show neither T_s nor T_t but some indicated temperature T_i. This indicated temperature depends not only on how the directed kinetic energy is brought to rest, but also on viscous and heat transfer effects in the boundary layer of the probe. The capability of a probe to affect this conversion is its recovery factor r, defined as

$$r = \frac{T_i - T_s}{T_t - T_s}$$

Although each installation should be judged on its own merits, it is generally desirable to use a probe of special design described in the literature as "total temperature" or "stagnation" when the gas or vapor velocity is in excess.

For example, the difference in $T_t - T_s$ in air at a velocity of about 100 m/s is of the order of 4° C, while at about 160 m/s it is 11 °C. An ordinary round thermometer well has a recovery factor of about 0.7, so that the kinetic energy error ($T_t - T_i$) is about 1 °C at 100 m/s and about 3.5 °C at 160 m/s. It is possible to reduce this error by increasing the size of the pipe at the point of measurement, thus reducing the fluid velocity. However, the heat transfer effects discussed in the next paragraph should be considered. In some installations the kinetic error may be insignificant, and it may actually be desirable to increase the velocity to overcome other effects.

Steady State

Heat transfer equations for probe located in a moving fluid stream where the directed kinetic energy is negligible are so complicated as to be of little value in a discussion of correction of installation effects. An approximate relationship for a probe installed in a vessel may be obtained by considering a heat balance at equilibrium:

$$h_c\,(T_g - T_i) = h_r\,(T_i - T_w) + \frac{kA}{L}\,(T_i - T_b)$$

(Convection) (Radiation) (Conduction)

where h_c is the convection coefficient of heat transfer, h_r is the radiation heat transfer coefficient, k is the thermal conductivity of the probe materials, A is the cross-sectional area of the probe at the wall, L is the length of the probe in the stream, T_i is the indicated temperature at L, T_g is the true gas temperature, T_b is the temperature of the probe at the wall, and T_w is the temperature of the vessel wall.

For purposes of analysis, the equation may be rewritten as

$$T_g - T_i = \frac{h_r(T_i-T_w) + (kA/L)\,(T_i-T_b)}{h_c}$$

It becomes readily apparent that h_c should be as large as possible. The value of h_c may be increased by increasing the mass velocity of the gas (aspiration of the measurand past the probe, or reducing the size of the duct); however, kinetic energy effects must then be considered. The convection coefficient may be increased by reducing the diameter of the probe, which within strength limitations is always good practice.

The effects of radiation may be discussed from the following elementary definition:

$$h_r\,(T_i - T_w) = Q\sigma \int_0^L Cdx\,(T_x^4 - T_w^4)$$

where Q is the emissivity of the probe surface, σ is the Stefan-Boltzmann constant, C is the circumference of the probe, x is the distance from the wall, and T_x is the temperature at x.

The emissivity of a blackbody is unity and that of a perfect reflector is zero. If the probe can be maintained in the fluid stream in a bright and shiny condition, the effects of radiation will be negligible. If the temperature of the vessel wall is the same as the gas temperature, radiation is no problem. This is usually accomplished by insulating the pipe wall at least as far as the probe can "see," and farther if possible. The smaller the probe diameter and hence its circumference C, the smaller the radiation error. When it is not practical to maintain a shiny surface, nor to insulate or reduce size, then the probe may be shielded. When shields are used, the shield temperature is higher than that of the wall ($T_w < T_g$), and the more shields used, the smaller the radiation error.

Conductivity effects may be minimized by selection of probe materials of low thermal conductivity, reducing probe cross-sectional area, and increasing the insertion length. Often in making an installation, the insulation in the area where the probe is to be inserted is removed and not replaced, with a consequent lowering of $T_b(T_w < T_g)$, and a corresponding increase in the conductivity effect. Sometimes this is done deliberately to keep the external portions of the sensor at a low temperature. Therefore, care should be exercised in the application of a sensor that makes this a necessary requirement. The insulation should always be replaced and the external portions of the probe lagged to maintain T_b as near as possible to T_g.

Dynamic Effects

It is a common practice to characterize the response of a thermal element to a nonisothermal state change by a thermal time constant. No one time constant can describe the response characteristics of anything but a simple, idealized element. For purposes of discussion, consider a probe with first-order response. Within the probe there is no resistance of heat flow, so that the probe itself is pure capacitance. Resistance to heat flow is in the fluid film only. The only mode of heat transfer is by convection. The thermal time constant of this idealized probe is

$$t = wc/h_cS$$

where t is the thermal time constant, w is the mass of the probe, c is the specific heat capacity of the probe, h_c is the convection coefficient of heat transfer, and S is the surface area of the probe.

This equation indicates that for fast response the mass of the probe should be as small as possible, the specific heat small in value, and the surface area and heat transfer coefficient large. It should be noted that weight, specific heat, and surface area are properties of the probe itself, but that the convective heat transfer coefficient is dependent upon properties of the fluid, its mass velocity, and the diameter of the probe. The requirements of low mass and small diameter are not compatible with large surface area unless fins are used.

Although no actual probe has a time constant described by the equation, many approximate it closely enough for engineering measurement purposes. It should be noted that the time constant for a probe consisting of a protective housing and a sensor is not the same as that for either component, nor is it equal to the sum of the two. It should be further recognized that the actual time constant of the probe is a function of the installation conditions as well as of the probe. The time constant data for a sensor given in this chapter cannot be used directly unless they were determined for the exact conditions for which the sensor is to be used.

Strength Effects

Two kinds of probes are equally useless, those that measure temperature inaccurately and those that fail due to lack of strength. Factors that tend to promote accurate measurement are also those that tend to reduce strength as shown by the tabulation which follows.

It is apparent from all the above discussion that sensor selection and probe design necessarily result from a series of engineering compromises.

Ideal for Measurement		Ideal for Strength
Long-conductivity errors reduced.Active portion must be in the flow stream.	Length	Short-impingement forces reduced.Higher natural frequency.
Thin-reduced conductivity loss. Faster response.	Strength (cross-section area)	Thick-greater moment of inertia,less stress. Higher natural frequency.
High-increased heat transfer. Faster response.	Mass Velocity	Low-reduced impingement forces. Lower vortex trail frequency.

4.2.4.9 Summary

Temperature measurement is unique in that a primary standard for temperature cannot be realized. There are two basic temperature scales--one theoretical, the other empirical. Over a period of years a number of widely used temperature measuring instruments have been highly developed commercially. It is not possible to separate the performance of a temperature sensor from installation effects.

Two important areas vital to the knowledge needed for intelligent selection and application of sensors were not discussed. There are industrial and/or commercial installation "rules of thumb" and the purpose for which the temperature is being measured, which in turn creates the measurement requirement. These two areas are related because the installation practices were developed in order to meet the measurement requirement. Where experience has demonstrated that a measurement requirement is being satisfied by a "rule of thumb" such as "insert the thermometer at least x diameters into the flow stream," an analysis of the type suggested in the section on Installation Effects is a waste of both time and money.

It should be obvious from the discussion above and the theoretical relations shown that accurate temperature measurements are quite difficult. Accordingly, it is very important to carefully and realistically assess the temperature measurement accuracy required before money, time, and effort are expended on the actual measurement system. This caution applies to all sensors, but perhaps more so to temperature sensors because of their deceptively simple nature.

TABLE 11

Temperature Sensors
Comparison of Sensing-Transduction Elements

Type	Advantages	Disadvantages
Thermocouples	Low cost Simple Wide variety of types Good accuracy	Low voltage output Requires reference junction High temperatures degrade performance and life Requires stable amplifiers
Resistance-temperature detectors (RTD)	Wide temperature range Excellent accuracy Good stability Very good linearity	Higher cost Less rugged than thermocouples
Metallic (platinum)		
(nickel)	Good linearity	Limited temperature range
Semiconductor (silicon transistor)	Good accuracy Good linearity Low cost Fast response Good sensitivity	Limited temperature range
(Thermistor) (metal oxide)	Moderate accuracy Excellent sensitivity Fast response	Limited temperature range Nonlinear Requires aging

4.2.5 Force and Torque

4.2.5.1 Introduction

Force and torque measurements find application in industrial and military systems. The thrust of rocket propulsion systems, the torque generated by internal combustion engines, the weight of a liquid-filled tank in a chemical plant are generally measured with sensors which measure force in terms of the displacement of an elastic element. This displacement, in turn, is converted into an electrical signal.

The homogeneity of the material of the sensor, the mechanical design and workmanship, and the transduction elements used all have a bearing on the quality of measurement of which the sensor is capable. The following material has been excerpted with permission from the ISA Transducer Compendium [8].

An understanding of the general area of force and torque measurement must be based on a familiarity with the two terms. The following are commonly accepted definitions for force and torque.

Force is either a push or pull exerted on a body. It may produce motion of the body or cause deformation of the body, or it may be balanced by an opposing force so that no motion occurs.

Torque is a force that tends to produce rotation about an axis. If the body referred to is a system of particles which is not deformed by any system of forces acting on it and the fixed distances between these particles are maintained, then the body may be considered a rigid body. Thus all particles of the body experience the same motion (provided rotation is not permitted). This allows one to consider the mass of the body as being concentrated at its center (center of gravity) and the total force as acting at this point.

Applying a force at an off-center point of a rigid body tends to produce rotation about an axis through that center. This tendency is the moment of that force, or the torque exerted by that force. Expressed mathematically, torque (T) is the product of the force (F) and the perpendicular distance (L) from the axis of rotation to the line of action of the force.

In a non-rigid or elastic body, the force or torque will result in a deformation of that body. The body will return to its original state after the removal of the force or torque, provided that the elastic limit of the material has not been exceeded. Under these conditions, the stress developed within a body to withstand an outside load is proportional to the strain to which the body is subjected by that load (Robert Hook's law).

Sir Isaac Newton's observations and interpretations of the relation between motion and the action of forces on bodies led to his deduction of the three fundamental laws of motion which bear his name. Force sensing is generally based on his second law: "An unbalanced force acting on a body causes the body to accelerate in the direction of the force; the acceleration being directly proportional to the unbalanced force and inversely proportional to the mass of the body." Expressed mathematically this becomes

$$a \propto F/m$$

where a is the acceleration of the body, F is the unbalanced force acting on the body, and m is the mass of the body. Solving equation for F, we find

$$F \propto ma$$
$$F = kma$$

where k is a constant of proportionality whose value depends on the units employed. By the proper choice of units, k will be unity, and the force is then

$$F = ma$$

where $m = W/g$ (W = weight, g = acceleration due to gravity); thus,

$$F = \frac{W}{g} a$$

It will be noted that this relation permits the measurement of acceleration in terms of force or force in terms of acceleration. See section 4.2.2 on the measurement of motion (acceleration).

The validity of Newton's laws depends on the particle concept and on the assumption of rigidity. An unbalanced force system acting at the center of gravity will thus result in a linear acceleration of the body as indicated by the relation above. Similarly, angular acceleration is related to torque by the expression

$$\alpha = \frac{T}{I}$$

where α is the angular acceleration of the body, T is the unbalanced torque action on the body, and I is the moment of inertia.

Thus, in summary, it can be stated that an unbalanced force acting on a body will cause either a distortion or a displacement on that body, depending upon the rigidity of the body. The distortion or displacement occurs in accordance with Hook's and Newton's laws governing the behavior of elastic or non-elastic bodies. The conversion of this distortion (deformation) or motion to an electrical signal provides the means to determine the value of the force. The instrument or device that performs this conversion is the force or torque sensor.

4.2.5.2 Materials Compatibility

Unlike the cases of pressure and flow, force or torque cannot inherently be corrosive or abrasive. Nevertheless, there are still compatibility problems in regards to the operating environment of the sensors and section 3.5 should be consulted for information on this.

4.2.5.3 Units of Measurement

Having defined force and torque, it is now appropriate to discuss the units in which these quantities are measured.

In the International System of Units (SI) the unit of force is the newton. The newton thus replaces the kilogram force unit and is the force which gives an acceleration of 1 meter per second^2 to a mass of 1 kilogram.

In the English system, the unit of force is the poundal, which is defined as the force required to give a mass of 1 pound an acceleration of 1 foot per second^2.

In the gravitational or technical system of units (used extensively in engineering), it is the usual practice to measure forces by scales and balances calibrated by comparing them with the pull of the earth upon standard masses. Thus a mass of n pounds (weight) is equal to ng poundals, where g is the local acceleration of gravity in feet/s^2.

1 pound force (lbf) = 4.44822 newtons
1 poundal = 0.138255 newtons
1 newton = 7.23300 poundals

The unit of torque in SI units would be the newton-meter or meter-kilogram force. In the English system it would be the poundal-foot while the technical units would be the pound (force)-foot. It is interesting to note that the units of torque and energy or work have the same dimensions in their respective systems (length times force in mass units). They are differentiated by reversing the force and length units in the product. Unfortunately, the units in the English and metric systems are interchanged which leads to confusion. Commercial torque transducers, which one would expect to be categorized in force-length units (technical units), are generally categorized in length-force units such as inch-pounds.

1 pound (force) foot = 1.35582 newton meters
1 poundal-foot = 0.0421402 newton meters
1 newton-meter = 23.7303 poundal-foot

4.2.5.4 Range Considerations

Practical measurements of force range from fractions of newtons to 5×10^7 newtons (more than 10 million pounds).

Torque measurements range from about 7×10^{-2} to 10^6 newton-meters (10 ounce-inches to 750 000 pound-feet).

4.2.5.5 Sensing Principles

A great many sensors are commercially available for monitoring force or torque. They accomplish the conversion of these phenomena to an electrical signal. Typical of the kind of parameters which are changed due to these phenomena are resistance, inductance, and capacitance. In addition, changes in some of the electro-mechanical properties of the materials themselves (permeability, dielectric strength, magnetostriction, electrostriction, and the piezoelectric effect) are also employed to produce signals related to the physical change or motion of the sensing device.

Force Sensors

Most of the force sensors presently in use are designed for the measurement of load or weight. The sensor, or load cell, is inserted between the body to be weighed and a reference platform. Since the body is at rest, a force equal in magnitude but opposite in direction to the downward pull of gravity must be balancing the weight of the body.

This balancing force, so extensively used for calibration purposes, exists in the stored molecular energy of the deformed element of the sensor. The efficiency of the mechanical-to-electrical conversion depends upon the method used to monitor this deformation (displacement).

The deformation of the load column of the sensor results in a strain at its surface. Either foil or wire strain gages are bonded to the surface of the load-bearing column. The strain is transmitted to the wire or foil strain gages via the bonding cement, changing their resistances in accordance with the relation shown in section 4.2.1.7, and given in this form:

$$\frac{\Delta R}{R} = GF\xi = \frac{\Delta L}{L}$$

where ΔR is the change in resistance of the gage, R is the original gage resistance, GF is the gage factor supplied by the manufacturer, and ξ is the strain or elongation set up in the load column and is equal to the change in length of the column divided by its original length, or $\Delta L/L$.

The usual arrangement for strain gages on such a load member is to have them "back to back," with two gages mounted axially and two radially (at right angles). The latter indicates only the lateral contraction in accordance with Poisson's ratio. This arrangement permits the electrical connection of the gages to be made in a full Wheatstone bridge circuit, thereby increasing the signal output. Any changes in the dimensions of the gages due to ambient temperature changes will affect all four gages similarly and will be cancelled out electrically.

Changing the mechanical features of the attachment devices permits the use of this type of load cell for the measurement of tension loads as well as compression loads. Other types of load cells make use of different sensing elements. Two such configurations involve the use of a load beam and the use of a proving ring. The former is usually a simple cantilever beam with strain gages bonded adjacent to the fixed end. The latter is a circular ring with gages mounted on the surface.

Various sensitivities and ranges are obtained by changing the material as well as its thickness. Ranges of the loads which can be measured vary from about a tenth of a pound force to over twelve million pounds (0.4 newton to about 50×10^6 newton). The use of unbonded strain gages, careful calibration, and benign environments can result in an accuracy of this type of load cell between 0.1 percent and 0.25 percent.

Factors which affect the accuracy are hysteresis, repeatability, and thermal sensitivity. Contributing to the hysteresis effect is the creep which occurs both between the gage wire and its carrier and between the carrier and the member to which it is bonded.

This type of load cell is capable of both steady-state and dynamic load measurement. Either dc or ac excitation may be provided the gage or gages, depending on the type of instrumentation system being employed. It should be noted that metallic wire or foil strain gages as well as semiconductor strain gages can be used as transduction elements. In addition, variable capacitance or reluctance, or differential transformers can also be used. These transduction principles are discussed in more detail in the section on pressure, 4.2.1; the advantages and disadvantages of the transduction principles are summarized in tables 2, 3, and 4.

Force gages using a piezoelectric element for the sensor are suitable only for dynamic work. Deformation of the crystal results in the generation of an electrical charge. This type of gage has a range capacity of from 1/2 ounce to over 5000 pounds (1.4×10^{-1} to 2.2×10^{4}N). The frequency range is from 2 Hz to beyond 15 000 Hz and the linearity is approximately ± 1 percent. The sensor is essentially very stiff, ensuring a very high natural frequency of the system and permitting the gage to be a load-carrying member in the structure.

Torque Sensors

The most common of the torque sensors consists of an elastic member, usually in the form of a short accurately machined shaft, which is inserted in a line of shafting between the rotating driving unit and the rotating load. In transmitting the torque, this shaft deforms (twists) and sets up shear forces normal to and along the same axis as the load. These shear forces have tension and compression components at 45° to the axis. By bonding foil or wire strain gages along these 45° components, the torque or twist is measured in relation to the tension or compression at the surface of the shaft. The gages are positioned and connected into a bridge circuit, cancelling the effects of bending and thrust strains. The bridge unbalances linearly with the amount of torsional strain.

The sensitivity of torque sensors is a function of the design. Thus, by reducing the diameter of the portion of the shaft on which the gages are mounted, the sensitivity is increased.

The torque developed in such sensors is related to the physical dimensions of the sensing portion and to the material used. Thus

$$\text{Torque} = \theta \ \frac{\pi C D^4}{32L}$$

where C is the modulus of rigidity of the material, θ is the angle through which the shaft twists, and D and L are the diameter and length of the sensing portion of the sensor. The use of a full bridge eliminates temperature-unbalance problems in the strain gages themselves, but temperature still affects the sensitivity.

The limiting items in the use of this type of torque gage are the temperature limits of the bearings, the bearing speed and the slip-ring surface speed. Until recently, a rotational speed of 5000 to 7000 rpm was maximum, and a slip-ring surface speed of 5000 ft/min was not to be exceeded if noise problems were to be avoided. For conventional slip-ring assemblies, operation to 12 000 rpm is now practical. Special designs can operate at higher speeds.

Other techniques to obtain the torque signal and eliminate the use of slip-rings involve more complex electronic circuitry and larger sensors. Two of these are magnetically coupled and optically coupled sensors. A magnetically coupled device adapts a linear differential transformer pick-off to sense the twist of one end of the torque bar with respect to the other. A primary winding of the magnetic circuit is located on the input end of the sensor. The circuit is excited by means of a carrier oscillator. As the winding (or magnetic core to which it is attached) approaches one of the secondary windings of the sensor, it moves away from the other. The induced voltage increases in the closer winding and decreases in the other, resulting in an output amplitude that is proportional to the magnitude of the torque. The relative phase of the output will depend upon the direction of rotation of the input shaft. Processing this signal through a phase-sensitive converter will result in a dc voltage whose amplitude is proportional to the torque and whose polarity is related to the direction of rotation. The frequency response of such a system is limited to frequencies up to approximately 10 percent of the carrier frequency.

Two types of optical transduction elements are available for use with torque sensors. In one of these, photocells are used to develop two separate and identical pulse trains, one from the input end of the torque shaft and one from the output end. As torque is transmitted and the sensing part of the sensor twists, a time displacement (or phase displacement) occurs between the two pulse trains. The leading edges of one train of pulses causes an electronic gate to open and allows oscillator clock signals to operate an electronic counter. The leading edges of the second train of pulses stops the counter. For a given shaft speed, the counter total is then proportional to the time displacement between the pulse trains, and thus is proportional to the torque.

In the second type of optical torque sensor, two matched sectioned or segmented discs are mounted so that one is attached to the input end of the torque shaft and the other to the output end of the shaft. Light sources and photocells are arranged and the optical discs positioned so that the light passing through the clear sectors of one disc is partially obscured by the opaque sectors of the other disc. This provides a zero-torque quiescent current. The application of torque will then vary the photocell current from this quiescent level. The quiescent current can be adjusted so that the cell output range is in the most linear portion of its characteristic range. Table 12 shows a comparison of transduction elements commonly used in torque sensors.

An additional technique which is sometimes employed to circumvent the slip-ring problem in torque sensors is by the use of small radio-frequency, telemetry transmitters mounted in the rotating member. Here the power source for both the torque sensor and the transmitter must be entirely self-contained and a suitable antenna provided for radiating the energy to a nearby receiving antenna and receiver.

4.2.5.6 Application Considerations and Problems

In the preceding discussion of typical force and torque sensors, there is brief mention of the accuracy to be expected from them. It is appropriate to expand on this aspect of the ability to measure force and torque and on the factors which limit accuracy. The accuracy of the system depends upon both the sensor and its associated instrumentation.

Nonlinearity Effects

In the conventional load cell, the load-supporting element is usually a column, loaded in compression. Within the elastic limit of the material, the length of the element decreases linearly with the load. The cross-sectional area increases in accordance with Poisson's ratio. Load cells are designed so that the compression of the supporting member is small compared to its length. The strain gage bonded to its member also functions in its linear range. By operating in this region, almost no nonlinearity is experienced. When larger portions of the range of a sensor are used, the high end of the loading curve is approached. Here a larger deformation results from each corresponding loading increment. This nonlinearity of deformation accounts for the major share of the load cell's nonlinearity. Strain gages mounted to the column will exhibit similar nonlinear behavior themselves at large loads. In addition, they will also be measuring the nonlinearity of column deformation. Special load cells with a deviation curve close to ±0.5 percent can be obtained.

Hysteresis Effect

Another factor affecting the accuracy of a sensor is hysteresis. This is characterized by a sensor output which is not the same for identical values of load, but depends upon whether the load is increasing or decreasing. Hysteresis, the maximum separation between the full-range average hysteresis loop and the calibration curve, for typical load cells, may vary between ±0.01 percent and ±0.05 percent of full scale, but can be reduced if the loading is applied in only one direction and the cell calibrated in the same direction.

Temperature Effects

A third factor affecting the accuracy of load cells is temperature, which causes two effects. The first is a change in output sensitivity due to a change in the modulus of elasticity of the load member. Nominal values for this error are approximately 0.02 percent for a 1 °C change in temperature. Second, temperature variations will cause unequal changes in the resistance of the bridge arms, changes which can affect the no-load readings by approximately 0.001 percent of full-scale output per 1 °C.

Temperature-compensating resistors are often added to the cell input circuitry to compensate for this condition. The net thermal error can be reduced to ±0.001 percent of the applied load per 1 °C. Temperature transients may also cause errors and extreme caution is required to keep them to a minimum.

Load Alignment Effects

Alignment of the load on the cell is another factor which can result in errors. The load cell can only measure the load component which is normal to its base. Thus a misalignment of the force vector by 2.5° will result in a vector force normal to the sensor base which is 0.1 percent less than the force desired to be measured (cos 2.5° = 0.999).

Repeatability and Dynamic Behavior

Repeatability of this type of load cell is approximately ±0.01 percent of the applied load, because the only moving part is the deformed load member.

It can be seen that load cells can be capable of greater accuracy than most other types of sensors, largely because as a class they are very simple mechanical systems. However, it should be noted that this is a static accuracy. The dynamic behavior of load cells has received little attention and, to the author's knowledge, there are no existing facilities for the dynamic calibration of force sensors.

In general, one would expect their dynamic behavior to be not too dissimilar to pressure sensors. That is, one would expect to find multiple resonances and little damping. The section on dynamic calibrations (6.2.2) should be consulted.

TABLE 12

Torque Sensors
Comparison of Transduction Elements

Type	Advantages	Disadvantages
Strain gage	Continuous resolution High frequency response Excellent linearity ac or dc excitation	Slip rings required Noisy Low output Bonding adhesive may creep
Magnetic element	Does not require slip rings Good sensitivity Rugged	Poor resolution
Optical element	Does not require slip rings Good sensitivity Rugged	Poor resolution

4.2.5.7 Future Trends

Study of possible future trends in force or load sensors suggests the use of integral microcomputers to correct for nonlinearity and temperature effects, combined with the use of semiconductor strain gages.

Exploration of other sensing principles will continue.

4.2.6 Level

4.2.6.1 Introduction

The discussion which follows is based largely on the chapter "Level" in the ISA Transducer Compendium [8] and is concerned primarily with liquids.

The measurement and control of liquid level is probably the simplest and oldest achievement in man's instrumentation progress. Level devices can be found wherever there are vessels that require measurement or control of liquid level. They range from the simplest toilet bowl float valve to sophisticated systems used on spacecraft. Level devices may either sense the presence of the level or measure the actual location of the level or surface.

Level devices are used frequently to control liquid levels at a specific point within a narrow band, or to comply with a programmed demand. The success or failure of a chemical process may depend upon the accurate control of two immiscible liquids. Savings of valuable space and vessel costs are realized by the accurate level control of boiler water programmed to steam demand.

Level devices are also used to maintain an inventory of stored liquids. In this regard, the accuracy of measurement may represent considerable profit or loss.

4.2.6.2 Materials Compatibility

The remarks made in this regard in section 3.5 in the chapter on pressure apply here as well. The compatibility considerations generally apply to all types of sensing systems and those parts (or components) of sensors which are in direct contact with the measurand.

4.2.6.3 Units

Level is frequently only an intermediary, i.e., that indication from which the desired measurand is inferred. A simple example is the familiar gas gage of the automobile. It is a float device which sends an electrical signal proportional to the level at which the float rides in the gasoline above the bottom of the gas tank. The dashboard indicator reading converts that into, basically, a fraction of the volume of gasoline still in the tank. Level is measured in terms of length above a specified datum plane. As will be indicated later, pressure is often used to indicate level.

4.2.6.4 Level Device Principles

Level devices are classified as either Direct Method or Inferential Method instruments.

In the Direct Method, the actual physical position of the medium is sensed or observed in relation to some datum point. The visual observation of level in a gage glass, as measured by an "inch and foot" scale, is an example of direct measurement.

In the Inferential Method, the physical position of the medium is implied by the measurement of another variable that can be related to the actual level. An example is a bubbler system as discussed in the section on head devices.

Level devices are more commonly classified by a common physical characteristic as follows:

1. Visual Devices
   Dip stick, hook gage, plumb bob and tape, open-end manometer, gage cock and gage glass.

2. Float (Power) Devices
   Floats connected by rod or tape to pointer and scale readout; rod or gear-driven switch mechanism; rod to magnetically actuated switches; rod to a pneumatic amplifier (pilot), then to an indicator or a final control element; or rod to hydraulically driven pointer.

   Floats that travel up and down a center post and either make electrical contact with a resistor wound on the center rod or are magnetically coupled to a tape and dial indicator.

3. Displacer Devices
   Hollow cylinder or sphere connected through a packless pressure barrier to a pneumatic amplifier (pilot), then to an indicator or a controller, an electrical switch, or a motor-driven tape.

4. Head Devices
   Bubbler-pressure gage, direct connected pressure gage or differential pressure detector, diaphragm box (entrapped air and pneumatically force balanced), dip tube to fluidic element.

5. Electrical or Electronic Devices
   Current through liquid-conduction, nuclear radiation, capacitance, sonic or ultrasonic, thermistor, photoelectric, radio frequency.

This handbook is concerned primarily with sensors that produce an electrical output signal. Visual devices normally do not have an electrical output. Float and displacer devices convert the level sensor into a displacement which is then transduced into an electrical signal, while devices use pressure sensors to achieve the desired output. The large number of level sensors falling under all of the above classifications are too extensive for detailed coverage in this section. Readers are referred to the technical literature for such coverage [8,9]. The following material is intended to summarize some of the pertinent characteristics of commonly used level sensors with electrical outputs.

4.2.6.5 Float and Displacer Devices

These two types of level sensors can provide an electrical output by the use of displacement or force transduction elements. Except for the fact that the actual displacements involved are usually very large, ranging from inches to tens of feet, the characteristics of the displacement sensors are quite similar to those used for other measurands. Tables 2, 3, and 4 show some of the characteristics. In view of the large physical displacements involved, speed of response tends to be slow. Absolute resolution is poor, although resolution in terms of the full-scale ranges can be quite good. A discussion of the characteristics of the sensing element follows.

In the float (power) sensor a hollow sphere is designed to float in the liquid. The vertical motion of the float is translated to an external rotational element through a bearing and stuffing tube. The rotational motion can actuate a displacement sensor, such as a potentiometer or an electro-optical encoder. A variation has the float attached to a taut perforated tape which turns a sprocket wheel, which actuates the displacement sensor.

Floats connected to tapes are primarily used to indicate level over the full range of depth of a container. Floats connected to tapes have been used to measure level in vessels to a depth of over 70 feet. Float devices are used where moving mechanical parts can be tolerated. Float devices are also well suited for applications in which level changes are slow and subject to a minimum of perturbations.

Float-to-tape devices are generally used on atmospheric or low pressure tanks and where temperatures are below 250 °F. Float-to-rod devices can be used over wide pressure and temperature ranges. A typical high temperature-pressure rating would be 600 °F and 800 psi.

Corrosive media are handled by the selection of corrosion-resistive metals, plastics, or elastometers in the manufacture of the wetted parts.

In general, float devices are simple and when properly applied and maintained will provide many years of reliable service. Many new devices appear on the market with novel techniques for coupling to switches or controls. Instead of sensing displacement, one can measure the force required to keep the float in position to overcome changes in buoyancy of the liquid caused by changes in level. Some devices use the force balance mechanism.

Displacement devices came into prominence in the late 1930's. It is thought that over 80 percent of all process type level controls employ displacement devices. They are offered by many companies. A wide variety of innovations is noticeable, particularly in the packless mechanisms, the transduction elements, and the materials of construction; however, the basic design features are similar.

These devices are essentially steady-state sensors with long response times.

4.2.6.6 Head or Pressure Devices

The approach is different depending on whether the liquid level to be sensed is in an open (to ambient pressure) vessel or a closed one. For the open vessel, a pressure indicator or sensor is connected either directly to the lower level of the vessel or through an extension tube that transmits the pressure exerted by the overhead liquid. The pressure device is calibrated in level units. The relationship is simply pressure = liquid density x liquid height above the point of measurement. It is obvious that density changes will result in erroneous readout.

A pressure sensor connected to the lower section of a vessel is a very direct and simple application. Such an installation is not suitable for media that are either corrosive or contain solid particles. A buffer fluid between the vessel connection and the pressure sensor connections is sometimes useful for these conditions.

An air bubble device may be used to avoid the problems of directly connected pressure devices. In this system air from a pressure source higher than the maximum possible vessel head pressure is bubbled through a dip tube resulting in a pressure buildup equal to the level head, because the excess air is free to flow out of the bottom of the tube. Bubbler systems are subject to clogging and air flow pressure drop errors due to operational faults.

The entrapped air diaphragm box may be used for media that are adversely affected by bubbling air. The liquid overhead pressure acting on the flexible diaphragm compresses the air entrapped in the connecting tube. The resultant increased pressure is sensed by a pressure device calibrated in level units.

For a closed vessel, a differential pressure (D/P) sensor is connected to a low level sensing point and to a point above the liquid in the vapor phase of the vessel through a reference leg. This technique is used to cancel the vessel pressure effect, because both sides of the D/P device are subject to the same pressure. The success of this technique depends upon the maintenance of a constant reference leg. One technique is to locate the D/P device above the vessel and to provide a piping installation designed to avoid the accumulation of either liquid or solid deposits in the reference leg. In a technique used in a nuclear plant pressurized water vessel, the reference leg is filled with water and is maintained at a fixed height, because steam will condense to keep the condensate pot filled to the spillover level. This technique, like all others, is subject to system errors that are best seen by an examination of the equation describing the differential pressure to level relationships:

$$\Delta P = P_2 - P_1$$

where:

ΔP - Differential pressure measured by the D/P device in psid.

P_2 - Pressure exerted on the high side of the D/P device by the reference leg R_L.

P_1 - Pressure exerted on the low side of the D/P device by the liquid uncompensated vapor heads.

$$P_2 = D_{RL} \cdot H_{RL}$$

$$P_1 = D_{ML} \cdot H_{ML} + D_{VL} \cdot H_{VL}$$

$$\Delta P = D_{RL} \cdot H_{RL} - (D_{ML} \cdot H_{ML} + D_{VL} \cdot H_{VL})$$

where:
D_{RL} - density of the reference leg.
H_{RL} - height of the reference leg.
D_{ML} - density of the measurand leg.
H_{ML} - height of the measurand leg.
D_{VL} - density of the uncompensated vapor leg.
H_{VL} - height of the uncompensated vapor leg.

From this relationship, various factors must be considered or the operational variations from calibration values will result in errors.

The special considerations include:

(1) The density of the reference liquid will depend upon the temperature gradient from the condensate pot to the detector. Vessel temperature changes and the resultant gradient changes or reference leg ambient changes will affect the reference leg density.

(2) The density of the measurand and the vapor leg will also vary with vessel temperature and pressure changes.

(3) Sudden vessel pressure decreases may cause the reference leg liquid to vaporize.

Other considerations pertaining to direct-connected pressure-type level sensors follow. Such devices are limited only by the vessel height because they are available in pressure ranges from several inches of water to over 10 000 psi. The air bubbler systems may be limited by the air pressure services available. An air supply of over about 120 psig is not commonly available.

The diaphragm box is usually applied to low head systems of 10 to 20 feet of water, but can be applied to systems of up to 100 feet of water.

Reference leg differential pressure (D/P) systems can be used in systems of up to many thousands of psi, but are often limited by the range availability of industrial D/P devices--several inches of water to several hundred psid. Despite the system design problems associated with the use of D/P detectors for level sensing, it still remains a popular solution for systems at elevated temperatures and pressures.

4.2.6.7 Electrical or Electronic Devices

Electrical or electronic level devices are characterized as sensors that generally have no moving parts, wherein a change in level results in a change in an electrical property such as current flow, capacitance, resistance, voltage, or inductance. A brief discussion of some of these devices follows.

(1) Conductivity

A current-through-liquid conduction device operates on the principle that the electrical path between a probe (electrode) and a conducting tank wall can be completed by the medium contained in the tank. The consequent current flow is used either to operate relays directly or solid-state amplifiers that are used to operate final control elements.

This type of sensor is used for media that will not ignite by arcing and that have resistivities less than 20 000 Ω-cm. Two probes can be used either for high and low level control or for narrow band control for media whose surfaces are turbulent. A sensing system with a solid-state amplifier is used for poorly conducting media with resistivities of up to 20×10^6 Ω-cm. The devices generally incorporate a sensitivity adjustment to accommodate one thousand to one or greater ratio of media resistivities. The current level in the electronic systems is well within the safe limits prescribed for flammable vapors. These devices are used primarily for control purposes with municipal water systems, a variety of chemical solutions, and boiler feed water systems. They are not proportional devices suitable for measurement of continuously changing levels.

(2) Nuclear Radiation

There are several types of nuclear radiation devices that are currently available. One consists of a gamma source (cesium 137, cobalt 60, or radium 226) located on one side of a tank, a detector located on the opposite side of the tank, and electronic circuitry for signal conditioning and indication. The intensity of the radiation received by the detector is directly proportional to the source strength and the thickness of the materials between the source and the detector. The gamma radiation absorbed by the vessel walls is a constant that is cancelled by the circuitry. The gamma absorption characteristics of the gas or vapor above the medium change the amount of gamma radiation striking the detector. The detector consists of one or more self-quenching Geiger-Muller detector tubes that convert incident pulsed gamma energy into proportional pulsed direct current. The solid-state circuitry associated with the detector provides for: regulated voltage (required to bring the detector to its operating plateau of 800 to 1100 volts), pulse shaping, integrating network (for averaging the statistical noise inherent in the system), and an output amplifier that includes gain and zero adjustments. A typical output range would be from 0 to 10 mV to 0 to 50 mV. Re-calibration may be necessary to account for half life of the radioactive source.

Nuclear radiation devices were initially developed to measure difficult media, i.e., highly viscous, or corrosive substances or media at high pressures. These devices may now be economically applied to some routine problems. These are also not proportional measurand devices.

(3) Capacitance

The capacitance level device consists basically of a large capacitor formed by the tank and a metallic sensing element (probe), with the medium (and/or gas or vapor) as the dielectric between the two metallic elements. Changes in level change the capacitance of the tank-probe capacitor, which is a part of an oscillator circuit. For single point sensing or control, the oscillator circuit is detuned when the level rises to the probe. The RF output of the oscillator circuit is converted to a rectified voltage, which is amplified and used to operate a relay or solid-state switch. If the medium has a dielectric constant between 2 and 100, a bare metal rod insulated from the tank can be used. If the medium is conducting, the probe must be insulated. This is usually done with a plastic, elastomer, or ceramic coating over the probe. An example is a plate type probe that senses the variable air capacitance between the sensing plate and the medium surface. The circuitry compares this capacitance with a reference capacitor in the sensing circuit.

The measurement accuracy of capacitance devices may be adversely affected by conditions that change the dielectric constant of the medium such as temperature, entrained gases, or suspended solids.

Capacitance level devices are applicable for a wide variety of media-water, jet fuel, ammonia, oil, paint, sewage, beer, gasoline, and a host of other products. A suitable probe insulator does not appear to have been found that will permit using a capacitance probe in high pressure water service.

(4) Sonic and Ultrasonic

There are two basic types of sonic or ultrasonic level devices. One is the acoustical loading, point-sensitive type with a sensor probe containing a driver coil wound around a magnetostrictive rod and powered by an ultrasonic oscillator. The sensitive surface of the probe attached to the rod acoustically propagates at an ultrasonic frequency only when the surface is exposed to compressible medium (gas or vapor above the liquid). The sensor probe also contains a pickup or signal coil wound around the rod that generates a sympathetic ultrasonic signal. The signal is fed into a circuit that triggers a relay or solid-state switch for indication or control. This occurs when the medium contacts the sensitive probe and dampens its oscillation. Devices of this type are available that operate at sonic frequencies as low as 120 Hz. Such devices are available with wet to dry signal ratios of 1000:1 and a sensitivity of 0.002 inch of level change. They are not affected by changes in dielectric constant, viscosity, temperature, resistivity, pressure, density, clinging droplets, coating buildup, or foam.

The second type of sonar device can be used for continuous level sensing. In this system a pulsed sound wave is generated and beamed to the target (the medium interface). The sound wave bounces off the interface and is reflected to the sensor's receiver. The device measures the time for the pulse to travel from the transmitter to the receiver and provides a signal that is related to level. Sonar devices are available with sensitivities of 0.01 inch per foot of distance from the transmitter receiver to the level surface. The receiver-transmitter head may be designed for locating at the bottom of the tank or at the top of the tank. The accuracy of this device may be adversely affected by changes in the density of either the liquid medium or the gas, which in turn affects the speed of sound through the sound-carrying medium.

Sonic and ultrasonic devices have a range of applicability similar to that of capacitance devices.

(5) Thermistor

The thermistor level device senses a point change through a change in the resistance of a self-heated, probe tip mounted thermistor. This is due to the ability of the medium to conduct heat away from the sensor probe as the level rises to cover it. An ac voltage is impressed across the thermistor to produce self-heating. Changes in ambient temperature around the probe are a source of error and must be compensated for in the design. A technique used to eliminate a source of error employs a second thermistor that is not self-heated, but which changes its resistance in response to temperature changes. This resistance is used in the measuring circuit to cancel out the effect of ambient temperature change. The circuitry consists of a differential amplifier that compares the resistance at the self-heated thermistor to a set point resistance selected with the sensitivity control potentiometer.

Since the thermistor is basically a temperature device, its accuracy will be affected by those conditions that adversely affect the heat transfer rate of the probe. The response time is also slower than other point-level devices but is reported to be nominally one second.

Thermistor level devices are applicable to most media that will not experience wide variations in temperature. Other temperature sensors such as thermocouples and resistance thermometers using similar techniques have been applied successfully. Most recently silicon semiconductor sensors have become available, using self-heating-induced resistance changes as indicators of the presence or absence of liquids.

(6) Other Sensor Types

Similar in principle to sonic level sensing are techniques which use other types of propagating waves. Optical light-sensing devices are used to seek the location of interface levels using reflection or transmission of light. Radio-frequency and microwave techniques have also been described in applications whose opaque materials prevent optical sensing.

The characteristics of electrical and electronic devices discussed are summarized below.

TABLE 13

Summary of Characteristics of Electrical and Electronic Level Sensors [8]

	Point Sensing	Continuous Sensing		Typical Rating	
Device Type	Typical Accuracy	Typical Range	Typical Accuracy	psi	Degrees F
Current probes	±1/16 in	-	-	500	400
Nuclear radiation	±1/8 in	8-72 in	-	-14 to +160	unlimited
Capacitance	±1/8 in	1 in-12 ft	±2% FS	1000	-100 to +450
Sonar	-	1-25 ft	2-3% FS	600	-40 to +350
Ultrasonic	better than 0.1 in	-	-	1000	0 to 500
Thermistor	±1 in	-	-	3000	15 to 300

4.2.6.8 Application Considerations

The calibration requirements influence the selection and use of level sensors to some extent. One can briefly summarize this.

Calibration of point level sensing devices used at low pressures and for most media can be made with a gage glass or open end manometer, while the calibration of continuous level sensing devices used at low pressure and for most media can be made with a plumb bob and tape.

Calibration of sensing devices at elevated pressures and temperatures requires special, and usually individual, treatment depending upon the medium and the operating conditions. A typical solution to the calibration of a continuous device is to install high and low point sensors using a completely different principle of operation.

In general, the electrical and particularly the electronic devices have offered the greatest area for advancing the art in the past ten years. The acceptance of new level devices is slow, particularly if the simpler and older devices are working well. The pneumatic varieties require no special attention in hazardous areas. New devices are making entry into industry primarily where the media are difficult to measure or to accommodate a new overall plant system (all electronics or computer). In addition, there has been some reluctance to introduce new devices, because this would add to the training and stocking burden of the user.

4.2.6.9 Future Trends

Future trends in level sensing are divided into two broad categories [70]. One involves the development of solid-state (no moving parts) sensors which sense levels either discretely or continuously and all of which have electrical outputs suitable for transmission to remote control centers. Various techniques are now being researched, including electromagnetic, radar, and time domain reflectometry, focused and broad beam acoustics, and optical and laser devices. It is also likely that there will be future developments of electrochemical devices.

The second category will involve the incorporation of electronics technology as an integral part of the system including analog signal processing, digital logic, and microprocessor control to accomplish a number of functions. These will include linearization, conversion (e.g., level to volume; pressure to level, etc.), automatic calibration, multiple sensor array switching, control, display, logging, and maintenance and fault diagnosis.

4.2.7 Humidity and Moisture

4.2.7.1 Introduction

The measurement of moisture in gas has in recent years become increasingly important in industrial applications and in engineering research. In military ATE applications, humidity (moisture) is primarily an environmental parameter influencing device life and operation by way of corrosion. In certain combustion-related applications, the moisture content of all combustible gases influences the efficiency of burning. The following discussion is based, largely, on the section "Humidity and Moisture" in the ISA Transducer Compendium [8].

Humidity, in many cases, is measured with mechanical instruments designed for this purpose a century ago. This discussion will focus on humidity sensing devices with an electrical output, although mechanical hygrometry will be discussed briefly in section 4.2.7.3 below.

4.2.7.2 General Considerations

The methods, devices, and instruments designed or proposed for determining the water vapor content in a gas are legion. They range in complexity from simple mechanical hygrometers that function through dimensional changes, through the routine gas analysis apparatus of the gas chemist, to instruments that measure one or more of the physical characteristics of a gas. It is from this wide variety that a choice must be made for a particular application--a choice that is governed by such factors as range, sensitivity, accuracy, cost, portability, speed of response, commercial availability, continuous or intermittent operation, and indicating or recording operations.

4.2.7.3 Non-Electrical Hygrometers

It seems appropriate to briefly cover two non-electrical methods (psychrometers and mechanical hygrometers) since they are useful for the environmental humidity measurements.

(1) Psychrometer

In its elemental form, the psychrometer is comprised of two thermometers. The bulb of one thermometer is covered with a moistened wick and is referred to as the "wet bulb"; the bulb of the other thermometer is left bare and is called the "dry bulb." Evaporative cooling depresses the temperature of the wet-bulb thermometer below that of the dry-bulb thermometer. From the wet and dry bulb temperatures and the ambient pressure, the vapor pressure or relative humidity can be determined.

The sling psychrometer, using two mercury-in-glass thermometers, is the common form of this instrument. Ventilation is obtained by swinging the thermometers. Unventilated psychrometers are unreliable and hence rarely used for scientific, engineering, or technical work.

Among the factors influencing the performance and accuracy of the psychrometric method are (a) the sensitivity, accuracy, and agreement in reading of the thermometers, (b) the speed of air past the wet bulb thermometer, (c) the incident radiation on the thermometers, (d) the size, shape, material, and wetting of the wick, (e) the relative positions of the wet and dry bulb thermometers, (f) the temperature of the water used to wet the wick, and (g) the purity of the water.

The psychrometer is a simple, relatively inexpensive instrument which can be used for either intermittent indication or continuous recording of wet and dry bulb temperatures. Since it does not yield the moisture content of a gas directly, computations must be made, or alternately, recourse must be had to tables, charts, nomograms, or curves. These computational aids are available only for water vapor-air mixtures.

The psychrometric method may be used over a dry bulb temperature range of 0 to 100 °C. At lower temperatures there is a marked decrease in sensitivity and accuracy. In addition, there is an increase in lag due to the ice that surrounds the wet bulb in place of the film of water. Over the range of dry bulb temperatures of about 5 to 40 °C, it is possible to achieve an accuracy of about ±2 percent relative humidity. Under normal operating conditions, the accuracy is more apt to be of the order of ±3 to 4 percent relative humidity.

(2) Mechanical Hygrometer

Mechanical hygrometers are based on the fact that many hygroscopic materials undergo dimensional changes with changes in ambient relative humidity. These dimensional changes, through suitable simple lever systems, may be made to actuate a pointer or move a pen across a chart. Instruments of this type are known as mechanical hygrometers. Such materials as hair, cotton, wool, silk, wood, goldbeater's skin, nylon, plastic, paper, and whalebone have been used as the dimensionally variable humidity elements. Of these, hair is probably the most widely used material.

The main virtues of the mechanical hygrometer are its simplicity of design and construction and its low cost. It indicates relative humidity directly over a moderate range of temperatures. Its reliability decreases with decreasing temperature. Its chief defects are a lack of stability under normal conditions of use and appreciable hysteresis.

At best, the mechanical hygrometer has an accuracy of about ±3 percent relative humidity at room temperature under stable conditions. It has a time lag of the order of minutes, so that with changing humidity the accuracy of indication decreases. For optimum performance it should be re-calibrated at frequent intervals.

(3) Dew-point Hygrometer

A principle that is basically mechanical but lends itself to electronic control, with electrical output, is that of the dew-point hygrometer.

When water vapor is cooled, a temperature is reached at which condensation occurs to liquid or solid. The dew-point method provides a convenient technique for ascertaining this temperature. The procedure is to alter the temperature, pressure, or volume of a water vapor-gas mixture in such a fashion that condensation just occurs. The temperature at which condensation is initiated, for a given pressure and volume, is defined as the dew-point temperature.

Condensation may be detected by the appearance of dew or frost on a surface, usually a polished metallic mirror, or as a fog or cloud. By far the most common method of inducing condensation is to lower the temperature of a mirror and to observe the condensation thereon by reflected or scattered light. The formation of dew or frost on a mirror surface can be detected visually, photoelectrically, or electrically through a change in surface resistance.

In theory, the dew-point measurement is influenced by several factors which are of such indeterminate nature as to make an estimate of the accuracy difficult. It is not always possible to measure the temperature of the mirror at the surface or to assure that no gradients exist across the surface. The visual detection of the inception of condensation cannot be made with complete assurance nor is it probable that two different observers can detect dew or frost at the same instant. The automatic photoelectric detection of the dew point usually depends upon achieving an equilibrium condition on the mirror surface during which the amount of dew or frost remains constant.

At temperatures below freezing, the initial formation of a condensate on a mirror may be either liquid or ice. Condensates of supercooled water have been observed as low as -27 °C. At extremely low temperatures, the deposition of frost assumes a glossy appearance which is difficult to detect visually.

The use of the dew-point method presupposes that no other component of the gas mixture under test will preferentially deposit or condense before water vapor and hence yield an erroneous answer. One decided advantage is that the dew-point method may be used at high pressures.

4.2.7.4 Electrical Hygrometers

Instruments of this type consist of two parts: a humidity-responsive resistor, the sensor, and an electrical or electronic circuit for detecting and indicating the magnitude of the resistance of the sensor.

(1) Electrolytic Solution Sensor

The most common form of sensor is one in which an aqueous electrolytic solution serves as the variable resistor. The electrical resistance of this type of sensor is a function of the concentration of the solution, which in turn is a function of the ambient relative humidity and temperature. The solution can be applied directly to an impervious insulating surface on which electrodes have been affixed. However, this combination is relatively unstable so that frequent calibration is needed to assure accuracy of indication.

(2) Surface Resistivity Sensor

Another form of sensor utilizes the surface resistivity of selected impervious materials like glass, porcelain, and plastics. Water is absorbed on the surface of these materials and retained by physical bonding forces, forming a thin film whose thickness, and possibly continuity, is a function of relative humidity. This film of moisture provides a leakage path for current flow. There probably are minute quantities of soluble salts or gases present on the surface which contribute to the conductivity of the film. The net effect is that as the relative humidity changes from 0 to 100 percent, the surface resistivity may decrease six or more decades. One interesting version of this sensor comprises an insulating surface on which a thin film of salt is deposited under vacuum. A second version consists of a plastic surface converted into a thin film of ion exchange resin.

(3) Volume Resistivity Sensor

In a manner analogous to the use of the variation with relative humidity of the surface resistivity of impervious solids, the variation of the volume resistivity of some porous materials can be used for humidity sensing. There are many substances which absorb water vapor, but relatively few that do so with sufficient reversibility and reproducibility. Highly porous substances, as, for example, underfired clays, natural fibers, and textiles have a high capacity for moisture absorption. Water vapor diffuses and permeates into the pores and capillaries of these substances, greatly affecting their volume resistivities. Unfortunately, the porous nature of these materials, which makes them so highly hygroscopic, often contributes undesirable characteristics that seriously detract from their usefulness as sensors. For one, the time involved for a porous material to reach equilibrium with change in relative humidity is often excessively long. Then too, a porous material too often possesses appreciable hysteresis and drift. In spite of their shortcomings, porous solids find some application as sensors. Typical of this class of sensor are sintered ceramics, underfired clays, and plaster of Paris.

There is a class of electric hygrometer sensors that depends on dimensional changes to produce changes in resistance. Many materials change in length or volume or both as they absorb or desorb water vapor. The classic examples are hair, vegetable fibers, and wood. These materials are routinely used in hygrometry to actuate mechanical systems that move pointers over dials for indicating relative humidity, or operate switches in humidity control systems. Dimensionally variable materials may be coated or impregnated with conductive substances. The latter will expand and contract as the humidity-sensitive material expands and contracts. By the proper choice of the conductive substance, a measurable change in resistance is achieved. The most successful version of this type of sensor is the so-called carbon film element. It consists of an insulating base, with electrodes, which is coated with a mixture comprising a dimensionally variable plastic binder, carbon particles as the conductive medium, a moisture retaining agent, and a nonionic dispersing agent.

The electric hygrometer has certain features which make it useful for a wide variety of applications. The sensor is usually small and relatively inexpensive, although the cost of the measuring circuit may not necessarily be low. The indications are in terms of electrical quantities so that remote indicating or recording is feasible. On the other hand, the electric hygrometer is an empirical device that requires calibration. It has an appreciable temperature coefficient so that the calibration must cover a range of temperatures and with each measurement with the hygrometer there must be an auxiliary temperature measurement. To a limited extent, circuitry can be designed to correct or compensate for the temperature coefficient.

The performance of a sensor may be influenced by polarization, exposure to fog, clouds, or saturated gas, and contamination of the sensitive surface. Those sensors that use an aqueous solution without binder on an impervious surface are inherently faster in response but less stable than the binder type or the impregnated fiber, fabric or ceramic types. Of all the sensors, those that depend on surface adsorption, like the salt film sensor, have the fastest response, but to measure the high resistances of such sensors requires special circuitry and handling. Sensors whose operation is based on volume resistivity tend to be very sluggish in response and to exhibit hysteresis and drift. The carbon element usually displays a "hump" or reversal in its relative humidity-versus-resistance characteristics which makes it bi-valued in relative humidity at high resistances.

(4) Thermal Conductivity Sensor

Another approach to humidity sensing with an electrical output uses a thermal-conductivity bridge. A change in thermal conductivity with composition is used as the measure of the relative proportion of one component of a binary gas mixture. A typical apparatus involves the use of two concentric cylinders in a cell, one heated and the other maintained at constant temperature. If the design is such that radiation and convection are eliminated, then the rate of heat transfer from the hot to the cold cylinder will be proportional to the thermal conductivity of the gas in the space between the two cylinders. The inner cylinder is normally a heated wire whose resistance varies with its temperature and whose temperature, in turn, varies with the rate of heat transfer to the outer cylinder, which usually is the wall of the cell. If two cells, one filled with an invariant reference gas and the other with the test gas, are arranged in opposite arms of a Wheatstone bridge circuit, the bridge output will yield the percentage composition of the binary gas mixture. Further, if the binary mixture consists of water vapor and a dry gas, then the reference cell can be filled with the dry gas, the test cell with the mixture, and the output will be a function of the water vapor content.

The method has the obvious advantage of giving a continuous indication or recording of moisture content. It is limited by the fact that it is not specific for water vapor but indicates any change of composition of the gas entering the instrument. Then too, slight changes in physical dimensions of the cells, oxidation of the inner surfaces, and changes in wire resistance contribute to drift and instability in indication and lack of reproducibility in calibration.

(5) Refractive Hygrometer

A more sophisticated and complex approach to humidity sensing by electronic means involves refractive hygrometers.

The refractive hygrometer utilizes the change in refractive index with change in water vapor concentration to measure the moisture content of a gas. The refractive index of a gas is defined as the ratio of the velocity of a given radiation (i.e., radiation of a given frequency) in vacuo to that of the same radiation in the gas. Since the velocity of electromagnetic radiation in vacuo is constant, only the velocity in the gas needs to be measured. The latter can be accomplished by measuring either wavelength or frequency, keeping the other constant and using the relationship $v_g = f\lambda$. Radiation at optical, radio, or microwave frequencies may be used. At optical radiation, wavelength is measured. At radio and microwave frequencies, wavelength is usually fixed and the refractive index of the gas is allowed to determine the frequency of radiation measured as the resonance frequency of a circuit or cavity.

At radio frequencies, a small capacitor is used in the resonant circuit of a variable oscillator. Changes in refractive index, and hence in dielectric constant, are reflected as changes in the resonance frequency of the circuit. The variable frequency is compared with a reference frequency and the small difference is detected, measured, and related to vapor pressure.

At microwave frequencies, two identical cavity resonators are employed. Into one of these cavities, the test sample is introduced, into the other, dry gas. The resulting difference in resonance frequency between the cavities is then a measure of the vapor pressure.

The refractive hygrometer is capable of detecting the vapor pressure with high sensitivity. By using an appropriate servo system, the instrument may be made completely automatic and recording, with a speed of response limited only by the flushing time and the lags in the electronic and recording devices. Its basic limitation arises from the fact that it may be used only with binary gas mixtures, for it does not uniquely distinguish changes in water vapor content from changes in content of other vapors or gases.

(6) Electrolysis Humidity Sensor

Yet another type of humidity sensor uses electrolysis.

Water is electrolyzed into gaseous oxygen and hydrogen by the application of a voltage in excess of the thermodynamic decomposition voltage, that is, more than 2 volts. The mass of water electrolyzed per unit time is directly related to the electrolysis current by Faraday's law. Thus it can be shown that the current flow is directly proportional to the volume ratio of water vapor to air and to the mass flow of gas. Therefore, given a constant mass flow rate, the current uniquely determines the water vapor concentration.

The electrolytic hygrometer continuously and quantitatively electrolyzes the water vapor content of water vapor-gas mixture and indicates its magnitude. It does this by maintaining a constant mass flow rate of the test gas through a electrolysis cell. Within the cell, the water vapor is adsorbed by partially hydrated phosphorus pentoxide. Voltage is applied to spirally wound platinum wires embedded in the absorbent, and the electrolysis current is measured.

At a pressure of 760 mm Hg and a temperature of 25 °C, a flow rate of 100 cm^3/min results in an instrument sensitivity of 13.2 μA/ppm. Vapor concentrations of 1 ppm can be detected. The commercial instrument normally has scale ranges of 10 to 1000 ppm, although with special techniques, higher concentrations can also be measured.

It is claimed that the instrument has an accuracy of 5 percent of the indication from 1 to 1000 ppm. It is relatively slow in response and requires long and continuous flushing with extremely dry gas before low vapor concentrations can be reliably determined.

There are other, less commonly used, methods for sensing humidity or moisture content of gases. More detailed information on all methods of moisture measurements can be found in the literature [9].

4.2.7.5 Application Considerations

As is evident from the discussion above, there are many different ways of measuring the moisture content of gases. Some are very complicated, others are simple but less accurate or reliable. In the selection of a sensor, the overall performance required must be carefully considered. It may be more practical, in the long run, to select a simple, although potentially less accurate method, possibly with a second sensor for redundancy, over a more sophisticated system.

In any case for most ATE applications, humidity is probably just an environmental parameter which needs only to be measured with <u>moderate</u> accuracy.

4.2.7.6 Current Problems and Future Trends

Problems with humidity and moisture sensors can be summarized briefly: their dynamic response tends to be slow; their performance at low temperatures is not always adequate; they are generally quite temperature-sensitive; and their calibration characteristics change with time.

A variety of sensing principles are under continuing investigation. Solid-state sensors of monolythic construction using a variable impedance transduction element with integral temperature sensor appear promising, as do piezoelectric devices in which absorbed moisture changes the resonant frequency of a crystal [71].

4.2.8 Other Measurands

In addition to the measurands discussed in some detail earlier in this handbook, there are some others which may play growing roles in future military ATE systems. Some of them are essentially physical parameters like concentration, viscosity, or density; others are of a chemical nature like ph level, oxygen content, or salinity. Sensors with electrical output do not exist in some cases or are only experimental at present. The measurement of many of these parameters is treated with reference to industrial (process industry) applications in a publication such as the "Handbook of Applied Instrumentation" [15]. Finally, it is somewhat desirable to monitor other parameters which require very specialized instrumentation techniques. This includes the detection of cracks in components and materials, the detection of leaks, and of corrosion and fouling. Discussion of most of these is beyond the scope of this present volume. Some areas, pertinent to military ATE system applications, are discussed briefly in the following section.

4.2.8.1 Wear

"Wear" is not a measurand as such, but it is one of the most important characteristics of any operating mechanism, vehicle, and propulsion system. One of the primary functions of ATE for such systems is to ascertain "wear," to anticipate malfunction or failure, and to indicate remedial action required.

Many factors determine "wear" including equipment design, material selection, operational parameters, environment, and others. A great body of detailed knowledge has been accumulated and is available in the literature. For the purposes of this handbook, it seems instructive to refer to a recent article on "Materials Selection for Wear Resistance" [16], which contains a table of typical wear monitoring techniques. This table, which follows, is a state-of-the-art summary. It is clear that while sensors can be used to ascertain some of the characteristics, analytical laboratory techniques are required for others. A case in point is the analysis of lubricating oil.

4.2.8.2 Lubricating Oil Analysis

An important area of concern in the operational life and maintainability of military prime movers lies in the characteristics of the lubricating oils of turbines and internal combustion engines. Future military ATE systems for ships and other vehicles are likely to require the development of special sensors which can respond to these physical and chemical properties of the lubricants.

At present, analytical methods are generally used to monitor used marine circulating oils to detect contamination and oxidation and to determine the effectiveness of shipboard purification practices [17]. In turbine service, water contamination may be present but significant quantities of dirt and wear metal are seldom evident. In diesel engines, on the other hand, it is possible to find water, fuel, soot, cylinder lubricant residues, dirt, and system metal. The reference [17] describes some of the test procedures used to examine the lubricating oils and thereby to assess the condition of the prime mover and the location of any source of impending trouble. Tests include appearance and odor, water content, density, flash point, viscosity, and the amount of insolubles present; graphic analysis has also been used on oil samples to attempt to assess the degree and source of contamination.

An approach to the analysis of bearing performance through the examination of wear particles from rear axle bearings of vehicles is described [18]. In this case an electron microscope and a scanning electron microscope (SEM) were used on particles extracted from a sample of rear axle lubricants. While the data indicate the methods to be useful in locating the wear particles, the report states "...no attempt is made to explain the mechanism of wear."

TABLE 14

Typical Wear Monitoring Techniques

Method	Remarks
Techniques dependent on effects of wear	
Temperature changes	Measurement of temperature changes between a moving surface and its surroundings; a rise may indicate increased wear.
Vibration	Increase in vibration follows increased clearances due to wear; e.g. the use of accelerometers or vibration analysis with numerical readout can automate techniques.
Optical	Spatial measurement (often incorporating holography) can be applied in some cases using special ports built into machinery.
"Kurtosis"	Advanced form of noise and vibrational analysis where the output over a range of frequencies is compared with recordings from the prior history of the equipment; significant changes occur as wear proceeds.
Operation analysis	Changes in torque, blowby, fuel consumption or exhaust gas analysis may be symptomatic of wear (but can also have other causes).
Techniques dependent on wear products	
Spectrographic oil analysis to particles	Can incorporate activation analysis, atomic absorption etc. as analysis method, regular samplings and analyses are made and increases in metal build-up in oil can be related to wear.
Magnetic chip detection	Small magnets collect ferrous metal chips from the oil pipline and are periodically removed and inspected; can be automated.
Ferrography	A sample of oil from the sump is diluted and magnetically separated over an inclined plane; metallographic examination of debris can reveal the amount and type of wear.
Thin-layer activation analysis	Part of the wearing surface is exposed to beams from a linear accelerator; induced radioactivity (which is kept to small levels) can be used to measure wear.

5. DATA ACQUISITION AND SIGNAL CONDITIONING

5.1 General Considerations

Although this is a Sensor Handbook, addressing sensor considerations in ATE Systems, the sensor cannot stand alone. The sensor is an important component of a Data Acquisition System (DAS), and while it may be the most critical and yet weakest link of such a system, it is appropriate to briefly discuss some of the other components of Data Acquisition Systems.

The following discussion of such systems is extracted, with permission, from "How to Configure a Data Acquisition System" by S. Kent Morgan [19].

The task of configuring such a system is difficult, with a vast selection of available hardware, an often confusing set of terminology, and the inevitable challenge of optimizing the performance/cost ratio for a specific application.

No two DAS users have exactly the same requirement. A DAS specifically configured to meet today's measurement needs can be obsolete tomorrow if it has inadequate flexibility. Therefore, a prime consideration for the DAS is growth capability for future needs.

In the case of ATE Systems, two major factors will influence the selection of data acquisition systems. One is the need for a number of measurements of the desired parameters of the Unit-Under-Test (UUT). Second is the need for acquired data to be processed by means of a computer programmed to achieve the objectives of the ATE in an optimum manner.

The trends toward computer entry and processing of data, greater automation, and improved data accuracy have led to digital DAS for dynamic as well as static data. A digital DAS is basically a system involving one or several analog-to-digital converters, and in the case of multi-channel inputs, circuitry for multiplexing, i.e., time-sampling the channels. Such a system is often referred to as a pulse-code-modulation (PCM) system, since the analog information is converted into an array of pulses. The location within the chosen time frame of a given pulse, pulse-position-modulation (PPM), or the pulse length, pulse-duration-modulation (PDM) represent quantitative values of instantaneous samples of the analog signal.

A pulse-code-modulation multiplex DAS can be thought of as a sophisticated data logger; it is also a time division multiplex system. In time division multiplex (TDM), the various measurands are sampled in time sequence, and the pulse-coded data for all measurements transmitted sequentially over the same transmission lines. Such a system offers high throughput capability as well as flexibility in sampling rates and sampling sequences; the operating parameters of each element can be under computer control, offering "hands off" flexibility in reconfiguring the system between tests and even during testing.

A major reason for using a PCM DAS system is that a considerable improvement in data accuracy can be realized over instrumentation recorders or frequency division multiplex (FDM) techniques. (In FDM each measurand is transmitted at a different frequency, modulated by the measurand's dynamic frequency.) This technique requires complex demodulators (discriminators) with potential stability and linearity problems.

Once the input signals have been digitized, the PCM serial bit stream is essentially immune from noise in the instrumentation or transmission systems. With 10-, 12- and even 14-bit encoding available, system accuracies of better than 0.1 percent can be achieved for dynamic as well as static data. Note that such accuracy claims can be made, and verified, only for the electrical signal portion of the DAS. The error contribution of the sensor is the subject of much of this handbook.

Another advantage of the digital approach is that it is most amenable to computer control. This approach can provide a rapid and efficient means of reconfiguring the system for different test requirements.

It should be noted that such digital systems will probably require an intermediate analog signal conditioner (amplifier) between the sensor (basically an analog device) and the digital data processing components of the DAS.

In the selection of the DAS, ten basic questions need to be answered; all or most of these need also be addressed in the selection of system components, including the sensor. The particular factors to be considered in regards to sensors form the major portion of this handbook. The questions and factors are summarized in table 15.

TABLE 15

Considerations in Selecting Data Acquisition Systems and Components

Questions	Factors
1. What are the given system inputs?	Type, quantity, duration, signal level, bandwidth, dynamic range.
2. What are the desired system outputs?	Type, quantity, accuracy, format, display, storage.
3. What are the system environments?	Thermal, mechanical, electromagnetic interference, portability, meteorological.
4. What is the useful life goal?	Life span, duty cycle, environment, mission profile.
5. What are current budget constraints?	Capital funds, program funds, lease or buy, make or buy.
6. What is the total useful life cost?	Initial cost, operational cost, maintenance cost, down-time cost, expansion cost.
7. What are availability goals?	Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), vendor vs in-house maintenance, required spares inventory.
8. What data processing is required?	Real-time, off-line, arithmetic, monitor and alarm, compression, display, storage.
9. What system configuration changes are required?	Degree, frequency, turnaround time, automation, adaptive.
10. What expansion capability is required?	Input: quantity, level, bandwidth, range. Output: quantity, display, storage.

The answers to these ten questions describe what the system has to do; it is then up to the designer to determine how to arrive at the best mix of hardware, software, and systems integration to meet his requirement.

5.1.1 Data Acquisition System (DAS) Parameters

Once the general system has been defined, the next step is to quantify the following system parameters:

1. Number of channels
2. Data bandwidth per channel
3. Test event duration
4. Required dynamic range
5. Total system accuracy.

The (data bandwidth x number of channels) - product provides a quantitative measure of the system speed. In sampled data systems, such as the data logger or PCM multiplex described above, the system speed is generally expressed in terms of the (sampling rate of each channel x the number of channels) - product. This product is called the system "throughput rate." As the system throughput rate increases, the cost per channel also increases.

The event duration for a specific test may last from milliseconds to years. For short-term transient testing, data are often recorded on analog tape or stored in a digital memory for subsequent playback, processing, and display. Long-term data, such as operation or mission history, are usually recorded on digital cassette tapes at timed intervals and collected on a periodic (e.g., quarterly) basis for processing. Between these two extremes, the more typical application involves real-time monitoring and quick-look display of events lasting up to an hour, with off-line processing and analysis performed within a one-day turnaround time.

In recent years, the ability to gather large volumes of raw data has exceeded the capability to fully process these data. As a result, instrumentation engineers may be inundated with stacks of computer printouts and cabinets filled with magnetic tapes. In some cases these data are required for archival retrieval purposes. In many cases the data volume could be reduced significantly through the use of data compression techniques. Caution must be used, however, to avoid loss of significant information. In configuring the processing portion of the DAS, the design engineer must consider carefully the volume of expected data.

"Dynamic range" and "accuracy" are often confused, but there is a definite distinction. "Dynamic range" refers to the ratio of the maximum input signal for which the system is useful, to the noise floor of the system. The "accuracy" figure for a system is impacted by the noise floor, nonlinearity, temperature, time and power supply instabilities, crosstalk, etc. In selecting an 8-, 10- or 12-bit analog-to-digital converter (ADC), the design engineer must not assume that the system accuracy will necessarily be determined by the resolution of the encoders; i.e., 0.4 percent, 0.1 percent and 0.025 percent, respectively. In fact, if the sensor or the signal conditioning equipment preceding the ADC is limited to 1 percent full-scale accuracy, for example, no significant benefits are gained by utilizing a 10- or 12-bit system over using an 8-bit system and suppressing the least significant bit.

Although the cost of increasing the dynamic range of a system is often relatively modest, the cost of achieving comparable "accuracy" may become progressively prohibitive.

In discussing the selection of the components of a DAS system, the reference cited [19] makes an important statement in regard to sensors. It is quoted below to emphasize the basic goal of the Sensor Handbook: to enable careful selection of the optimum sensor for its mission, optimum being adequate in every sense.

5.1.2 Sensors

"The importance of selecting the right sensor cannot be overemphasized. You can spend $100 000 to obtain a high-quality, 0.01 percent accuracy DAS that is a complete overkill if the sensor accuracy is only ±5 percent.

"Although 90 percent of all sensors employed in data acquisition are either strain gage, thermocouple, or resistance devices, it is still necessary for the design engineer to be familiar with other sensor types. These sensors are described in the general technical literature; additionally, transducer manufacturers publish a large body of specifications as well as some application literature. Essential as the fundamental theory of sensor operation is, it is also necessary to know how to install, cable, terminate, and calibrate these devices. There is definitely an art to their proper implementation in a physical system.

"Despite the quest for the 'Universal Digital Sensor,' it just has not been discovered and is not likely to become an economic reality in the next few years. Although all of the elements required for this digital sensor exist in separate chip form, it remains for the semiconductor people to put it all together. The technology certainly exists to do this, but the non-recurring investment to develop the extremely large number of different sensors required vs the number of sensors purchased each year does not now make this a viable investment. Therefore, for the foreseeable future, the design engineer must interface with conventional sensors."

5.1.3 Signal Conditioning

In order to convert the sensor output to a signal suitable for further processing, signal conditioning is required to provide:

1. Excitation
2. Completion networks
3. Calibration
4. Amplification
5. Filtering

With the exception of self-generating elements such as thermocouples, most sensors require some form of excitation. This is generally in the form of a constant voltage or constant current source and can be either dc or ac depending on the particular sensor. Although constant voltage excitation has certainly been the most popular for strain gage excitation, constant current excitation offers advantages in transfer function linearity. DC excitation usually provides acceptable excitation accuracy, but where long leads are involved and dc offsets are anticipated, the use of ac excitation can provide improved accuracy.

Completion networks are passive components, external to the sensor, which complete the electrical network to form a complete bridge to enhance signal conditioners. They provide the user with flexibility in selecting different types of sensors. For instance, the user can change the completion networks to accommodate one, two, or four active arms in a strain gage network. For maximum flexibility, these completion networks should be on plug-in cards to facilitate system changes.

Some form of system calibration is mandatory in most DAS. In addition to providing at least two-point calibration for system drift correction, the calibration feature provides verification of proper system operation before, during, and after a test event. Many types of calibration are available, ranging from simple, manual, zero, and full-scale calibration to automatic zero and automatic gain correction within the signal conditioning unit. Although the linearity of state-of-the-art amplifiers is typically as good as the tolerance of the calibration resistors, multi-point calibration is still desirable to provide positive assurance that the entire electrical system is operating properly over its full dynamic range.

It should be emphasized that these calibrations do not include the sensor. At best, the transduction element is included, for example in a "shunt" calibration. A complete end-to-end system calibration, from measured to final output, is the only valid system verification. This is discussed more fully in later sections.

The output of most sensors is in the order of millivolts and amplification may be required to raise the signal amplitude to a level suitable for further processing. Additionally, because the common-mode electrical interference may be much higher than the desired signal level, differential input amplifiers are often essential. One of the most difficult things for the engineer to determine is exactly how large the common mode environment will be in the final system installation. Values may range from 1 V to 150 V peak, usually 60 Hz ac, while some special applications may run as high as a few thousand volts.

From a cost standpoint, there is a significant crossover point for common mode voltages greater than the power supply voltage of the amplifier. This is typically ±15 V and falls in the middle of the normal commond mode bounds. Unfortunately, even if the common mode voltage is just slightly greater than the specified level (e.g., 20 V), this can render the amplifier quite useless. Therefore, if a marginal condition is anticipated, the prudent designer will select the higher common mode capability.

In straight analog DAS, filtering at the output of the signal conditioner is sometimes employed to band limit the required signals. In digital sampled-data systems where broadband data are encountered, presampling filters (PSF) should be used ahead of the multiplexer to limit the maximum signal frequency to the minimum necessary for adequate definition of the measurand. This helps to reduce aliasing errors, which occur when the measurand is sampled at too low a rate relative to the highest signal frequency to permit the signal to be accurately reproduced by the sampled data.

The importance of aliasing errors in a system is often underestimated by users not familiar with sampled data systems. It can be shown when considering aliasing error with sampling frequency for various low-pass filters that even when sampling at five samples per data cycle, a five-pole low-pass output filter is required to achieve less than 1 percent rms aliasing error for a sinusoidal signal. Note that this error is independent of the number of bits of encoding by the ADC.

5.1.4 Multiplexing and Analog-to-Digital Conversion (ADC)

In selecting a multiplexer/ADC, the designer can choose from either low level or high level multiplexer systems. Using differential switching, the low level system samples the analog inputs and presents these signals to a single programmable-gain amplifier prior to digital conversion. The high level multiplexer utilizes a single amplifier for each channel to raise the signal level prior to high level single-ended analog multiplexing and digital conversion.

Since the low level approach requires only one amplifier, it enjoys a considerable cost advantage over the high level approach. However, the low level approach has disadvantages, such as a limit on throughput rate. In switching from a high to low input signal, the multiplexer and the programmable gain amplifier must be given time to allow switching transients to settle out. For a system with wide-range gain control, the throughput rate is typically limited to about 10 000 samples-per-second (sps). With a single amplifier per channel, the rate can exceed 1 000 000 sps.

Although active filters can be used for low level inputs, they must be correctly leveled, offset, or dc-decoupled. If this is not done, active devices can introduce unacceptable dc errors at low level inputs. The presampling filters used in many low level multiplexers are passive. Practically, this limits the input filter to a two-pole configuration which requires a normalized sampling rate of 30 times the data rate to ensure less than 1 percent aliasing error with broadband noise. A DAS system with a 10 kHz throughput rate and 100 channels would have a maximum data rate of 3.3 Hz per channel. Other disadvantages of the low level approach are that failure of the programmable amplifier results in complete system failure; also, an overload on one channel can cause errors on sequential channels until the amplifier recovers.

5.1.5 Sample Rate

"How fast do I really need to sample?" is probably the most frequently asked question by users of digital DAS. Nyquist's well known theorem, often quoted and usually misused, states that an ideally bandlimited signal can be perfectly reconstructed from samples taken at a uniform rate equal to or greater than twice the highest signal frequency. Unfortunately, ideally bandlimited signals are rather hard to come by in practical applications. If ideal "boxcar" filters (filters with flat amplitude and linear phase response, and with infinite attenuation at frequencies beyond the design filter limits), are not used in a system using a sampling rate of twice the highest signal frequency, sidebands created by the sampling process will overlap, producing aliasing errors.

A "boxcar" filter can be represented by a presampling filter with an infinite number of poles. However, for practically realizable filters, there is a direct tradeoff between the number of poles required and the minimum sampling rate required for a constant error. For example, to achieve less than 1 percent aliasing error, a system using presampling filters with two, three, or five poles must be sampled at about thirty, ten, and five samples per data cycle, respectively.

If a particular physical phenomenon has a natural bandlimiting rolloff, this effect can be added to the presampling filter rolloff to achieve the net overall effect. If a phenomenon has a natural rolloff of 12 dB per octave above the highest frequency, a three-pole filter with a similar cutoff will give the overall effect of a five-pole filter. As a general rule of thumb, the five-times per cycle sampling rate with a five-pole filter yielding less than 1 percent aliasing error is a good guideline. Filter design is a sophisticated subject and the examples are given only as approximations for discussion purposes. Obviously, if the bandwidth and sampling rate capabilities are available, the higher sampling rates should be utilized.

It is an unusual system in which all channels have identical data bandwidths, thus requiring identical sampling rates. Typically, there may be a wide disparity between the highest- and lowest-frequency channels of the system. In order to accommodate these efficiently, faster commutation rates and slower subcommutation can be used for those channels which are higher or lower, respectively, than the average rate.

5.1.6 Bit Rate and Data Resolutions

In selecting the number of bits of encoding, a reduced quantization error (i.e., greater resolution) must be weighed against the resultant higher cost and lower speed. If the signal to the multiplexer/ADC can be kept near the rated full-scale input by the preceding signal conditioner/amplifier circuits, the quantization error is merely ±1/2 of the least significant bit (LSB) or 1 part in 2 times 2^m where m is the number of bits. However, if the actual signal is only 1/8 of full scale, the resultant quantization error has the same impact as a ±2-bit error on a full-scale signal.

A common problem in strain gage systems is one of a relatively small dynamic signal of interest superimposed on a large static offset. If the signal conditioning amplifier does not have programmable offset, the ADC must have additional resolution to yield a quantization error equivalent to full scale. For example, with a design full-scale input of ±5 V, a 10-bit ADC operating with up to ±3.75 V compensated offset and only ±1.25 V of dynamic signal is equivalent to a 12-bit unit operating at ±5 full scale with no offset compensation.

As noted before, ADC resolution is not the same as system accuracy, but most ADC manufacturers try to keep the ADC accuracy consistent with the ADC resolution. From a practical standpoint, 10 to 12 bits ought to be adequate for most applications, where errors of ±1 LSB represent ±0.1 percent to ±0.024 percent of full scale, respectively. Eight-bit ADC's may be adequate for quick-look or high speed systems, while 14 bits (and greater) are typically reserved for slow-speed or wide-dynamic-range systems. The ADC has a limit for throughput which is usually specified in terms of conversion time. Exceeding the throughput rate of the ADC is obviously to be avoided. Generally, for a given cost, the greater the number of bits, the slower the ADC. For a given throughput rate, the cost of the ADC may increase nonlinearly with the number of bits.

Although a multiplexer/ADC may indeed have a ±1/2 LSB accuracy with static inputs and low throughput rates, the absolute accuracy of any system will be degraded with dynamic input signal and higher throughput rates. For example, multiplexers using solid-state switching have a number of dynamic error sources that increase with throughput rate, including:

1. Turn on/turn off time of multiplexing switches.
2. "Pump back" or charge injection into the input signal path.
3. Multiplexer settling time.
4. Output amplifier settling time.
5. Cross-talk between channels.

5.1.7 Sample and Hold

In most multiplex/ADC systems, a sample-and-hold circuit is used at the output of the multiplexer buffer amplifier to store the output of one channel while the multiplexer is sequencing to the next channel. The sample-and-hold module also has time-sensitive errors which include:

1. Sample-to-hold errors, including aperture time uncertainties and settling time errors, and
2. Hold-to-sample errors, including acquisition and settling time uncertainties.
3. The change of input signal with time in the "hold" mode.

These errors can become significant as the throughput rate increases, since each of these times is a fixed value for a specific module.

The sequential sampling of channels in the DAS will result in a definite, but predictable, time skew of the sampled values of different channels. This may be negligible in many cases, but for systems in which accurate time correlation between channels is important (such as for phase relationships between vibration channels), simultaneous sample-and-hold's can be inserted between the presampling filter and the multiplexer. These sample-and-hold's, operating from a common command circuit, will provide a simultaneous sample of all channels at the frame rate of the multiplexer. Although time deskewing can be performed offline using a computer system, the hardware sample-and-hold provides a straight-forward, real-time solution to time correlation.

5.1.8 Transmission Media

The physical location of the DAS is seldom identical to that of the data reduction system. The previous discussions have assumed that a serial communication link over a single conductor pair is required. For distances up to a few hundred feet, a parallel link using a multiconductor bus structure may be used between the acquisition and reduction systems. Although there have been a myriad of different bus structures, recently three standards have emerged: the CAMAC, the IEEE-488 bus (HPIB-HP, GPIB-Tektronix), and ARINC 429 (MIL-STD-1533). The IEEE-488 appears to have the greatest potential for universal acceptance. Although originally conceived as a common communication link between instruments, this bus can also serve for setup and control as well as the transmission of acquired data from one subsystem to another.

For relatively short, fixed-point communication links of up to a mile or so, either twisted-shielded pair or coaxial cable is generally used. The bandwidth and signal-to-noise ratio over relatively short lengths are extremely good. For greater distances, the signal losses and high-frequency attenuation as well as installation costs become quite significant. For longer distances, either an RF link or telephone link is required. Because both of these systems are bandlimited carrier systems, some form of modulator/demodulator (MODEM) is necessary.

All of the transmission media listed add some noise and distortion to the transmitted signal. For relatively slow data rates with a limited number of channels, the degradation in an analog transmission scheme such as FM may not be significant. For large systems with high data rates, the natural noise immunity of digital transmission techniques is unquestionably superior. In any event, the designer must determine the key characteristics of the transmission media prior to configuring the system. These include bandwidth, distortion, noise, and dynamic range. The fundamental limiting parameters for any transmission link are available bandwidth and practical transmission distances. Typical limiting parameters appear below.

Medium	Typical Distance	Bandwidth
Parallel Bus	50 feet	250 kilobits/s
Twisted-Pair	1000 feet	100 kilobits/s
Coaxial Cable	1 mile	10 megabits/s
Fiber Optic Cable	Several Miles	10 megabits/s

The last-named is commercially available, at reasonable cost, and immune to electrical and electromagnetic interference.

5.1.9 Demultiplexing

At the receiving end of the transmission link, data channels using frequency division multiplexing (FDM) or time division multiplexing (TDM) must be demultiplexed (to sort out each channel) from the parallel or serial data stream. In FDM, each channel has a unique frequency assignment, while in TDM each channel has a specific time slot assignment relative to the start of each frame.

In FDM systems, demultiplexing is accomplished with frequency-to-voltage converters called "discriminators" (frequency discriminators). These select each channel from the transmitted subcarrier frequency spectrum with bandpass filters and convert the selected frequency to an analog voltage that is proportional to the instantaneous frequency of the subcarrier. After the subcarrier frequency is selected by the bandpass filter, it is limited, detected, and filtered. The output is an analog voltage that is typically within 1 or 2 percent of the actual data source input voltage.

For improved accuracy, direct digital outputs, and reduced costs in large systems, TDM offers significant advantages over FDM. In order to extract each data channel from a serial TDM data stream, the demultiplexing equipment must synchronize with the incoming data. In a PCM system, this attraction includes bit synchronization to accurately derive the bit clock, frame synchronization to determine the start of each frame of data, and word counting to identify each data word within the frame.

These functions are performed with a PCM demultiplexer (usually called a "decommutator" or "decom") which can be obtained in either fixed or tunable and manual or computer-controlled hardware. Although it is possible to use a computer to assist in decommutating a TDM signal, it is usually faster and more cost effective to use dedicated hardware. This hardware includes a direct bit-parallel, word-serial output to a computer interface as well as quick-look analog or digital display. In either a manual or computer-controlled system, random selection of either single or multiple channels for quick-look display is usually available.

5.1.10 Data Distribution

In most systems, it is not necessary or even desirable to take all of the incoming data and distribute it to all of the recording, computing, and display peripherals. A few critical parameters are usually monitored in real time by the test directors to check for out-of-limits conditions. Some direct "pseudo" real-time displays of parameters are required by instrumentation analysts, but most of the data are recorded on mass storage devices for off-line analysis and archival history. In order to route various data channels to the required computer/storage/display peripherals, some form of data distribution is required.

Although a computer is capable of performing this function, it may seriously limit the data throughput rate as well as the number of other different processing functions that the computer is called upon to perform. A dedicated data distributor is in essence a hard-wired special-purpose computer designed to efficiently distribute data from a single (or multiple) input port(s) to various output devices. In doing so, the distributor can also provide either a time tag or special identification tag to aid in processing or reconstruction of the original data. This function can be manually or computer controlled, but is most often implemented in a computer control mode because of the variety of test requirements.

5.1.11 Data Compression

As the number of data channels and throughput rates have increased, the major problem in DAS has become what to do with all of the data. For example, even a medium-speed DAS operating with a sampling rate of 50 000 sps will accumulate almost 1.5 billion words of data in a single 8-hour day. Rather than supply storage capacity for all of the data, it may be desirable to perform some data compression which can reduce the amount of storage requirements by one to two orders of magnitude.

The essential function of the data compressor is to pass only those data which represent changes from previous data; redundant data should be rejected. Data compression can be performed under either software or hardware control. Although software control provides the most flexibility, the maximum throughput capability is usually lower than that of a hardware compressor.

There are many different algorithms which can be selected for data compression. These algorithms are simply different formulas which set the criteria for whether or not a data word should be passed or rejected. One example would be to pass a data word if its value is outside two preset limits; another example would be to pass the data word if the difference between the previous data word and the current data word is greater than a preset amount. Each compressed data point must be accompanied by the channel identification, and the time corresponding to the sample, in order to completely reconstruct the data. For data channels that have a significant amount of data point redundancy, data compression can be very efficient. However, because of the additional data required for channel identification and time tagging, data compression may actually result in decreased throughput if the input data are changing at high rates.

Data compression can be extremely important where real-time analysis of high throughput rates is required. If the input data rate is in the neighborhood of 250 000 words per second (wps), most computer systems simply cannot ingest the full amount of data, process it, and provide real-time feedback to test observers. With a hardware data compressor, the throughput rate can be reduced to 10 000 to 20 000 wps which can be easily accommodated by a typical minicomputer subsystem.

5.1.12 Computer Interfacing

The outputs of most large DAS ultimately interface with a computer system. All computer manufacturers offer standard computer digital interfaces which can accept low- to medium-speed data from the system and/or control the DAS. A typical minicomputer interface consists of a 16-line data bus with a few accompanying "handshake" lines.

For high-speed data transfers, some form of buffered data channel computer interface is required. For example, a DAS with a 200 000 word per second throughput to the computer system would require a high-speed buffered data channel that can either load the computer memory or disk storage directly. These buffered data channels can absorb data bursts of short durations at a high throughput rate and retransmit blocks of data to the computer at a reduced average rate. These buffered data channels also have multiple ports available that allow program-controlled switching from one source to another. This switching enables merging of housekeeping information, such as time code, along with the main data stream.

5.1.13 Computer Processing

Detailed configuration of a DAS computer system is beyond the scope of this section, but the major questions that must be answered by the engineer in his computer system selection are as follows.

1. Processing Power and Speed Requirements
   What arithmetic capabilities are required? Are floating point and hardware multiply/divide required? What processing must be done in real time, and how much time is allowed after the test for complete offline analysis?

2. Memory Requirements
   Basically, what size and what cycle times are required? Must all memory be non-volatile, or is a mixture of volatile and non-volatile memory acceptable?

3. Input/Output Requirements
   What is the maximum average throughput rate? What is the maximum burst mode throughput rate? Will standard or special input/output circuits be required to handle the data rates?

4. Options
   What main frame options will be required? What type of system clock is required (fixed, programmable, internal, external, etc.)? Is additional solid-state memory expansion required?

In summary, it should be obvious that the capabilities of the DAS have a major role in establishing the capabilities of a sensor-based measurement system.

6. SENSOR CALIBRATION

6.1 Performance Characteristics

6.1.1 General Considerations

The primary requirement imposed on any sensor is that it measure the parameter (measurand) it was designed to measure within the required limits of uncertainty. How well the sensor is likely to meet this requirement depends on the performance characteristics of the sensor, which are obtained from a series of calibrations and evaluation tests. Sensor performance can be predicted or verified depending on the completeness of the knowledge of its performance characteristics. Calibration and evaluation tests must exist to establish all the needed performance parameters.

It cannot be emphasized too strongly that the continuing ability of a sensor to perform its measurement function acceptably must be established through periodic re-calibrations. It is not sufficient to perform only initial acceptance calibrations prior to installation of the sensor in the UUT. It is also necessary to be able to perform periodic in-place (field) calibrations in the actual operational environment. Field calibrations are greatly facilitated by sensors with self-test capabilities so as to assure that such calibrations test the entire measurement chain. In many cases, sensors with comprehensive self-test capabilities do not exist yet.

For the purposes of this handbook, the operating environments in which sensors are used may be categorized into three regimes as follows: (1) operation at laboratory conditions, (2) operation in severe environments, and (3) operation over an extended period of time. Practical experience with sensors suggests that this order of listing also represents the order of increasing performance degradation. It also represents the order of decreasing knowledge of the actual type and magnitude of performance degradation.

Operation at laboratory ambient conditions, for short periods, and in a well controlled environment, eliminates the need for concern over the effects of severe environments or the effects of long periods of operation. The concerns are with the two major modes of measurement which the sensor is called upon to perform: static (or quasi-static) measurements and dynamic measurements.

(1) Static Characteristics

The performance characteristics which determine the sensor's ability to measure static (or quasi-static, i.e., very slowly changing) measurands are established by means of static calibrations. These characteristics include such parameters as sensitivity, zero output, linearity, hysteresis, repeatability, resolution, creep, and dead band. Static calibration procedures for many sensors have been published and incorporated in standards documents, and although gaps exist in some areas, the general field of static calibration for sensors is covered reasonably well.

(2) Dynamic Characteristics

With rare exceptions, sensors are called upon to measure time-varying quantities. It is necessary not only to know the amplitude of the measurand at a given time, but how it is changing at that time, since such changes may require rapid corrective action.

If the sensor is to be used to measure (or follow) such dynamic changes, the dynamic characteristics of the device must be known. Calibrations to establish the dynamic characteristics such as amplitude response, phase response, resonant frequency, and damping are less well developed than static calibrations. Those dynamic calibrations that are available tend to cover relatively narrow amplitude- and frequency-ranges and may have other restrictions.

(3) Other Factors

Even at laboratory ambient conditions, there are factors external to the sensor which can affect its performance. Power supply variations, electrical noise, mechanical vibration, and lead resistance variations will tend to degrade the measuring ability of the sensor.

It is evident that a considerable number of performance characteristics must be known before one can estimate the quality of measurements performed by the sensor in a benign operating environment such as at laboratory ambient conditions.

(4) Operation in Severe Environments

The majority of sensors do not operate in a benign environment. They are subjected to a variety of harsh environmental conditions which can greatly influence their performance.

Such environments affect sensors in two major ways. Measurement performance is adversely affected while the sensor is subjected to the specific environment. Such changes in performance are generally reversible and disappear when the particular environment no longer acts on the sensor. An example is extremes in temperature which can change sensitivity. However, the action of the environment of the sensor may also result in an irreversible, and thus permanent, change in performance such as a zero shift.

It is essential to be aware of both types of effects to adequately assess sensor performance. Environmental parameters that have proven to be important are briefly discussed in the following paragraphs and will be covered in more detail later.

Temperatures above and below laboratory ambient are the most frequently encountered environments which influence sensor performance. It is often possible to compensate the sensor output for temperature effects, provided the operating temperature is known and constant. This is true whether the entire sensor is at the operating temperature or only a part of it, such as the diaphragm of a pressure sensor. In the latter case, however, a temperature gradient may exist between the sensor and the surrounding environment, causing errors. If this gradient is stable, compensation can still be effective. If the process or environmental temperature varies, temperature compensation cannot be effective. In fact, compensating networks within the sensor may actually degrade the output. Thermal transients can cause unexpectedly large measurement errors unless sensors are specially selected or are protected against them. It is also known that sensors last longer at constant temperatures within their rated range than those exposed to wide temperature excursions.

As with temperature, measurements performed by a sensor can be severely affected by the presence of shock and vibration environments which may generate spurious signals and otherwise interfere with sensor performance.

The presence of moisture may cause undesirable shunting of resistive and capacitive elements, as well as current leaks to ground. More important, however, exposure to humidity can result in corrosion of metal parts and components and can lead to component failures.

There are a number of other environmental parameters which may affect the measurement performance of sensors, including dust and sand, salt spray, high-level acoustic excitation, electromagnetic radiation, magnetic fields, and ionizing radiation. More details of their effects appear in later sections.

In many cases, the electrical connector of the sensor has been a source of problems and apparent sensor failures. A connector of proven reliability, but extra cost, is a worthwhile investment to assure good sensor performance.

(5) Operation Over Extended Periods of Time

In some aerospace and defense applications, sensors are expected to perform properly and reliably over short periods of time, from minutes to hours. In industrial applications and defense ATE applications, on the other hand, the periods of time over which these devices are expected to operate may range from days to years.

When extended-time operation is considered, durability (stability) and reliability are particularly important factors. The reliability of many devices can be computed from knowledge of component failure rates. This information has been applied to critical aerospace applications and expressed as meantime between failures. This concept of reliability, however, is usually concerned with the total failure of the device, but does not address the deterioration of the sensor performance. The sensor's lack of stability or durability has received relatively little attention, but is of vital importance in the case of ATE systems.

It is good practice to calibrate all measurement systems before each use. It is not sufficient, however, to verify only once the performance of any measurement system that is used over an extended period of time. Continuing operation of any measurament system tends to lead to degradation of performance. Consequently, it is necessary to recheck system operation and sensor calibration at selected limits. At present there seems little agreement as to the proper time intervals for such field calibrations. Economic considerations play a large role in the decision, particularly when such re-calibrations require interruption of the process or disassembly of systems.

There are a large number of factors which have a bearing on the performance characteristics of sensors. The factors can be grouped into (a) those inherent to the sensing or transducing principle, design, and fabrication, (b) those due to the environment in which the sensor operates, and (c) those due to the continued, long-term operation. Comparatively little work has been done, or at least published, to thoroughly establish these factors.

There is also a lack of adequate test methods or theoretical concepts to attempt to predict the influence of these factors. Later sections will discuss, in more detail, sensor characteristics and existing test methods used to determine those characteristics.

(6) Anticipated Needs

It should be apparent, however, that additional resources will be needed in the following two-fold approach to assure optimum performance for sensor-based ATE systems:

- The development of performance concepts and test methods to verify sensor performance under the variety of operational and environmental conditions.
- The design and installation of measurement systems with the capability of in-place calibration is highly desirable for any kind of industrial process application. It is particularly critical for any system or process meeting national defense needs, including ATE systems for military applications.

In view of the importance of sensor calibrations to the proper functioning of ATE systems, and because of the scattered nature of information in this area, the handbook section on calibrations is more detailed than other sections.

6.1.2 Qualification Testing

The purpose of qualification tests is to establish the suitability of a type or class of sensor for a particular application. Sensors for use in military applications are almost always required to be qualified according to prescribed military standards, such as those listed in section 8.3.2 of this handbook.

Qualification tests are intended to thoroughly explore all those characteristics of the sensor which might have a bearing on the sensor's proper performance of its measurement function. Qualification tests are usually performed on a selected sampling of the type or group which they are intended to represent. Once such a type or group of sensors has been "qualified," individual devices must still undergo acceptance tests, which are discussed below. In addition, depending on the number of sensors being procured, it may still be desirable to subject new samples periodically to complete qualification tests to assure that quality has not deteriorated since the first samples were qualified.

Qualification testing is exhaustive, complicated, extensive, and expensive. Not all laboratories are equipped to carry out such a qualification test program. Sophisticated test methods are used (and sometimes new ones must be developed if existing ones are inadequate). Qualification testing by its nature requires expertise, since it involves not only static and dynamic calibrations, environmental tests, durability and reliability investigations, but also proper interpretation of test results. Examples of some of the test methods developed for such testing are provided by the work of the NBS InterAgency Transducer Program [1], and are discussed below.

Qualification testing includes procedures which are covered under Static Calibration (section 6.2.1), Dynamic Calibration (section 6.2.2), Operating Environment (section 6.3), and Durability and Reliability (section 6.4). However, there are some test procedures which do not really fall within any of these sections and these are discussed here.

(1) Visual Examination

The first step of any qualification test procedure is a thorough visual examination of the sensor. Check for defects in workmanship: loose parts and connections, missing screws, damaged surfaces, improper fit with mating connectors, missing labels, etc. If sensor dimensions are critical, such as for proper fit into a tight location, they must be verified.

(2) Mechanical Inspection

The next step is a check of the mechanical aspects of the sensor. For example, in the case of a pressure sensor check for absence of leaks or, in the case of a turbine flowmeter, verify the freeness of rotation of the wheel. Other checks include flatness of mounting surface for accelerometers and fit of screws for mounting. This type of inspection is typically performed as one mounts or connects the sensor to the calibration system for the basic static calibrations, and prior to the electrical tests. Clearly, if any mechanical problem is present, it is best to eliminate it prior to investing any further efforts, such as the electrical tests.

It may be desirable, following the visual examinations, to examine the sensor's electrical system by checking for open connections and shorts, and measuring input and output impedances. Sometimes it is less time consuming to actually connect and prepare the sensor for the basic static calibration and discern any electrical problems from the calibration data.

In any case, certain types of electrical tests are needed to establish operating characteristics.

(3) Tests for Effects of Excitation Variations

Most sensors exhibit changes in sensitivity and zero-measurand output when operated at excitation values other than the nominal values recommended by the manufacturer.

The tests consist of static calibrations at laboratory ambient conditions and at excitation values both above and below nominal values. If the manufacturer gives a maximum allowable value for the excitation, in addition to the nominal value, the former poses the upper limit for the tests. In the absence of a maximum value, tests are usually performed at excitation values from 50 percent of nominal to 125 percent of nominal.

The test starts with an initial static calibration at the nominal value of excitation to serve as reference. The sensor is then disconnected from the excitation source and permitted to cool down for two hours. At the end of this time, the power supply output is adjusted to deliver 50 percent of the nominal excitation value and the sensor is reconnected. After a stabilization period of about 45 minutes, a static calibration is run. The procedure is repeated for 75 percent, 100 percent, and 125 percent of the nominal excitation (and, possibly, at the "maximum allowable excitation") if that is not likely to cause any damage. When the data are evaluated, one can then determine the effects of variations in excitation on the performance characteristics of the sensor.

(4) Tests to Establish "Warm-up" Effects

Sensitivity and zero-output of sensors may change somewhat from the time the sensor is connected to the excitation source until complete internal thermal equilibrium is reached. For this reason, a stabilization period of about 45 minutes is considered good practice before static calibrations and other tests. Under certain conditions of use, however, a sensor may be expected to perform measurements shortly after being energized. In order to evaluate the performance under such conditions, the following test procedure is followed.

The test equipment, including excitation power supply, is turned on and permitted to stabilize with the sensor disconnected from the excitation source. The sensor is connected and a series of three-point static calibrations is started one minute later. The calibrations are made at zero-measurand, at full range, and at zero-measurand again. NBS experience suggests calibrations at 5-minute intervals during the first half-hour, at 10-minute intervals during the next half-hour, at 15-minute intervals during the following hour, and half-hour intervals during the following hours.

These calibrations monitor closely the expected initially rapid changes in the sensor and permit data work-up and plotting after the first hour. The tests are stopped when sensitivity and zero output have been stable for about one hour.

(5) Test for Contact Noise for Potentiometric Sensors

Contact noise is the result of the variations of contact resistance at the sliding contact of the potentiometric element. The importance of this characteristic depends on the current level, the magnitude of the change in contact resistance, the nominal resistance of the winding, and the resistance of the load circuit. The higher the load impedance, the less will be the effect of a given contact resistance change.

A circuit for this test is shown in figure 4. With switch S closed, the potentiometer slider is moved over the resistance winding by means of a sinusoidal measurand input. The height on the oscilloscope of the noise pips generated is noted. With the slider at rest, i.e., no input, the resistance required to produce a vertical signal on the CRO equal to that of the noise pips when switch S is opened, and closed, is determined. This resistance is then the same as the change in slide contact resistance during the sinusoidal input. This test may be performed at one or more specified levels of current.

The test described next is really a combined mechanical-electrical test and should be performed before the basic static calibrations.

(6) Tests for Effects of Mounting Force or Torque

Pressure sensors, particularly flush-diaphragm instruments, may exhibit changes in sensitivity and zero-pressure output as a result of case deformation in mounting when they are mounted in fixtures. Sensors with integral pressure fittings for tubing are not normally subject to this effect.

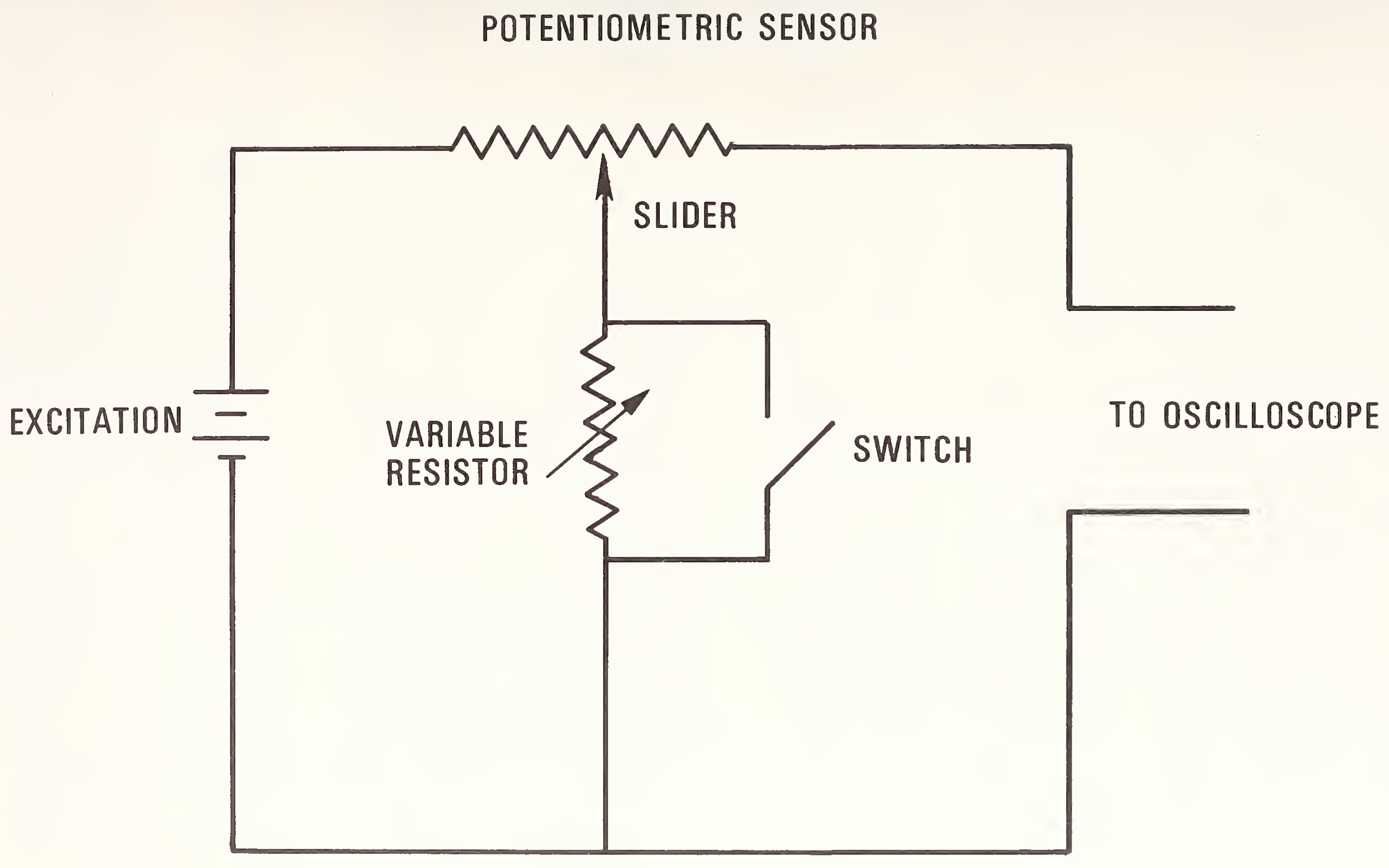

Figure 4 CIRCUIT FOR CONTACT NOISE TEST

The tests to determine effects of mounting torque are static calibrations at various levels of mounting torque. (Manufacturers' literature generally gives no information on recommended mounting torque.) It is prudent to perform this test early in the evaluation sequence. It is possible to proceed by mounting the sensor in the test fixture and using a calibrated torque wrench to tighten it in increments while running a static calibration at each level of mounting torque (these may be abbreviated calibrations; five points are adequate). The maximum torque used for many commercial sensors should not exceed 30 inch-pounds, in the absence of any information from the manufacturer.

Similarly, mounting force and torque may have an effect on the characteristics of force sensors, flowmeters and accelerometers. A judgment should be made in the case of each sensor application as to whether mechanical mounting conditions are likely to have an effect on the performance of the sensor. Appropriate tests should then be devised to verify the effects.

(7) Proof or Overload Tests

Proof or overload tests are part of the qualification procedures. They are used to verify the integrity of the sensing element (or sensor case, depending on the device) to measurand amplitudes well above the rated range. In the case of pressure sensors, such a test is designed to assure that no safety hazard exists when the pressure exceeds the rated value. This test is usually referred to as a proof test, a term used for such tests for ordnance items.

The overload test using amplitudes only 10 percent or 20 percent above rated is used to check the effects of such an overload on the calibration of the sensor and its subsequent performance. Overload or proof tests may destroy or permanently damage the sensor and are therefore used only in qualification testing, never in acceptance tests.

(8) Tests for Effects of Position

Some sensors may be position sensitive, that is, their output may be influenced by gravity acting along a particular axis of the device. An example is a turbine flowmeter which can show different amounts of bearing friction depending on its orientation. Low range acceleration sensors and low range pressure sensors may also be position sensitive. It is desirable to establish the uncertainty due to position (or orientation) by calibrations performed with the sensor in each of three orthogonal orientations in the earth's gravitational field.

If this test cannot be carried out due to time or resources constraints, the reference static calibrations must always be performed with the sensor having the same orientation as it will in the final installation.

(9) Tests of Directional or Transverse Sensitivity

Acceleration sensors are prone to errors due to vibrational inputs along axes other than the sensitive one. It is not practical to construct a sensor which has no transverse sensitivity. Fabrication tolerances and inhomogeneities in materials will result in erroneous output signals due to transverse inputs. For this reason it is very important, in the calibration of accelerometers, to make sure that the input motion is free of transverse components.

Transverse sensitivity is not easy to determine experimentally. One approach is a constant frequency and amplitude mechanical motion applied to an acceleration sensor at right angles to its sensitive axis. Measuring the resultant output at a number of points of a 360° coverage can produce a plot of transverse sensitivity. From this, the least transverse sensitive orientation can be established and used in the selection of subsequent installation orientation.

There seems to be some indication that transverse sensitivity, particularly of piezoelectric accelerometers, is also a function of vibration amplitude and frequency. It may not be economical to run a complete evaluation program to pin this down in detail. One should consider the possibility of errors due to this when reducing vibration data.

In a similar manner, the application of force to a load cell at an angle to its sensitive axis can also cause output errors. This effect can be checked for by deliberate and controlled variations of input angles during static calibrations.

6.1.3 Acceptance Testing

Even when a sensor type has been "qualified," it is still necessary to assure the proper performance of each individual sensor. This is done with an acceptance test, sometimes referred to as "Individual Acceptance Test" (IAT).

Acceptance tests, in contrast to the qualification tests discussed above, are kept as brief as practicable, since often large numbers of sensors must undergo these tests. The tests are used to establish function (i.e., proper signal output, no internal shorts), and static calibration parameters like sensitivity, linearity, hysteresis, and repeatability. If the application is a critical one, additional tests from the qualification sequence may also be performed. Subjecting specified samples to additional tests is another option.

Generally speaking, the acceptance test is also an integral part of any qualification test program. The main component of the acceptance test is the static (base or reference) calibration which will be treated in more detail in section 6.2.1.

6.2 Laboratory Measurement Tests

6.2.1 Static Calibration

6.2.1.1 Basic Considerations

Static calibrations of sensors at laboratory ambient conditions constitute the fundamental calibrations to which all further tests are referenced. The established performance characteristics (defined in the glossary) are established from the results of these static calibrations. This approach is used for all types of sensors, except those which inherently cannot respond to zero frequency (steady-state) stimuli. Piezoelectric sensors fall into this category and their characteristics must be evaluated with the aid of dynamic calibrations, which will be covered later.

The high cost of acquiring calibration equipment, and the high labor cost for the skilled personnel necessary to operate it, make it imperative that the static calibration procedure adopted is the most efficient and practicable one. The procedure must be one which produces the greatest amount of useful information about the sensor with a minimum expenditure of calibration- and data analysis-time. The recommendations in this section will help to realize these objectives.

Finally, the following discussion and recommendations are based on the assumption that the overwhelming majority of sensors are designed to be inherently linear devices, i.e., the electrical output-measurand input relation is essentially linear over the entire operating (calibration) range of the sensor.

6.2.1.2 Number of Calibration Points in Single Calibration

(1) Zero Output

The recommended calibration sequence starts with a measurement of sensor output with zero measurand applied to the input. There are three reasons for this:

- In most measurement situations, the sensor is exposed to zero measurand first, before the process is started which produces the actual measurand amplitudes which are to be measured.

- In case of gage pressure and differential pressure sensors, zero measurand means simply ambient pressure on both sides of the sensing diaphragm. This does not require a separate controlled source of pressure and simplifies the test. In other types of sensors, zero measurand means no flow, no vibration, no force, or no displacement from rest. This test can also apply when a constant and well known measurand near one end of the range exists. Examples are laboratory ambient pressure, temperature, humidity, position, or acceleration (gravitational).

- Electrical malfunctions of sensors will frequently show up when the output is measured with zero measurand or constant input. Some types of drift can also be checked in this manner.

(2) Full-Scale Output

The next most important point is the full-scale point, i.e., the measured output with the full-scale value of the measurand applied to the sensor. In all measurement situations, the sensor should be chosen so that the maximum measurand will not likely exceed the full-scale range of the sensor.

In those cases where measurand amplitudes might exceed the full-scale value, it is desirable to check the sensor's characteristics beyond this value. Manufacturers' recommendations should be followed and caution exercised to prevent permanent sensor damage due to overranging. In normal calibration practice, however, the full-scale measurand input should not be exceeded.

(3) Three Point Calibration

If the sensor has previously been found to be a linear device with a known, or acceptable, amount of hysteresis, a three-point calibration may be adequate for many purposes. Among them are: in-place calibration immediately before use, and quick checks of sensor stability during extended storage or during operation in hostile environments. A three-point calibration starts with zero measurand input, then full-scale input, followed by zero input again. Such a calibration will yield values of zero output, zero shift (hysteresis at zero input) and sensitivity (assuming linear input-output relation). It will not yield information on linearity or hysteresis, nor will it establish confidence in the sensitivity, since that value is based on a single point above zero input.

(4) Eleven Point Calibration

A calibration sequence commonly used involves eleven points with equal intervals between them. Each interval corresponds to 20 percent of the full-scale range for a unidirectional sensor (0% to +100% FSR). The eleven calibration points of a single calibration for this sensor are attained by a sequence which starts with zero measurand, then increases input in steps of 20 percent of full scale to 100 percent FS (full scale) and retraces the points until zero measurand is reached. For bidirectional sensors (-100% FSR to 0% to +100% FSR), and some full-scale ranges of unidirectional sensors, it may not be feasible to calibrate at cardinal 20 percent FS points or to manage an eleven-point calibration; it may be necessary to use additional points. Nevertheless, the eleven-point static calibration of a unidirectional sensor will probably be the most commonly encountered basic calibration.

(5) Twelve-Point Calibration

In theory, data reduction from an eleven-point calibration by means of the least-squares straight line computation is biased slightly since there are two output values corresponding to each measurand input, except at the full-scale point. To give equal weight to the latter point, a twelve-point calibration has been proposed. In this, after the full-scale point has been reached and the corresponding output read, the input is raised a little more, reaching perhaps 105 percent FS or 110 percent FS. Then the input is dropped again until the full-scale point is reached again and the corresponding output is read again. The remainder of the procedure follows as before in the standard eleven-point calibration. Since there are now two output values corresponding to full-scale input, all points have equal weight in this twelve-point calibration. An experiment carried out at NBS comparing eleven-point calibrations to twelve-point calibrations on the same sensor indicated only insignificant differences in the computed slope (sensitivity) of the sensors. It should be noted that a twelve-point calibration may put additional stress on the sensor, since it is actually overranged by 5 percent or 10 percent during this calibration.

(6) Twenty-One Point Calibration

A calibration sequence sometimes used involves twenty-one points with equal intervals between them, with each interval equal to 10 percent of the full-scale range for a unidirectional sensor. The calibration points, in sequence, follow that for the eleven-point calibration described above except at the smaller intervals, ending at zero measurand.

For a bidirectional sensor, with equal spans about zero measurand, a twenty-one point calibration is also possible. The sequence for this starts at zero measurand, proceeds in 20 percent FS steps to full scale, returns to zero measurand, continues in the negative direction to minus full scale, and returns to zero measurand again. An experiment carried out at NBS comparing eleven-point calibrations with twenty-one point calibrations on the same sensor indicated that differences between calculated parameters were insignificant for the two sets of data. In view of the doubled calibration time, it is not recommended to use a twenty-one point calibration sequence for most unidirectional sensors.

(7) Twenty-Two Point Calibration

In a similar manner to the twelve-point calibration above, an additional full-scale point can be added to a twenty-one point calibration by increasing the input to 105 percent FS or 110 percent FS and then dropping back to the full-scale value. Again, this does not offer any noticeable advantage over the twenty-one point calibration.

(8) Recommended Calibration

The eleven-point calibration sequence is recommended for the static calibration of unidirectional sensors on the basis of the discussion above. For the less common bidirectional sensors, a twenty-one point calibration is suggested.

6.2.1.3 Number of Calibration Cycles

It is necessary to perform more than one static calibration on a sensor in order to be able to predict anything about the future performance characteristics of the device. "Repeatability" is the term used to describe the short-term variations in parameters with time; "stability" refers generally to long-term changes over periods of months or years. The basic parameters of interest are the slope of the best straight line through the calibration points: the sensitivity, the intercept of this line on the output axis, the linearity (frequently given as the largest deviation from the best straight line), and the hysteresis: the maximum deviation in output readings at the same value of measurand. These terms, and others, are defined in the glossary.

It seems desirable at this point to delve briefly into some statistical considerations on repeat calibrations. The material is derived from the NBS "Handbook on Experimental Statistics" [20].

A value derived from a single calibration run can be considered a sample in a "population of calibrations" for a particular device under certain well-defined test conditions. It is desirable to be able to make statements about expected future values of the significant parameters. One would, ideally, like to state the average value of a particular parameter for the entire "population of calibrations." Since this population is infinite, this cannot be done. It is, however, possible to obtain an average value of this parameter from a limited number of calibrations and then set up a stated tolerance interval about this average. One can then assert with some numerical confidence that the population average will fall within this interval.

The statistics for this have been worked out in some detail in available tables. The only assumption is that the "population of calibrations" follows a normal distribution. The average value of a parameter A, $\bar{A}$, from the original calibrations is used as an estimator for the "true" value. To go from $\bar{A}$ to the confidence interval, within which the "true" value is expected to lie, one uses Student's "t" distribution [20].

The bounds of the confidence interval are:

$$\left(\overline{A} + t\frac{S_a}{\sqrt{N}}\right) \text{ and } \left(\overline{A} - t\frac{S_a}{\sqrt{N}}\right)$$

where N is the number of calibrations and S_a is the standard deviation of the parameter average. The value of "t" depends on the desired confidence level and the number of degrees of freedom of the data. In this case the latter is a number which is one less than the number of calibrations from which the data are obtained.

Values of "t" extracted from reference [20] are shown below for two-sided confidence intervals at the 90 percent, 95 percent, and 99 percent confidence levels.

TABLE 16
Student's "t" Values

Degrees of Freedom	Value of "t" at various confidence levels		
	90%	95%	99%
1	6.314	12.706	63.657
2	2.920	4.303	9.925
3	2.353	3.182	5.841
4	2.132	2.776	4.604
5	2.015	2.571	4.032

The table shows that the interval does not shrink much beyond two degrees of freedom, except for the 99 percent level where the turning point is three degrees.

For most calibrations, a confidence level of 95 percent should be adequate and reasonable. The true population average would then be expected to be inside the interval 95 percent of the time. Based on those considerations three static calibrations performed in succession are recommended. They yield the desired data on repeatability and stability within acceptable confidence intervals and without the use of excessive calibration time.

Section 7 contains additional information on the data reduction and error analysis to establish the sensor's performance characteristics.

6.2.1.4 Static Calibration Procedures

Calibration procedures for different types of sensors are different but certain common features exist. It is possible to briefly describe general principles for such procedures in roughly the sequence in which the calibrations are to be carried out. It is important that the particular procedures for a given sensor must be carefully specified based on measurement needs, user experience, and good professional judgment. The accurate establishment of the sensor's characteristics and, therefore, its ultimate ability to measure correctly depend entirely on the quality of the calibration. The following discussion is designed to illustrate the general principles involved.

(1) Equipment

The basic equipment necessary for the static calibration of a sensor consists of the measurand, a source of electrical excitation for passive sensors, and the device which measures the electrical output of the sensor. The combined errors or uncertainties of the entire calibration system should be sufficiently smaller than the anticipated tolerance of the performance parameter under investigation to result in meaningful values. Conservative practice in a calibration hierarchy specifies a ten-fold quality ratio, i.e., use of a "0.1 percent" pressure gage to calibrate a "1.0 percent" pressure sensor. This approach may be unrealistic in the case of the better and more "accurate" sensors coming into the market. A three-to-one ratio represents a reasonable approach in view of the customary root-sum-square combination of uncertainties.

Measuring instruments should be checked against standards periodically, and traceability to the National Standards must be provided for. Environmental conditions during the static calibration must be constant (laboratory ambient for baseline calibrations), and specified, to permit possible corrections to the data from the calibrations.

The source of the measurand should be continuously variable over at least the full-scale range of the sensor. Alternately, the measurand may be provided in discrete levels as long as the transition from one level to the next during calibration is accomplished without creating a hysteresis error due to measurand overshoot.

Procedure

1. The sensor is first inspected visually for mechanical defects, poor finish, improper identification markings, and such other flaws as may make it unacceptable. The electrical connector and the input port, mounting base, or similar measurand interface are also inspected.

2. The sensor is connected to (mounted on) the calibration system component from which the measurand is applied to the sensor. In connecting (or mounting) the sensor, care must be taken that the recommended force or torque is not exceeded. Case distortions from the use of excessive force or torque may lead to incorrect calibration data. It is good practice to check the entire setup for proper connections and fit. In case of pressure sensors or flowmeters, the system must be checked for leaks. The excitation source and output measuring (readout) device are connected to the sensor via cabling. Then the sensor is energized. It is good practice to turn on everything except the sensor's excitation, sufficiently ahead of the calibration procedure to permit adequate time for warm-up of the calibration components. One hour is customary for this; a half-hour is the minimum recommended time. (See section 6.1.2 for "tests to establish warm-up time.")

3. It is good practice to permit a similar warm-up period for the sensor as well, prior to the calibration and to watch all components and

indicators for any signs of malfunction. The "warm-up period" (see glossary) of the sensor, an important performance characteristic, is usually established through separate qualification tests prior to this static calibration.

4. The static calibration sequence is performed next. As explained in detail in sections 6.2.1, three eleven-point static calibration cycles are carried out sequentially (for bidirectional sensors--twenty-one points) and the data reduced as explained in section 7.2 below. Those calibrations yield information such as sensitivity, zero measurand output, linearity, hysteresis, repeatability, and resolution (see glossary).

5. Additional repeated calibration cycles, at specified time intervals, can be used to establish stability, as indicated by zero shift- and sensitivity shift- with time.

6. The application of the full-scale value of the measurand for a specified short period of time and measurements of sensor output during and following this period of time can be used to establish creep.

7. Application of a specified value of measurand above the full-scale range, followed by a static calibration cycle, will indicate the overload capability of the sensor.

8. In the case of differential pressure sensors (such as used in flowmeter applications), both input ports may be fed from the same high pressure source to determine the effect of line pressure on the zero measurand output. The effect of line pressure on sensitivity requires application of an accurately known pressure differential between the pressure ports in the presence of a constant high line pressure at both ports. This is a very difficult procedure requiring sophisticated equipment.

9. It may be desirable to establish electrical characteristics of the sensor such as input impedance, output impedance, and insulation resistance. Conventional techniques are used for this.

   It should be noted that for sensors which interface with computers, sensor linearity may be a critical parameter, if calibration points can be stored in memory for look-up and the software provides interpolation. The static calibration procedures at laboratory ambient conditons described above are the Individual Acceptance Test (IAT) (section 6.1.3) for each sensor. They are also an integral part of the Qualification Tests (section 6.1.2). Similar procedures at other than laboratory ambient conditions are used to establish environmental performance and durability and will be discussed in more detail in sections 6.3 and 6.4.

6.2.2 Dynamic Calibration

6.2.2.1 Basic Considerations

Sensors are almost always required to measure physical quantities which vary with time. A purely static measurement is a rarity; furthermore, certain types of sensors, such as piezoelectric devices, have no static (zero frequency) response at all. For these devices, and to correctly evaluate the performance of sensors which measure time-varying measurands, dynamic calibrations are required.

As in the case of static calibrations, one must apply a measurand with accurately known characteristics and measure the resulting sensor output with comparable accuracy. It is generally difficult to generate measurands with accurately known (or well controlled) dynamic characteristics. Consequently, dynamic calibration procedures are less well developed than static calibrations. Also dynamic calibration procedures are not available for certain amplitude and frequency ranges of some measurands.

One approach to dynamic calibration (and sometimes to static calibration) of sensors is the use of a "reference" sensor mounted close to the sensor to be calibrated and subjected to the same measurand. This procedure has merit only if one has a stable, dependable reference sensor with well known characteristics. Even under such circumstances, it is highly desirable to be able to verify the dynamic performance of this sensor periodically. Also, the concept of both sensors being subjected to exactly the same measurand becomes less tenable when measurands have high amplitudes or high frequencies. Ultimately, then, to assure adequate knowledge of the dynamic characteristics of any sensor, it is necessary to subject it to some form of a dynamic calibration.

There are a number of considerations applying to dynamic performance characteristics and the methods used to establish them.

Much of the following discussion is based on material in ANSI Standard B88.1-1972, Guide to the Dynamic Calibration of Pressure Transducers [21], but it can be applied to sensors in general.

The sensor properties or characteristics of interest to a user will depend to a large extent on the application involved. This section defines and discusses some of the properties most often required. These properties sometimes can be described in terms of the "transient" response of the device to a step input, or in terms of its "steady-state" response to sine wave excitation, or both.

In defining sensor properties related to dynamic response, the transfer function of the sensor provides valuable information. The transfer function is the ratio of output to input (expressed in the frequency domain), and forms the basis for the frequency response parameters. Once the transfer function is known, the input vs time for any output can also be calculated. These topics have been treated by those working in the fields of servo mechanisms and network theory, where it is often necessary to describe system behavior in both transient and steady-state terms. This approach, using the transfer function concept, has much to offer in the consideration of dynamic calibration of sensors.

Because of the limitations of periodic generators, responses to aperiodic generators must be depended upon to provide much of the needed information of sensors. Measurements of frequency response using sine wave inputs are easily defined and understood, whereas, the necessity to convert from the time to the frequency domain makes analysis with aperiodic inputs more difficult.

Single Degree of Freedom System

A description of sensor dynamic properties is usually based on the assumption that the sensor is a linear second-order system with a single degree of freedom, e.g., a simple spring-mass system with damping. Some sensors may be found to be more complex than such a simple system and their analysis is correspondingly more difficult. Since a large percentage of sensors now in use can be treated as simple single-mass and single-spring systems, a detailed analysis of such a system is justified.

It must be emphasized, however, that the assumption of a simple single-mass spring (single degree-of-freedom) system does not always apply and the assumption must be carefully considered in the case of measurements of high-frequency phenomena. In such cases, one must consider not only the fact that the sensor may be a complex multi-degree-of-freedom system, but also that the interface between sensor and measurand (i.e., the connecting plumbing for a pressure sensor, or the mounting surface for a vibration sensor) may interpose additional spring-mass systems.

With this caveat in mind, one can then consider the assumed underdamped single degree of freedom system.

The typical spring-mass mechanical system (see fig. 3) which provides the first resonance of a sensor, is described by a linear second-order differential equation:

$$\frac{d^2x}{dt^2} + \frac{c}{m}\frac{dx}{dt} + \frac{kx}{m} = \frac{f(t)}{m} \tag{6.1}$$

where c indicates the damping, k the spring constant, m the mass, and f(t) the forcing function (provided by the dynamic calibrator). The use of the Laplace transform allows the formation of the transfer function from equation (6.1):

$$\frac{OUT(s)}{IN(s)} = \frac{k\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{6.2}$$

where

OUT(s) is the Laplace transform of the output,
IN(s) is the Laplace transform of the input,
K is the steady-state sensitivity
ω_0 is the natural frequency of the system in radians per second = $\sqrt{\frac{k}{m}}$.

The natural frequency is the frequency of free (not forced) oscillations of the sensing element of the sensor without damping ($c = 0$). In practical terms, it is the measured frequency at which the sensor has a 90° phase shift.

s is the complex variable = $j\omega = j\ (2\pi f)$, where f is frequency

ζ is the damping ratio (ratio of actual damping to critical damping).

The response of an underdamped second-order system is treated in numerous texts; the "Shock and Vibration Handbook" [22] is noteworthy.

The model of eq. (6.2) assumes that the sensor can respond to static measures (put $s = j\omega = 0$ into eq. (6.2) with sensitivity K. Often sensor systems with their associated electronics cannot respond to static measures and in this case the model can be modified by incorporating the equivalent of a high-pass RC stage with the transfer function. For example, a piezoelectric sensor with a dominant mechanical resonance can be approximated by the transfer function:

$$\frac{OUT(s)}{IN(s)} = \frac{k\omega_o^2}{s^2 + 2\zeta\omega_o s + \omega_o^2} \cdot \frac{s}{s + 1/RC} \qquad (6.3)$$

Now when $s = 0$, the response is zero.

Equations (6.2) and (6.3) are written in terms of the variable s, and describe the system behavior in the frequency domain. When the input function is specified, the inverse Laplace transform can be used to derive an equation yielding the time domain function. Assume the application of a pressure step of height A to the sensor described by eq. (6.2). The time response of the output voltage is

$$B(t) = A \left[1 - \frac{1}{\sqrt{1-\zeta^2}}\ e^{\left(\frac{\zeta\omega_d t}{\sqrt{1-\zeta^2}}\right)}\ \sin\left({}_d t + \text{arc tan}\ \frac{\sqrt{1-\zeta^2}}{\zeta}\right)\right] \qquad (6.4)$$

where ${}_d = \omega_o \sqrt{1-\zeta^2}$. This equation yields the time response $B(t)$ of the system to a specified input.

Based on the equation describing this model of the sensor, one can then describe certain properties of the sensor in the frequency and time domains.

Amplitude response is the amplitude of the transfer function versus frequency (often called the "frequency response"). It can be computed from eqs. (6.2) or (6.3) by substituting $j\omega$ for s and computing the resultant magnitude. When this is plotted, it is frequently normalized (by dividing by the value of the sensitivity) to show deviations from a flat amplitude response.

The amplitude response contains a great deal of information relative to the sensor, such as resonant frequencies, bandwidth, and the damping of the resonance (or resonances of the real system). It is most desirable to determine this experimentally using an accurately known sinusoidally varying measurand. This is also true of the other parameters discussed below.

Slew rate is another dynamic property, describing the maximum change in amplitude of the output as a function of time.

Phase response shows phase variations of the transfer function versus frequency. It can be derived from eqs. (6.2) or (6.3) by substituting ω for s and computing the phase as ω is varied. In the time domain, phase influences the instantaneous shape of the response to an input signal and contributes to a time lag in sensor response.

Resonant frequency (ω_r) is the measured frequency at which a sensor responds with the maximum output amplitude. Most sensors have more than one resonance, and the lowest in frequency, or "first" resonance, is usually considered important. If the first resonance is the dominant one, the second-order system approximation may be valid. The normalized amplitude response at resonance is governed by the amount of damping in the system.

Dynamic nonlinearity. As indicated in the discussion of static calibrations, sensors are almost always designed to be inherently linear devices. Deviations from linearity are normally established from the static calibrations. Dynamic responses can also show deviations from linearity, due to additional factors like overranging, nonlinear elasticity, and other factors. Dynamic nonlinearity is best described by a family of frequency-response curves. If present, such nonlinearity can degrade measurements considerably. In general, sensors with dynamic nonlinearities should not be used at all.

The discussion thus far has assumed that sinusoidal stimuli are used for the derivation of these frequency-response curves.

There are some other dynamic characteristics such as creep, sag, and hysteresis, which are essentially time-dependent factors. To determine these most effectively, the dynamic calibration requires a somewhat different approach. Quite frequently, a step function, ramp function, or other transient measured input is used. Such approaches must be used in cases where it is not possible to generate the necessary sinusoidal measurand. In such cases, techniques exist by means of which the transient output of the sensor can be manipulated to yield the transfer function of the sensor.

The following properties in the time domain are descriptions of the sensor's response to a specified transient input, usually a step function.

Ringing frequency (ω_d), sometimes referred to as damped natural frequency, is the frequency of free oscillations in the sensor output resulting from a step change in measurand. The ringing frequency is indicated by the number of oscillations per unit time. For the linear second-order sensor, the ringing frequency (ω_d) is related to the resonant (ω_r) by

$$\omega_d = \sqrt{\frac{1-\zeta^2}{1-2\zeta^2}}\;\omega_r \quad . \qquad (6.5)$$

Damping is the energy dissipating characteristic which, together with natural frequency, determines the upper limit of frequency response and the response time characteristics of a sensor. In response to a step change of measurand, an underdamped (periodic) system oscillates about its final steady value before coming to rest at that value. An overdamped (aperiodic) system comes to rest without overshoot, and a critically damped system is at the point of change between the underdamped and the overdamped conditions.

Damping ratio (ζ) is the ratio of the actual damping to the damping required for critical damping. In eq. (6.2) the coefficient ζ is the damping ratio. Typical sensors have damping ratios much less than unity, consequently, values of ω_d and ω_r very nearly coincide. The damping ratio is defined specifically for a linear second-order system. Sensors with more resonances are approximated by associating a "damping ratio" with each resonant frequency.

The damping ratio is a useful parameter in both the time and frequency domain. In the time domain, ζ is related to the amount of overshoot and influences the number of ringing cycles present after a shock excitation. In the amplitude response, ζ is related to the height of the peak at the resonant frequency.

Rise time is the length of time required for the output of a sensor to rise from a small specified percentage of its final value to a large specified percentage of its final value when excited by a step change in measurand. Rise time is related to sensor frequency response.

Overshoot is the amount of output measured beyond the final steady output value in response to a step change in the measurand. The maximum theoretical overshoot of an ideal second-order sensor is 100 percent; this occurs when ζ is zero. Overshoot is determined as:

$$\text{percent overshoot} = 100\, e^{-\left(\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)} \qquad (6.6)$$

for the conditions $\zeta \leq 0.1$.

Settling time is the time required after the application of a step change in measurand for the sensor output to settle within a small specified percentage of its final value (5% is often used). For the ideal second-order sensor with small ζ :

$$t_s = \frac{3\sqrt{1-\zeta^2}}{\zeta\omega d} \qquad (6.7)$$

The settling time increases with smaller ζ and ω_d. The number of oscillations at ω_d required to settle within 5 percent of final value for the ideal second order transducer is:

$$N = \frac{3\sqrt{1-\zeta^2}}{2\pi\zeta} \qquad (6.8)$$

The major disadvantage of the use of transient stimuli is the fact that they are less well controlled or known and that certain modifying assumptions must be made for data reduction.

In the case of the most commonly used transient stimulus, the step function, the inherent assumption in data reduction is that it is indeed a mathematically precise step. Actual measurand stimuli produced by dynamic calibrators cannot be true step functions with infinitely fast rise times. In actuality, the input is a form of ramp-function with a finite rise time and frequently a slightly time-varying amplitude as well.

The advent of Fast Fourier transform analysis capability in dedicated analyzers or the use of FFT-programmed computers has greatly reduced the efforts of deriving frequency response curves from transient calibrations. The resultant increasing use of non-sinusoidal dynamic calibration techniques requires increased care in data reduction and interpretation, however, because the underlying assumptions and limitations are not always understood or clearly stated.

Summary information on the more commonly used dynamic calibration techniques appears in the following sections.

6.2.2.2 Sinusoidal Stimuli

(1) Dynamic Pressure Calibrations

While there are similarities in dynamic calibrations using sinusoidal stimuli for most types of sensors, it is helpful to treat the different sensor types separately.

In the case of pressure sensors, ANSI Standard B88.1-1972 [21] provides considerable detail on their dynamic calibration using sinusoidal and transient input stimuli. The following is abstracted from that document.

The dynamic calibration of pressure sensors requires that the measurand produced by a dynamic pressure generator vary in time in both a known and an appropriate manner. With some generators the pressure-time relationship can be predicated quite accurately. With others, the pressure-time relationship can be established accurately only with the aid of comparison to reference pressure sensors. Reproducibility is a highly desirable characteristic of the dynamic pressure generator, but it is not an essential characteristic. When it is lacking, full dependence on the reference sensor is required.

Dynamic pressure generators fall into two basic classes: aperiodic and periodic. The aperiodic generators are characterized by the pulse shapes they produce, such as the step or the peaking pulse. Quick-opening valve devices and pulse generators produce pressure rise times generally in the millisecond range or less. The rise times and the pressure amplitudes generated by these devices vary markedly from one type of aperiodic pressure generator to another. The shock tube, for example, is capable of generating pressure steps having rise times in the nanosecond range. The pressure step, as used in this treatment, is defined as a change in measurand in which the rise time is less than one-fifth the rise time of the sensor measuring it.

(2) Sinusoidal Pressure Generators for Gaseous Media

Sinusoidal pressure generators are the most useful of the various periodic pressure generators available. Although these devices are adjustable over some range of frequency, they are limited in dynamic pressure ratio, dynamic amplitude, and in their useful frequency range. Non-sinusoidal pressure generators of significant usefulness include the square wave or rectangular wave generators, which may be considered as a special case of the aperiodic or step-function generators.

The dynamic calibration of a pressure sensor can ideally be accomplished by sensing known inputs from a periodic pressure generator at known frequencies and amplitudes. The observed response, including the magnitude, waveform, and phase lag, can then be compared with the known input at various conditions. In order to calibrate with only one frequency at a time for accuracy and simplicity, a sinusoidal pressure generator (SPG) is required. In practice, there are limitations to this approach. First, the applied average pressure levels and dynamic amplitudes generally are not known by absolute means and must be measured by another sensor. The SPG generates a pulsating pressure in a small chamber which can be monitored simultaneously, both by a reference standard sensor and by the sensor being calibrated. The two sensors must be sufficiently close that they sense the same pressure, including amplitude, shape, and phase lag. Analysis of the output of the sensor being calibrated is thus entirely dependent on the performance of the reference sensor, and what is known about its performance. Currently this basic limitation of SPG utilization in a comparison process is not serious because available high-quality reference sensors have response characteristics exceeding the pressure, pressure amplitude, and frequency which can be obtained with available SPGs.

The governing limitations are associated with the ability of the SPG to provide the desired signal. An SPG, when used for calibrating a pressure sensor for a specific use, should satisfy the following:

- The pressure generated is sinusoidal such that frequencies, other than the fundamental one, are negligible.
- The frequency range generated covers the frequencies of pressure expected in the intended application.
- The operating pressure range covers the sensor's full-scale range or a large portion of the range.
- The dynamic pressure amplitude generated is large enough to identify possible nonlinearities in the sensor amplitude response.
- The SPG is operated with the same medium (gas or liquid) with which the sensor is to be used.

Often, all of these criteria cannot be met, and a less-than-desired match is obtained between the dynamic pressure measurand applied during calibration and that encountered in use of the sensor.

Many devices have been proposed and developed as SPGs. The widely used SPGs can be categorized as acoustic resonators, variable-volume generators, or variable-mass generators.

Any of several driving devices can be used to establish acoustic resonance within the chamber of an acoustic resonator. The frequency of resonance is fixed by the geometry of the chamber and the properties of the working fluid.

To obtain a specific frequency, the chamber length must be a multiple of the acoustic half wavelength. When another frequency is required, the geometry must be changed, or harmonics of the fundamental frequency must be used.

At resonance, the pressure waves may be distorted to a significant degree from the pure sinusoidal excitation because of gas dynamic phenomena. As the amplitude or frequency is increased, the nonlinearities associated with real gas, wall, and friction effects also become significant. At low dynamic pressure amplitudes, these generators can provide pressure pulses that are sufficiently sinusoidal for many uses.

In the variable-volume pressure generator, a relatively fixed mass of working fluid is alternatively compressed and expanded within a small chamber. The chamber is deliberately made small such that its natural frequencies are always higher than the frequencies imposed, and thus resonant effects are eliminated. A piston or diaphragm driver is used to vary the chamber volume and thereby the pressure in a repetitive manner.

Usually the gas compression is isentropic and the pressure, p, follows the piston position, ℓ , as follows:

$$\frac{p}{p_o} = \left(\frac{\ell_o}{\ell}\right)^{\gamma} \qquad (6.9)$$

p_o is the equilibrium pressure
ℓ_o is the driver (piston or diaphragm) position at the equilibrium pressure
γ = ratio of specific heats at constant pressure and volume (C_p/C_v).

Thus, as the piston travels in a sinusoidal manner, the pressure amplitude is represented by the expression:

$$p = p_o\,(1 + \alpha \sin \omega t)^{-\gamma}, \qquad (6.10)$$

and the dynamic pressure amplitude by the expression:

$$\begin{aligned}\Delta p &= p_o - p = p_o\;[1 + \alpha\;\sin \omega t)^{-\gamma}] \\ &= \alpha\gamma p_o \sin \omega t - \frac{\alpha^2}{2}\; p_o\;\; \gamma(\gamma+1) \sin^2 \omega t \;\; \ldots\end{aligned} \qquad (6.11)$$

where α = modulation factor which is always < 1.

Considering subsequent terms in the expansion with realistic coefficients, this dynamic pressure is clearly non-sinusoidal. The effects of fluid motion and viscosity also introduce nonlinearities in the waveform.

This class of generators is generally limited by the amplitude-frequency characteristics of the driving unit. In theory, non-sinusoidal input from the driving device could compensate for nonlinearities and thus a sinusoidal pressure pulse shape could be approximated. However, the dynamic characteristics of practical driver systems (e.g., crystal diaphragm or electromagnetically driven piston) naturally degrade into sinusoidal displacements as the frequency is increased, thus limiting the effectiveness of this approach.

The variable-mass pressure generator utilizes a fixed chamber volume and the rate of fluid flow into or out of the chamber is cyclically varied to develop the dynamic pressure pulsations. These flow-modulated devices provide a fast response so that relatively larger pressure amplitudes are available at high-frequency conditions compared to the variable-volume generators. The critical frequency limitation associated with acoustic dimensions of the chamber still apply. Operation is limited to frequencies appreciably below the natural frequency of the chamber which is dependent on the properties of the fluid used and the chamber dimensions.

A siren-type device is often used for this class of SPG with the gas entering the chamber through a critical flow orifice or nozzle from a constant pressure source and leaving the chamber through a larger critical flow nozzle. The throat of one of these nozzles is interrupted by a rotating disc or cylinder with throat-sized holes. The pressure in the chamber is dependent on both the rate of mass addition and the rate of mass discharge:

$$\frac{dp}{dt} = n \left(A_i - A_e \frac{p}{P_s}\right) P_s \tag{6.12}$$

where n is a constant given by

$$n = \frac{a}{v} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{6.13}$$

a = gas speed of sound

v = chamber volume
γ = ratio of specific heats of constant pressure and volume
A_i = inlet orifice area
A_e = outlet orifice area
p_s = stagnation pressure of supply gas.

In order for the dynamic pressure inside the chamber to be sinusoidal, two conditions must be met:

$$\bar{p} = \frac{2\hat{A}_1}{\hat{A}_e} \qquad \text{and} \qquad \frac{\Delta P}{\bar{p}} \leq n \frac{\hat{A}_e}{2\omega} \ll 1$$

where Δp is the dynamic pressure component

$\hat{A}_e$ = maximum exit area

$\bar{p}$ = average chamber pressure.

When these conditions are met, the expression for the dynamic pressure component becomes:

$$\Delta P = - \frac{n\hat{A}_e\bar{p}}{2\omega} \sin \omega t \tag{6.14}$$

Developments in fluidic devices provide the basis for a new generation of dynamic pressure generators. Fluidic pressure generators are, typically, low amplitude devices but are capable of wide dynamic range. The devices described so far make use of gaseous media and depend on the use of accurately characterized reference sensors.

For liquid media there is a fundamental dynamic calibration technique which produces sinusoidal stimuli. The following description summarizes the method [23,24].

(3) Sinusoidal Pressure Generators for Liquid Media

A dynamic pressure source intended for the dynamic calibration of pressure sensors can be used to produce sinusoidally varying pressures of up to 34 kPa zero-to-peak, over the frequency range of approximately 50 Hz to 2 kHz. The source consists of a liquid-filled cylindrical vessel, 11 cm in height, mounted upright on the armature of a vibration exciter which is driven by a sinusoidally varying voltage. The sensor to be calibrated is mounted near the base of the thick-walled tubular vessel with the pressure-sensitive element in contact with the liquid in the tube. A section of the tube is filled with small steel balls to damp the motion of the dimethyl siloxane working fluid with a viscosity of 10 stokes. This helps to extend the useful frequency range to higher frequencies than would be provided by an undamped system.

For the geometry described, both the amplitude of the sinusoidally varying pressure and the natural frequency of the liquid column may be calculated to first approximations by simple relations.

Damping is an important consideration because a damped system may have a higher useful frequency range than the same system undamped. With an undamped, single-degree-of-freedom system, the amplitude-frequency response remains constant within ±5 percent up to approximately 20 percent of the natural frequency. In a system with optimum damping (a damping ratio of about 0.6 of critical), the amplitude-frequency response remains constant within ±5 percent to about 80 percent of the natural frequency. To maintain a flat response to 2 kHz thus requires an undamped system with a natural frequency of 10 kHz or an optimally damped system with a natural frequency of 2.5 kHz. Other degrees of damping would require natural frequencies between those values to achieve the desired flat response to 2 kHz.

Four factors, in combination, determine the pressure levels attainable over the frequency range of interest. They are: (1) the force and displacement capabilities of the vibration exciter, (2) the density of available working fluids, (3) the height of the liquid column, and (4) the degree of damping. The last factor interacts with the others and depends on geometry, on the bulk modulus, and viscosity of the fluid. As noted above, damping need not be considered at frequencies below about 20 percent of the system's natural frequency because the amplitude-frequency response is flat up to this limit. Up to that limit, the amplitude of the sinusoidal pressure generated within the liquid column and acting on the sensor is given by:

$$P = ah_c{}^{\rho} \tag{6.15}$$

where

P = pressure (Pa zero-to-peak),
a = acceleration amplitude (g zero-to-peak),
h_c = liquid-column height above the center of the transducer diaphragm (m), and
ρ = density of liquid (kg/m^3).

The natural frequency of a liquid column is directly proportional to the square root of the velocity of sound in the liquid and inversely proportional to the height of the column. For an infinitely stiff, open-topped vessel containing the liquid, the system has one degree of freedom with a natural frequency given by:

$$f_n = 0.25 \frac{1}{h} \sqrt{\left(\frac{B}{p}\right)} , \tag{6.16}$$

where

f_n = natural frequency (Hz),
h = total height of liquid column (m), and
B = bulk modulus (Pa).

The quotient of B and ρ is proportional to the velocity of sound in the liquid.

In practice the tube is not infinitely stiff, but has some elasticity. For thick-walled vessels, a volume change in the tube itself is small enough compared to other volume changes that it may be neglected for practical calibrations. More important, the sensor diaphragm forms part of the tube wall, and since this diaphragm is displaced in response to pressure, an overall volume change occurs. The effect of this change is to lower the natural frequency as the effective bulk modulus is reduced. The effective bulk modulus may be defined by the relation:

$$B' = \frac{V}{\frac{V}{B} + dV_t} , \tag{6.17}$$

where

B' = effective bulk modulus (Pa),
V = volume of liquid in the tube (m^3), and
dV_t = change of volume resulting from unit pressure change (m^3/Pa).

In the NBS calibrator, steel balls are used for damping and the volume of the liquid is reduced by an amount equal to the total volume of the balls, although the column height remains unchanged. Damping can be adjusted by changing the number of steel balls and/or their size and/or the viscosity of the liquid medium as described in reference [24].

Taking the above factors into account, the natural frequency of the sensor-calibrator system is given by:

$$f_n = 0.25 \ \frac{1}{h} \quad \frac{\sqrt{B(V_c - V_b)}}{p(V_c - V_b + BdV_t)} \tag{6.18}$$

where

V_c = volume available for liquid with no balls present (m^3),
V_b = volume occupied by balls (m^3), and
h, B, ρ, and dV_t are as given above.

It is estimated that this dynamic pressure source has a total calibration uncertainty of about ±5 percent when calibrating a typical pressure sensor with a flush diaphragm [24].

(4) Dynamic Motion Calibrations

The basic considerations for the dynamic calibration of motion sensors are quite similar to those for pressure sensors and are outlined in section 6.2.2.1. Motion sensor principles are discussed in section 4.2 (additional, more detailed coverage can be found in references [22] and [25]). The motion sensor, in its common form of a damped spring-mass system, responds to a motion of its case by a corresponding displacement (or force) between the mass and the base. This displacement (or force) is transduced into an electrical signal which is proportional to displacement, velocity, or acceleration, depending on the relation of measurand frequency to the natural frequency of the spring-mass system.

The dynamic calibration of such sensors is then a matter of applying a known sinusoidal motion to the case of the sensor and measuring the resultant output. For sensors with very large full-scale ranges of acceleration, limitations of sinusoidal motion generators require another approach: This is the use of a transient input, such as a step or pulse input. Such methods will be discussed in section 6.2.2.3.

The most common dynamic sinusoidal calibrator for linear motion is the Electro Dynamic Vibration Excitor. It is a readily available commercial device similar to a large loudspeaker (without its cone) driven by an electronic amplifier. Typical systems can generate undistorted sinusoidal linear displacements with amplitudes up to about one inch peak-to-peak, frequencies from about 5 Hz to 10 kHz, and peak-to-peak accelerations up to 100 g's. At low frequencies, those systems are limited in displacement and therefore only capable of generating low amplitude accelerations. At high frequencies they are acceleration-(force)-limited, thus capable only of small displacements. Within these limitations, they are good working systems with the motion of the sensor easily determinable. The motion is calculated from measurements of displacement (optically or electronically) and frequency. Alternately, a "reference" sensor can be used, back-to-back, with the sensor to be calibrated. As discussed in section 6.2.2.1, the "reference" sensors must have stable and well known characteristics, and must be mounted as close to the sensor under test as practicable. The latter is particularly important at high frequencies. If this is not assured, the motions applied to the two sensors may not be identical and the resulting calibration erroneous.

For angular motion similar considerations apply. A device capable of generating angular sinusoidal displacements was developed at NBS about twenty years ago. It was an electrically driven torsion pendulum with a vertical axis. Its frequency range was about 0.5 Hz to 30 Hz, with a maximum angular acceleration of 40 rad/sec^2 [27].

The "Earth's Field Dynamic Calibrator for Accelerometers" was developed to calibrate accelerometers at frequencies from about 30 Hz down to about 0.1 Hz, by rotating the sensor at uniform velocity in the earth's gravitational field, the magnitude of which is well known. The electrical connections to the sensor are made through low noise sliprings. Air bearings and a magnetic coupling insure low friction and constant speed. This device has the limitation that the exciting force cannot exceed $\pm 1 g_n$, and the further limitation that the accelerometer under test must have negligible response to transverse excitation [26].

The "dual centrifuge" was developed in order to generate large acceleration amplitudes at low frequencies and overcome the limitations of the earth's field device.

It is capable of generating large amplitudes of acceleration in the frequency range from 0.5 Hz to about 30 Hz. It consists essentially of a small turntable mounted on a large one, each turning in a horizontal plane. The accelerometer is mounted on the small table with its sensitive axis in a horizontal plane. When the turntables are rotating with constant angular velocities, the seismic mass in the accelerometer responds to a sinusoidally varying component of the centrifugal force field generated by the rotation of the large table. A system of pulleys and timing belts is arranged so that the small turntable has zero absolute angular velocity in inertial space at all times (its motion is like that of the connecting rods for the drivewheels of a steam locomotive). The equation of motion of the seismic mass of the accelerometer is the same as for sinusoidal linear motion. Due to the character of the motion, the accelerometer is also subjected to transverse acceleration during each cycle and the output will reflect this in its departure from the ideal. The magnitude of the generated acceleration can be varied by locating the small turntable at various distances from the center of the large one.

The dual centrifuge can generate accelerations of $\pm 1\ g_n$ at 1 Hz, increasing to $\pm 100\ g_n$ at 10 Hz to 25 Hz [27].

It is possible to generate very large amplitude sinusoidal acceleration amplitudes through resonant amplification by driving beams or rods at their resonant frequencies [22]. This subjects the sensors, which are mounted at the end of the beam or rod, to large amplitudes of motion. Optical sensing of displacements or the use of reference sensors are employed to establish values of applied acceleration. Disadvantages of this method include limitation to operation at a resonant frequency, fatigue failures of beams or rods after a short time, and uncertainties in the measurement of displacement amplitudes.

(5) Dynamic Calibrations for Other Sensors

Dynamic calibration techniques for sensor types, other than the above, may be under development in measurement laboratories, although little information appears available. Low range force sensors can be tested similarly to acceleration sensors by generating inertial forces. If a heavy, known mass is mounted on the force sensor and the whole system is vibrated at known acceleration amplitudes, the corresponding dynamic force can be calculated. Due to force limitations of commercial vibration exciters, this approach is feasible only for relatively low range force sensors.

Clearly in the area of dynamic sinusoidal calibration methods for sensors, much more work needs to be done to meet test requirements.

6.2.2.3 Step Function Stimuli

As pointed out in section 6.2.2.1, the preferred method for dynamic calibration of sensors is the application of sinusoidal measurands. Limitations of this method, particularly when large amplitudes are required, call for other approaches.

The application of a well characterized transient such as a step function (actually a ramp function with very fast rise) can be used for dynamic calibrations.

(1) Dynamic Pressure Calibrations

Again, as in the previous sections, it is helpful to treat separately the step function calibrations for different types of sensors.

In the case of pressure sensors, ANSI Standard B88.1-1972 [21] provides details, which are summarized below.

A <u>shock tube</u>, in its simplest form, consists of two sections of tubing separated by a thin diaphgram. When these two sections are pressurized to different pressure levels and the diaphragm is suddenly ruptured, the higher pressure gas will immediately begin to flow into and compress the gas at lower pressure. At a distance of approximately 10 to 15 tube diameters downstream from the diaphragm, a well formed shock wave is established. This shock wave continues to move through the remainder of the gas in the low pressure section at approximately a constant velocity. Behind the shock wave the pressure suddenly rises to a new value resulting in a positive pressure step. The length of time the pressure remains constant behind the shock wave depends on several factors. These include the dimensions of the shock tube, the position in the low pressure section at which the pressure is being monitored, the degree of smoothness of the inner walls of the low pressure section, the type and design of the diaphragm, and the type, temperature, and initial pressure of the gas in each section.

When a shock tube is utilized for pressure sensor calibration, several parameters must be measured before the amplitude of the pressure step can be ascertained. These parameters include the shock wave velocity, V_s, and the initial absolute pressure, P_1, and temperature, T_1, of the gas in the low pressure section.

If a pressure sensor is mounted flush in the sidewall of the low pressure section, it will sense a change in pressure, ΔP, when the shock wave passes over it. The equilibrium pressure and particle velocity behind the shock wave are determined from the Rankine-Hugoniot relations [7]. When air is used as the working gas in the low pressure section, the amplitude of the pressure step can be computed from the following equations:

$$\Delta P = \frac{7}{6} P_1 \left(M_s^2 - 1\right) \tag{6.19}$$

with Δp and p_1 in compatible pressure units

and

$$M_s = \left(\frac{V_s}{344.5}\right) \left(\sqrt{\frac{298}{273+T_1}}\right) \tag{6.20}$$

where V_s is expressed in meters per second, T in degrees kelvin, and M_s is the shock wave mach number. When gases other than air are used, equations (6.19) and (6.20) do not apply.

Since the working gas temperature must be known, a convenient method of determining it is from a measurement of the static wall temperature of the shock tube. Except at very low pressures, the temperature of the working gas closely approaches that of the wall.

The shock wave velocity, V_s, is determined by measuring the time necessary for the shock wave to pass between points spaced a known distance apart along the path of the velocity vector. Because the velocity of the shock wave tends to decrease with distance, the last pair of points should be in close proximity (less than one tube diameter) from the sensor undergoing calibration. Several different types of sensors can be used to detect the passage of the shock wave past these points, the most common being pressure sensors, thin-film heat-transfer gages, and light screen photo-electric gas density sensors. The shock wave transit time, Δt_s, between pairs of sensors is measured with electronic timers or with calibrated oscilloscope sweeps. The shock wave velocity, V_s, is computed from the equation V_s = spacing between sensors/Δt_s. Because of the squared relationship between V_s and P, an uncertainty of 0.5 percent in the measurement of the shock wave velocity produces an uncertainty of at least 1 percent in the determination of pressure step amplitude.

When the pressure sensor is mounted flush in the sidewall of the shock tube, the rise time of the pressure step resulting from the passage of the shock wave depends on the shock wave velocity and the transverse length, d, of the sensor diaphram, in the direction of shock wave propagation. The time required for the pressure on the sensor to change from P_1 to P_2 ($P_2 = P_1 + \Delta P$) is given by the expression

$$t = \frac{d}{V_s} \tag{6.21}$$

The maximum theoretical rise time (10 to 90 percent) for pressure sensors with circular diaphragms mounted flush in the sidewall of a shock tube can be shown to be:

$$t_r = \frac{0.687d}{V_s} \qquad (6.22)$$

where d and V_s must be in consistent units.

The side-mounted mode of operation is recommended when:

- This is the manner in which the sensor will be used in the actual application.
- Maximum accuracy in the determination of the pressure step amplitude is desired.
- It is desirable to minimize sensor ringing.
- The incident wave is considerably "cleaner" than the reflected wave.

If the end of the low pressure section of the shock tube is sealed off with an end plate, the moving shock wave, in striking the plate, will be reflected by it. A pressure sensor mounted flush in the end plate will detect only the reflected shock wave. The reflected shock wave is characterized by a much shorter rise time (usually nanoseconds) and a higher pressure as compared to the incident shock wave (sidewall measurement). The rise time of the pressure step associated with the reflected shock wave is sufficiently short to excite all the ringing frequencies associated with any flush-mounted pressure sensor. When air is used as the working gas, the amplitude of the pressure step behind the reflected shock wave is

$$\Delta P = \frac{7}{3} P_1 \left(M_s^2 - 1\right) \left(\frac{2 + 4M_s^2}{5 + M_s{}^2}\right) \qquad (6.23)$$

where M_s and P_1 are defined as in equations (6.19) and (6.20).

Because of the complex relationship between ΔP and M_s in equation (6.23), any uncertainty in the measurement of the shock wave velocity, M_2, may produce an uncertainty in the determination of the pressure amplitude ΔP several times larger.

The pressure behind the incident and reflected shock waves remains constant for a period of time which is dependent on the design of the shock tube and on the type, the temperature, and the pressure of the gases initially in the two sections. For a given shock tube geometry, the longest duration of constant pressure behind the reflected shock wave is obtained when the shock tube is operated under "tailored" conditions. Depending on the operating conditions and shock tube geometry, the period of constant pressure behind the reflected shock wave may vary from a few hundred microseconds to several milliseconds.

The end-plate mounted mode of operation is recommended when:

- Ringing frequencies must be determined.

- This is the manner in which the sensor is to be used in the actual application.
- The maximum pressure step amplitude is required in calibration.
- The maximum duration of constant pressure behind the shock wave is desired.

Vibration of the walls and end plate of the shock tube occurs during operation. In order to determine the effect of this "ground shock" acceleration on the sensor output, the sensing end of the sensor must be blanked off from the pressure wave without significantly altering the acceleration components, and the resultant output measured. Acceleration effects can be minimized by utilizing heavy-walled tubing for the low pressure section of the shock tube, by using a heavy end plate and by shock-mounting the tube.

When a shock wave passes through the working gas, the temperature of the gas is suddenly raised. The new temperature, T_2, varies with the square of the shock wave mach number, M_s, as well as with the type and initial temperature of the gas. If the sensor is sensitive to transient temperatures, then the temperature step produced by the shock wave may cause errors in the sensor calibration.

To determine the extent of such errors and to reduce their effect, a temperature shield may be employed. Thin coatings of opaque insulating materials sprayed on or bonded to the diaphragm make good shields but may alter the sensor characteristics. A sensor should always be checked for transient temperature sensitivity. This will be covered in more detail in section 6.3.3.2.

A typical example of a shock tube built for, and used by, the National Bureau of Standards generates a pressure step function with a rise time of less than 10^{-8} seconds. The shock tube is 20 ft long and is divided by a cellulose acetate diaphragm into two chambers, 12 ft long and 8 ft long. The 12 ft section is filled with helium and the 8 ft section with dry air; the ratio of respective absolute pressures in these sections is set to be 2.7 to 1 over the entire range of operation of the shock tube. The pressure of the helium is set to a value approximately equal to the desired pressure amplitude of the step function. Upon rupture of the diaphragm, helium pushing into the air chamber generates a shock wave in the air which travels the length of the 8 ft section, and is then reflected from the rigid end wall at an increased pressure. The amplitude of the step function pressure to which a sensor in the end wall is exposed ranges from about 6 psi to 1000 psi and the duration of the pressure step at these values is about 4.5 milliseconds.

Shockless Step Pressure Generators form another class of devices for the dynamic calibration of pressure sensors. A number of devices have been developed which generate a rapidly rising pressure step between two pressure levels. Most of these units employ a quick-opening valve. At least one utilizes a burst diaphragm. The geometry of the generator and the opening time of the valve or burst diaphragm are chosen to preclude the formation of shock waves when the device is operated. Shockless step generators have been designed and successfully used to produce both increasing and decreasing pressure steps. Although most of these generators employ gaseous media, a few liquid devices have been developed and used. The shockless pressure step generator has the following advantages over other dynamic pressure calibrators.

- The magnitude of the pressure step generated by the device is determined by measurements of static pressure before and after the quick-opening valve is opened, thereby permitting good accuracy.
- The duration of the state of constant pressure following the pressure step can be made of any chosen time duration.
- Both the initial pressure on the sensor and the magnitude of the pressure step are controllable over very wide pressure ranges.
- This calibrator is superior to the shock tube from the standpoint of operational speed and simplicity of technique.

The dynamic characteristics of a shockless pressure step generator are determined by measurement with a calibrated reference sensor possessing a rise time of no more than one-fifth that of the measurand. The following dynamic characteristics of the generator should be known: rise time, overshoot, undershoot, and the inherent ringing frequencies with their associated damping ratios. Also of interest is the stability of both static pressure levels P_1 (initial pressure) and P_2 (final pressure).

When the pressure rise time is one-fifth that of the sensor undergoing test or calibration, the error in the measured value of sensor rise time is less than 1 percent. If this criterion cannot be met, the composite rise time must be analyzed carefully to determine each component of the rise time.

Vibration present during the operation of the shockless pressure step generator should be minimized by careful design. In general, the shorter the rise time of the device, the greater is the level of vibration acceleration (ground shock). In those units which utilize poppet values, it may be necesary to open the poppet valve more slowly when calibrating at very low pressures in order to keep the vibration effects on low range sensors to a minimum.

Associated with the pressure step produced by these generators is a dynamic temperature change whose amplitude is related directly to the pressure change, $P_2 - P_1$, and inversely to the rise time of the measurand. The effect of this dynamic temperature pulse on the response of both the test and reference sensor must be determined. When a gaseous medium is used in the shockless step generator, the rise time of the measurand is inversely related to the speed of sound in the gas. For this reason helium is used when very short rise times are desired.

The following is a brief description of several shockless step pressure generators developed in recent years. The first one was developed at the National Bureau of Standards [28]. The range of pressures of this pneumatic calibrator is from about 2 psi to 100 psi.

The rise time of the generated pressure is about 0.9 ms (much longer than that of the shock tube) and the initial oscillation superimposed on the step decreases to less than 2 percent of the step amplitude within 15 ms. The heart of the calibrator is a pneumatically operated quick-opening valve which applies air pressure from a large storage tank to the sensor under test. The tank pressure is set to the desired value by a pressure regulator and measured by a precision dial pressure gage. Since the volume of the storage tank is more than 100 times that of the combined internal volumes of the quick-opening valve and the fixture holding the sensor, gas flow and temperature change are held to a minimum. The pressure in the storage tank after the step is applied to the sensor, as indicated on the dial gage, is then equal to the amplitude of the pressure step within about ±1 percent. This calibrator is most useful for the inspection of sensors for dynamic errors at low frequency such as those due to hysteresis and creep.

Another type of step function pressure calibrator was developed at the U.S. Naval Ordnance Laboratory [29]. It is also based on a quick-opening valve mechanism, using a gaseous medium. It consists of a poppet valve with a long rod which quickly opens the passage between a pressure storage vessel and the sensor to be calibrated. The quick-opening action is accomplished by means of a weight which is dropped onto a plate attached to the far end of the valve rod stem. This device is capable of rise times as short as 50 μs and pressure amplitudes up to 1000 psi.

A liquid medium step function pressure calibrator was also developed at the National Bureau of Standards [30]. This calibrator consists of a conical valve with a long stem in a large pressure vessel. The sensor to be tested is mounted to face a small cavity in front of the conical valve. Application of pressure to a piston at the end of the long stem of the conical valve causes the latter to close. Pressure of the desired amplitude is built up in the large pressure vessel. The sensor cavity is brought to zero measurand and ambient pressure by a bleeder valve which is thereafter kept closed. A fast release of the pressure on the valve stem piston relieves compressive stress in the valve stem and the conical valve begins to open. As the pressure in the sensor cavity builds up, opening of the valve accelerates, so that a pressure step of short rise time is applied to the sensor. As in the pneumatic step function calibrator, the ratio of the volume of the large pressure vessel to that of the sensor cavity is very large. Like the pneumatic step function generator, static measurement of the amplitude of the pressure step to within about ±0.2 percent is possible using a precision dial gage. By the selection of cavity size, oil viscosity, and the diameter of the valve stem, a nearly optimum step function of pressure with a rise time of less than 3 ms can be obtained at most pressures from 500 psi to 3000 psi.

This device also is most useful for the inspection of sensors for dynamic errors at low frequency such as those caused by hysteresis and creep.

Pressure pulse generators have been developed to provide single peaking pulses of reasonably controlled amplitudes [31]. These pulse generators produce a dynamic measurand which is not a step function, but which may resemble a single half cycle of a sine wave. One technique employed to generate such a pulse is to drop a mass onto a piston in contact with the surface of an "incompressible" fluid contained within a fixed volume. The amplitude of the pulse is dependent on the fluid compressibility, the mass, its initial height above the piston, and the piston area. The pulse generator is not an absolute calibration device and requires a reference pressure sensor of known characteristics to monitor the pulse and provide a peak value measurement for the sensor under test. The greatest advantage of the pulse generator is the comparative ease with which very high pressure pulses can be generated. Care must be taken in the selection and location of the reference sensor used since results of the calibration are dependent on this comparison standard. The recommended conditions of operation of section 6.2.2 relative to the comparison sensor apply equally well to these generators. In order to achieve accuracy in calibration using a liquid medium pulse generator, it is essential that no pockets of gas exist in the vicinity of either the reference or test sensor.

(2) Dynamic Acceleration Calibrations

Several methods are available for the dynamic calibration of acceleration sensors.

Step acceleration (shock) calibrators are used to overcome some of the amplitude and frequency limitations of sinusoidal calibrators. The situation is similar to that for dynamic pressure calibrators.

Impact methods for high-acceleration calibration generate sudden velocity changes with reproducible amplitudes and time durations. They can be used to obtain calibrations up to about 30 000 g_n (where g_n is the acceleration of gravity). These methods make use of the fact that the velocity change during a transient pulse is equal to the time integral of acceleration:

$$v = \int_{T_i}^{T_2} a \, dt \qquad (6.24)$$

a = acceleration

where the initial or final velocity is taken as reference zero and the integration is performed to, or from, the time at which the velocity is constant. The voltage output of the sensor can be described as:

$$E = \frac{Sa}{gn} \qquad (6.25)$$

s_a = the calibration factor in volts per g
g_n = acceleration of gravity.

When the two relations (6.25) and (6.26) are combined, one gets

$$S_a = \frac{\int_{T_i}^{T_2} Egm \, dt}{v} \qquad (6.26)$$

Methods for determining the integral are described in the "Shock and Vibration Handbook" [22] and other texts. With the integral determined and the velocity known, the calibration factor of the acceleration sensor can be found.

Various devices for such impact calibration are described in the literature [22,32]. The Ballistic Pendulum consists of two masses suspended by wires or metal ribbons. These restrict the masses to motion in a common vertical plane. The sensor to be calibrated is mounted on the far end of the anvil mass. The hammer mass is raised to a predetermined height and then released, striking the anvil mass. The resultant velocity of the anvil mass can be calculated from optical displacement measurements as a function of time. The duration of the pulse input can be varied by the use of different contact materials between hammer and anvil. Typical times range from about 0.5 ms to 5 ms.

Another calibrator used a vertically Dropping Hammer Mass on which the sensor is mounted, impacting on a fixed anvil. The velocity change for this system can be calculated from the height of the hammer drop and the height of the subsequent rebound [22,32].

In the Drop-Ball Calibrator, the sensor is mounted on the bottom flat of an anvil mass held in position by magnets. A large steel ball is dropped from the top of the calibrator to impact the anvil. The anvil and sensor are accelerated in a short free-flight path until they are caught by a soft cushion. The anvil passes through an optical timing gate to enable measurement of the velocity after impact. Acceleration amplitudes and pulse durations can be varied by selecting the proper anvil mass, ball mass, and contact materials between ball and anvil. Attainable shock acceleration and durations range from 100 g_n at 3 ms to 10 000 g_n at 0.1 ms. Calibration uncertainties are estimated at about 5 percent to 10 percent [22].

There appears to be little information on dynamic calibrators for other types of sensors than those for pressure and motion. It would seem practical to adapt certain types of step pressure calibrators for the dynamic calibration of force sensors. A quick-opening valve pressure calibrator of the type developed at NBS [28] was modified so that the generated step pressure drove a piston against the input end of a force sensor. The electrical output signal indicated a compression force input with a rise time of shorter than 2 ms and an amplitude equivalent to the product of the pressure and the piston area. Such calibrators warrant future development. A variation of this approach could be used to apply a step force in tension, as well as in compression.

An experimental system for the dynamic calibration of flowmeters (turbine types) was reported by NASA several years ago. In it the flowmeter was elastically coupled to a pipe in which liquid flowed at a constant speed. The flowmeter was vibrated longitudinally along the axis of flow, thus modulating the flow, as seen by the meter. With constant meter displacement over a specified frequency range, a measure of the dynamic performance could be obtained. No commercial version of the system is available.

Temperature sensors are basically first-order systems, having no resonances. Their dynamic characteristics can be obtained from step function measurand inputs. The time constant of the sensor is generally all that is required. The time constants of most temperature sensors used in engine or ordnance monitoring ATE systems are relatively long, typically on the order of seconds. Consequently, it is probably only necessary to rapidly move the sensing end of the device from a medium at one known, steady-state temperature to another at a different steady-state temperature. No commercial version of such a dynamic calibrator is believed to exist.

6.2.2.4 Random Stimuli

Dynamic calibrations of sensors can be performed in a variety of ways, as discussed in the sections above. For ease of data reduction, and, usually, ease of generating the stimuli, preference is given to sinusoidal wave shapes, since all the energy of the stimulus is concentrated at one frequency. This simplifies the data reduction process as well. Other important dynamic stimuli are step and ramp functions, pulse (square, triangular, half sine) and random or white noise inputs.

The choice of method is normally dictated by the amplitude and frequency range (or rise time) required to characterize the sensor. The most desirable methods, however, may not be usable for other reasons.

The use of random input signals for dynamic calibrations of sensors is a more recent development. It became practical with the advent of sophisticated spectrum analyzers and computer based data reduction equipment. Random stimuli ideally contain signals with all frequency and phase components, thus the power spectral density of a white noise source is constant throughout its bandwidth. The term "white noise" is used in analogy to white light which also contains frequency components throughout the optical spectrum. The usefulness of random stimuli is primarily due to the fact that if they are applied to a lightly damped resonant system, that system acts as a narrow band-pass filter near the resonance. Thus the resonance (or resonances) of a physical system can be excited by random inputs and therefore identified. Random stimuli sources can often excite resonances far beyond those excitable from other dynamic calibration sources.

Random stimuli are used primarily in vibration testing at this time. A random vibration can be considered to be a sum of a large number (tending to infinity) of harmonic vibrations of appropriate amplitude and phase. The total power is the sum of the powers in the individual components. Power spectral density describes the power per unit frequency interval. For white noise the power spectral density is a constant at all frequencies making it especially suitable for dynamic calibration purposes. In addition, some environmental vibration testing using random signals has come into favor due to more realistic and shorter duration test possibilities. This is discussed in section 6.3.3. The "Shock and Vibration Handbook" [22] provides a good coverage of the subject of "statistical concepts in vibration."

The application of random stimuli to pressure sensors has been suggested, but no known commercial devices are marketed.

6.3 Operating Environments and Tests

6.3.1 General Considerations

Most military systems are designed for operation while being subjected to a wide variety of operating environments. To assure proper operation, the systems (and/or their individual components) must be tested. The discussion below is extracted from an engineering design handbook promulgated by the U. S. Army Material Command [33].

Environmental testing consists of subjecting equipment to various conditions such as temperature, vibration, radiation, and humidity, in order to determine or verify its capability to operate satisfactorily when subjected to such stresses. Strength, life, and performance tests, as well as other basic test types, may all involve environmental testing.

The effect of environmental conditions is an important consideration in reliable design of equipment. Environmental testing may be performed during the initial stages of equipment manufacture to determine its ability to withstand adverse use conditions.

Generally, there is a deliberate attempt to simulate as closely as possible the environmental conditions expected during equipment operation. Such simulations are performed, for example, in reliability demonstrations with samples of prototype hardware. Usually, certain critical features of the total operational environment are simulated at specific severity levels in order to uncover design and material weakness and those workmanship errors not uncovered during inspection. In still other cases (such as development tests), the operational environment may not be known and test conditions consequently cover a wide range.

All environmental tests have the common objectives of determining the effect of the environmental conditions on an item or verifying that the item is capable of proper operation under these conditions.

Environmental testing ranges in sophistication from very crude methods, such as using an improvised temperature chamber, to testing in very elaborate facilities permitting many combinations of conditions to be simulated. Tests may be purposely destructive (as in strength and life testing) or nondestructive (such as proof tests and burn-in).

The appropriate test conditions must be carefully selected. Basic factors to consider are:

- The possible environmental conditions during intended use of the equipment.
- The subset of these that must be used in testing.
- The capability for generating and controlling these test conditions.

The environmental factors that can affect the behavior of the item during field operations must be determined and simulated to the extent feasibile within the constraints of cost, schedule, and testing capability. Not all environmental conditions that affect behavior can be readily simulated, and very rarely can all be generated simultaneously to account for interaction effects. Trade-offs therefore must be made when selecting the test conditions.

It should be noted that environmental testing must consider all the environments encountered in manufacturing, storage, transportation, and handling, as well as those experienced during operational use.

The environmental conditions to be encountered by equipment are not always known in exact form. No one knows precisely, for example, the environmental profile that a field artillery rocket will experience throughout its life, including all types of environmental factors and their severity levels. It is only possible to select representative characteristics, such as averages or maximum levels, or major factors which adequately describe conditions for a test.

Environmental conditions of greatest interest from the reliability viewpoint are those that have detrimental effects on equipment operation. Table 17 lists typical detrimental effects of environmental factors. In many cases, effects not detectable when the factors are encountered singly appear when two or more are present simultaneously. For example, some electronic components function properly in either a low temperature or a vibrational environmental environment, but when the environments are combined, component leads break. Some possible combined effects on several environmental factors are illustrated in table 18. Combined environments do not always have adverse effects. For example, low temperature inhibits the growth of fungi and rain dilutes the corrosion effects of salt spray.

A less frequent effect occurs when one environmental condition creates another, e.g., when arcing between switch or relay contacts causes the formation of ozone, thus changing the environment and its effect.

Some conditions cause cumulative, nonreversible changes in the equipment; therefore, when considering equipment behavior, the history of environmental exposures must be considered. For example, heating from welding and soldering can cause permanent shifts in device characteristics; mechanical shock can result in permanent dislocation of a lead or a part; and nuclear radiation can cause permanent defects in semiconductor devices.

The need for conditioning items prior to environmental testing to simulate the historical effects must be considered. This conditioning is sometimes necessary to assure that the response during the test is representative of that in operational use. Knowing the environmental history is less important when the effects are reversible, but the reversibility of all important responses can be determined only through careful analysis. Ignoring the nonreversible effects that have occurred in previous tests and operations can result in misleading environmental test results. Of course, these effects may be difficult to assess or simulate, but just knowing of their existence can be very valuable for the test designer.

Experience is frequently the most useful guide for selecting the environmental factors and the severity levels and combinations of them to be used in a test. This prior knowledge based on experience can help reduce the number of environmental tests to those needed to ensure the successful operation of the item. This is an extremely important point: Testing is very expensive, both in terms of equipment cost and personnel time and cost. This point should be kept in mind also when being guided by one of the Standard Testing Documents. Best known among these are MIL-STD-202E (Test Methods for

Electronic and Electrical Component Parts), MIL-STD-810C (Environmental Test Methods), and, related, MIL-T-28800B (Test Equipment for Use with Electrical and Electronic Equipment, General Specification for). All three documents include, in the specified tests, various levels of severity. There is always a tendency to specify, or use, a more severe level (or a wider frequency range, or a longer test duration) than may be really necessary--"To be on the safe side!" In view of the costs and time involved in testing, test conditions should only be selected through close and continuing coordination between system designer and service user.

The difficulties associated with common environmental factors--such as temperature, vibration, and thermal shock--nearly always receive attention. Less familiar factors can sometimes be equally or even more important, e.g., hail and insects demand special attention to determine what characteristics and severity levels are required.

Hail, for example, may cause mechanical impact damage and the size, shape, velocity, and number per unit area of the simulated hailstones are the important characteristics. On the other hand, the vibration induced by the incident hail may be the most significant factor. Insects can cause both mechanical and chemical damage; both characteristics must be evaluated.

When there is little available knowledge about the operational environment or its effect on an item, it is often simpler and more economical to test and see what happens than to spend a great deal of time and money on an independent study. This is essentially the "build-and-test" approach, which has limited value for large and expensive items, but when used with discretion it can be useful for new designs or for new applications of old designs.

Tables 17 and 18 listing "Environments and Typical Effects" [33] follow. The experimental simulation of environmental conditions is discussed in section 6.3.2.

6.3.2 Simulation of Environmental Conditions

The need for environmental tests to simulate all or some of the conditions listed above has led to the development of sophisticated and detailed test methods. These include MIL-STD-202E, MIL-STD-810C, MIL-T-28800B, and others listed in section 8.3. These documents should be used for guidance in the specification and performance of environmental tests.

Several factors should be considered. It is not always possible to generate complex conditions, even with the most elaborate facilities. Air turbulence, gases, or insect conditions can be difficult to simulate. Many facilities are even limited in their capability to generate complex temperature profiles.

A great deal of effort has been devoted to developing sophisticated simulation facilities. But there may be other ways to determine if a device can withstand a hostile environment. First of all, it is the effect of the environmental conditions that is of interest, not just the conditions themselves. Therefore, substitutes should be considered. For example, pebbles might be used as a substitute for hailstones if mechanical damage from impact

TABLE 17

Environments and Typical Effects

Environment	Effects
High temperature	Parameters of resistance, inductance, capacitance, power factor, dielectric constant, etc., will vary; insulation may soften; moving parts may jam due to expansion, finishes may blister; devices suffer thermal aging; oxidation and other chemical reactions are accelerated; viscosity reduction and evaporation of lubricants are problems; structural overloads may occur due to physical expansion.
Low temperature	Plastics and rubber lose flexibility and become brittle; electrical constants vary; ice formation occurs when moisture is present; lubricants gel and increase viscosity; high heat losses; finishes may crack; structures may be overloaded due to physical contraction.
Thermal shock	Materials may be overstressed instantaneously causing cracks and mechanical failure; electrical properties may be altered permanently.
Thermal radiation	Causes heating and possible thermal aging; surface deterioration; structural weakening; oxidation; acceleration of chemical reactions; and alteration of physical and electrical properties.
Acceleration	Mechanical overloading of structures; items may be deformed or displaced; mechanical functions may be impaired.

TABLE 17 (continued)

Vibration	Mechanical strength may deteriorate due to fatigue or overstress; electrical signals may be mechanically and erroneously modulated; materials and structures may be cracked, displaced, or shaken loose from mounts; mechanical functions may be impaired; finishes may be scoured by other surfaces; wear may be increased.
Shock	Mechanical structures may be overloaded causing weakening or collapse; items may be ripped from their mounts; mechanical functions may be impaired.
Acoustic noise	Vibration applied with sound waves rather than with a mechanical couple; can cause the same damage and results as vibrational environment, i.e., the sound energy excites structures to vibrate.
Humidity	Penetrates porous substances and causes leakage paths between electrical conductors; causes oxidation that leads to corrosion; moisture causes swelling in materials such as gaskets, excessive loss of humidity causes embrittlement and granulation.
Salt atmosphere and spray	Salt combined with water is a good conductor which can lower insulation resistance; cause galvanic corrosion of metals; chemical corrosion of metals is accelerated.
High pressure	Structures such as containers, tanks, etc., may be overstressed and fractured; seals may leak; mechanical functions may be impaired.
Low pressure	Structures such as containers, tanks, etc., are overstressed and can be exploded or fractured; seals may leak; air bubbles in materials may explode causing damage; internal heating may increase due to lack of cooling medium; insulations may suffer arcing and breakdown, ozone may be formed; outgassing is more likely.

TABLE 17 (continued)

Zero gravity	Disrupt gravity-dependent functions; aggravates high-temperature effects as convective heat removal ceases.
Magnetic fields	False signals induced in electrical and electronic equipment; interference with certain functions; can induce heating; can alter electrical properties.
Electromagnetic Interference	Causes spurious and erroneous signals from electrical equipment and components; may cause complete disruption of normal electrical and electronic equipment such as communication and measuring systems.
Sand and dust	Finely finished surfaces are scratched and abraded; friction between surfaces may be increased; lubricants can be contaminated; clogging of orifices, etc.; materials may be worn, cracked or chipped.
Nuclear/cosmic radiation	Causes heating and thermal aging, can alter chemical, physical, and electrical properties of materials; can produce gases and secondary radiation; can cause oxidation and discoloration of surfaces; damages electrical and electronic components, especially semiconductors.
Solar radiation	Effects similar to those for sunshine, nuclear/cosmic radiation; and thermal radiation.
Albedo radiation	Albedo radiation is reflected electromagnetic (EM) radiation; amounts depend on the reflection capabilities of illuminated object such as a planet or the moon; effects are the same as for other EM radiation.
Winds, gust and turbulence	Applies overloads to structures causing weakening or collapse; interferes with function such as aircraft control; convectively cools surfaces and components at low velocities and generates heat through friction at high velocities; delivers and deposits foreign materials that interfere with functions.

TABLE 17 (continued)

Precipitation: sleet, snow, rain, hail, dew, frost	Applies overloads to structures causing weakening or collapse, removes heat from structures and items; aids corrosion, causes electrical failures; causes surface deterioration; and damages protective coating.
Clouds, fog, smog, smoke, haze, etc.	Can interfere with optical and visual measurements; deposition of moisture, precipitation, etc.; enhances contamination; can act as an insulator or attenuator or radiated energy.
Sunshine (ultraviolet radiation)	Causes colors to fade; affects elasticity of certain rubber compounds and plastics; increases temperatures within enclosures; can cause thermal aging; can cause ozone formations.
Chemical contaminants	Corrosion of metals may be accelerated; dielectric strength may be reduced; an explosive environment can be created; heat transfer properties may be altered; oxidation may be accelerated.
Insects, fungi	Can cause surface damage and chemical reactions; can cause clogging and interference with function; can cause contamination of lubricants and other substances.

TABLE 18

Illustration of Interacting Environmental Effects

	Salt Spray	Vibration	Low Temperature	High Temperature
High Temperature	Accelerate Corrosion	Increase Rate of Wear	Mutually Exclusive	
Low Temperature	Decelerate Corrosion	Intensity, Fatigue, Rupture, etc.		
Vibration	No Interaction			
Salt Spray				

is of interest. Or, if vibration induced by hailstones is of interest, then a vibration test already scheduled may be adequate.

Some effects are investigated more easily at a more fundamental level. Also, the environmental conditions sometimes may be separated into fundamental components. For example, a temperature profile may be simulated by high and low temperature levels and thermal shock. In such cases, effects such as nonreversibility, interactions, and aging must be accounted for.

Elaborate environmental test facilities are not always required. Simply heating individual circuit components with a soldering iron or hair dryer may in some cases be more informative than testing the entire circuit or assembly in an oven, since the contribution to temperature instability of each component may be examined. And, in the absence of certain capabilities, an improvised test may be better than none at all. For example, mechanical shock may be simulated by dropping the item from a prescribed height.

When facilities do not exist for generating combined environments, combined environmental effects must be simulated by using single environments in sequence. If the severity levels of the environments are set not to deliberately damage the equipment, the order of application is determined by whatever is most convenient. When tests cause damage, the order of environments must be considered carefully. First, one should apply those conditions least likely to damage the specimen. For mechanical parts, humidity and salt spray tests logically would usually be applied before vibration or a mechanical load test. An electronic part usually would be tested by applying vibration before high temperature. Such test sequencing allows the maximum amount of information to be obtained before damage occurs.

Ordering of environments for items composed of both mechanical and electrical parts is not clear-cut. The same basic criteria still apply, and the ability to repair the item can greatly influence the ordering.

If both single and combined environmental conditions can be generated, it does not necessarily follow that the combined testing is preferable. The final choice of an approach depends on what is to be accomplished with the test and is influenced strongly by factors such as time, cost, skills, and instrumentation.

Combined environmental testing has two significant advantages over single environmental testing:

- The ability to investigate the combined effects of multiple conditions since combined testing, in most cases, more closely approximates the real environment.

- Several conditions usually can be applied simultaneously in a short time, rather than in sequence, due to savings in setup and test time. Therefore, combined testing often saves money. The major disadvantage of this approach is that the initial equipment cost for combined testing may be higher.

In qualification and acceptance testing, combined environments are preferable. The increased confidence derived from the knowledge that synergistic effects are accounted for frequently permits the use of smaller safety factors.

When testing to relate cause and effect, combined environmental testing is used as an extension of single environmental testing. During the development phase, initial testing usually is applied to determine the effects of single environments. Combined environments are employed after single environmental effects have been determined and combined effects become of interest. Single environmental testing also may be preferable in long duration tests due to the impracticality of committing combined environmental test facilities for long periods of time.

The following section describes some of the environmental test methods in more detail.

6.3.3 Environmental Test Procedures

Environmental test procedures for military systems are described in great detail in the documents cited in section 8.3, specifically in MIL-STD-202E and MIL-STD-810C. It is instructive, however, to state considerations applying to test methods for the most common environments and summarize these methods.

6.3.3.1 Extreme Steady-State Temperatures

Temperature is the environmental parameter most likely to change during a sensor's application life, and it is necessary to evaluate the effects of thermal changes on the performance characteristics of the sensor.

All environmental conditions vary with time, to some degree, but for practical purposes it is possible to divide the regime into steady-state conditions and dynamic conditions. "Steady-state" represents changes that are long with reference to the time constant of the sensor, typically, times from hours to days, and "dynamic" implies changes that are short with reference to the time constant, typical time span from minutes down to fractions of a second. Two totally different approaches are called for in the test procedures for temperature environments, and they are treated separately.

The steady-state temperature test procedure consists of static calibrations of the sensor (dynamic in the case of sensors that do not have zero-frequency responses, such as piezoelectric sensors) after it has become stabilized at each of several prescribed test temperatures. Military specifications and standards must be consulted for the applicable parameter values. These tests are usually carried out with the aid of temperature chambers. Such chambers are equipped with controllers which permit the attainment and regulation of the desired temperatures either above or below laboratory ambient conditions, with heating and refrigeration elements in the walls of the chamber. A wide variety of temperature chambers are commercially available, depending on the temperature range desired and on the size of the object which is to be tested.

For the tests, the sensor is mounted in the chamber and connected to the measurand whose source is usually external to the chamber. For accelerometers a vibration exciter can be used to apply the desired acceleration by means of a column or rod protruding into the chamber through a flexible seal.

It is often possible (depending on available chamber space) to test several sensors simultaneously. This can greatly reduce overall testing time.

One should attach a temperature sensor to one or more of the test sensors in the chamber to measure chamber temperature, and to indicate when the sensors have reached a stabilized temperature level. The typical dial thermometer on the chamber can be used as a rough indicator of the temperature.

The test procedure involves eleven-point static calibrations performed at each test temperature. When testing two or more sensors of the same type and range, fewer points are sometimes taken for the static temperature calibrations of the second and subsequent sensors.

Unless otherwise specified, the temperature range over which the sensors are tested should leave a margin of safety of about 10 °C (18 °F) at the ends of the claimed operating range of the instrument. The testing is done in two parts with tests below laboratory ambient temperature followed by tests at elevated temperatures. This assures evaporation of any moisture which may have condensed inside the sensors during the low temperature tests.

An initial static calibration is performed (after the sensor has been mounted in the test chamber and permitted to stabilize at room temperature). For the low temperature tests, the desired low end of the range is reached in steps, usually of about 25 °C each. Then the chamber is permitted to warm up and an additional calibration is performed about halfway between the lower range limit and room temperature. A final calibration at room temperature completes this part. At each temperature, the sensor is allowed to stabilize for about 45 minutes, and the sensor case temperature is measured by the attached temperature sensor before, during, and immediately after each calibration.

Tests at elevated temperatures follow immediately, using as initial calibration the one just performed at room temperature. Again, the high temperature end of the range is reached in equal 25 °C steps. The majority of presently available sensors have an upper limit of about 120 °C (248 °F). If the limit is higher, additional steps are taken. After this, the chamber is permitted to cool down with one calibration performed halfway down to room temperature. A final calibration is then performed at room temperature. Results from this calibration will indicate if any permanent changes in performance characteristics have occurred as a result of the temperature tests.

Sensitivity at each test temperature is computed, and these values, as well as the zero measurand outputs, can be plotted as a function of the test temperature.

The testing and calibration of strain gage sensors is usually performed with constant voltage excitation. Some semiconductor strain gage sensors may show quite different temperature characteristics when excited from a constant current source. Where manufacturers' literature indicates that either type of excitation may be used, static temperature tests should be run with both types of excitation.

6.3.3.2 Thermal Transients

The temperature tests described above will not establish the performance characteristics of sensors operating in a rapidly changing thermal environment. Many sensors contain temperature compensating components that are designed to minimize changes in sensitivity and zero measurand output over a wide range of temperatures. Temperature compensation is effective only when these components and the sensing elements of the device are at the same temperature. Rapidly changing environmental temperatures will set up thermal gradients in the sensor. These may cause large zero shifts due to the temperature difference between sensing and compensating elements.

Tests for the effects of thermal transients are more difficult to perform than those for steady-state temperatures. At present techniques exist only for testing flush-diaphragm pressure sensors and piezoelectric accelerometers [34,35]. It is not known whether thermal transient test techniques for other types of sensors are under development.

Dynamic temperature effects are most pronounced in small, flush-diaphragm pressure sensors. A technique was developed at NBS for observing dynamic temperature effects in such sensors [36]. Briefly, it consists of immersing the sensing end into a pool of molten Woods metal at a temperature slightly below the upper limit of the sensor's operating temperature range. The output of the sensor during immersion may be displayed on an oscilloscope with an adequately slow sweep or recorded on a strip chart recorder for longer time periods. The testing time varies with the instrument, but generally three minutes are adequate from the initiation of immersion. During the test the sensor zero-pressure output will usually show a rapid initial negative shift lasting for a few seconds. This shift reverses and becomes positive, increasing until a maximum is reached, typically after about one minute. After this, the shift will decrease until ultimately the zero shift will reach the value expected from its static temperature characteristics for the temperature at which the sensor finally stabilizes.

Tests may be performed at other temperatures within the operating range of the sensor. For tests at low temperatures, the sensor can be dipped into ice water, as an example. This technique cannot be used effectively for other than flush-diaphragm devices due to the difficulties of introducing the liquid medium into the sensor cavity rapidly enough. It sould be noted that the thermal transient stimulus sets up a "thermal gradient," i.e., a heat flow condition, in the sensor which causes different parts of the sensor to be at different temperatures until stability is reached, thereby producing transient output signals.

Pressure sensors which measure gaseous pressures require testing for the effects of thermal transients in this medium by a different test procedure. The procedure using thermal radiation stimuli can also be applied to piezoelectric acceleration sensors, and probably to other types of sensors as well.

A simple and repeatable testing technique was developed at the National Bureau of Standards to obtain information on the zero shift and change in sensitivity of a pressure sensor by subjecting it to a thermal transient generated by a mechanically chopped cw laser beam [37]. In the NBS tests, commercial flush-diaphragm pressure sensors with ranges up to 50 psi (345 kPa) were tested. Zero shifts and changes in sensitivity of the order of 20 percent FS were measured due to thermal transients with power densities up to 10 W/cm^2. In this technique the sensor can be pressure-cycled while it is irradiated. In this way, zero shifts and sensitivity changes may be directly displayed in a procedure which requires a testing time of only about one minute for each sensor.

NBS also developed another test method for evaluating the effects of short-duration, thermal radiant-energy transients on pressure sensors [34]. In this method sensor output (zero-shift with the sensor at atmospheric pressure) is measured as the sensor is exposed to thermal radiation from the ignition of a photographic flashbulb or from the discharge of an electronic flash. Thermal energy pulses up to 0.1 J/cm^2 with durations of about 6 ms were generated using an electronic flash; pulses of up to 2.2 J/cm^2 and duration up to about 37 ms were generated using No. 22 flashbulbs. In the latter tests a sampling of 25 commercial pressure sensors showed zero shifts ranging from 0.5 percent to about 400 percent of the full-scale output.

A simple, inexpensive method was developed at NBS for determining the effects of thermal transients on the zero output and sensitivity of piezoelectric accelerometers [35]. Thermal transient stimuli were generated by mechanical chopping of the beam of an incandescent lamp, and were aimed to heat the top or side of the test accelerometer. In tests of 14 commercial accelerometers, zero shifts were observed with magnitudes as high as 640 g_n representing up to 7 percent FS. These results were obtained at a radiation power density of 1.8 W/cm^2 with 15 s transients. No changes of accelerometer sensitivity were found to exceed experimental uncertainties in these thermal transient tests.

It should be emphasized again that sensors in operational environments are highly likely to be subjected to thermal transients and should be tested accordingly. At the conclusion of such tests, a static calibration is recommended to check on possible damage sustained during the tests. In view of this possibility, dynamic temperature tests should be performed last in the evaluation of sensors.

6.3.3.3 Acceleration, Vibration, and Shock

Military systems are subject to environmental motions which can be divided into the three regimes of acceleration, vibration, and shock. It is generally understood that acceleration represents a steady-state, unidirectional measurand; vibration is the measurand acting over a range of frequencies; shock represents a single transient application of the measurand.

A variety of test methods are used to simulate each of the regimes. Military specifications of each service specify different amplitudes, frequencies, shock shapes, and durations; in addition, specific types of test equipment may also be called for. These must be followed when so specified.

Tests to establish the acceleration sensitivity of the sensor are carried out by mounting the instrument on a centrifuge and subjecting it to acceleration forces for various orientations of the sensor.

The sensor is usually tested along three orthogonal axes:

1. The cylindrical axis of sensor in line with the applied acceleration and its sensing end <u>away</u> from centrifuge center of rotation.
2. The cylindrical axis of sensor in line with the applied acceleration and its sensing end <u>toward</u> centrifuge center of rotation.
3. The cylindrical axis of sensor <u>perpendicular</u> to the applied acceleration.
4. Same as (2) with radial position changed 90°.

Typically in such tests, accelerations of 5, 10, 15, and 20 g_n are applied in each of the positions with zero measurand input, and the resulting output measured. The results are reported in terms of percent FS/g_n.

Two precautions must be taken. The pressure ports of a pressure sensor must be covered, otherwise in one of the testing positions the air impact pressure due to centrifuge rotation may cause erroneous outputs. Sensors which dissipate much electrical energy (certain high-voltage bonded strain gage sensors in particular) must be covered with a box to prevent air cooling due to rapid centrifuge spinning. The latter may result in outputs not representative of normal use.

Inadvertent effects, similar to those on other types of sensors, must be considered prior to the planning of the tests to assure proper interpretation of the test data.

Tests which establish the vibration sensitivity of the sensor are carried out by mounting the instrument on the table of an electromagnetic shaker and subjecting it to vibrational acceleration fields along the three axes used for the steady acceleration tests (1, 3, 4 above). Tests usually involve vibrational accelerations with a maximum amplitude of 40 g_n peak-to-peak over a frequency range wide enough to include those frequencies which the sensor is likely to encounter in actual use. The frequency range and amplitudes obtainable by typical commercial equipment are: frequencies between 2 Hz and 20 000 Hz, and acceleration levels up to about 100 g_n peak-to-peak.

During the test, the sensor output is displayed on an oscilloscope which is watched while the frequency of vibration is slowly varied through the desired range. The vibration amplitude is monitored and adjusted to keep the amplitude relatively constant within equipment limitations. Resonances appear as peaks in the output at certain frequencies. It may be difficult at times to ascribe such peaks to the sensor rather than to the shaker-sensor combination. The fact that peaks appear simultaneously in the sensor output and in the shaker motion does not necessarily indicate a shaker resonance. One possible way of identifying the origin of resonances is to use a piece of metal of the weight and size of the sensor as shaker load. If a peak in shaker motion appears at the same frequency as before, this frequency is a shaker resonance.

Frequently, no peaks are discernible. The vibrational acceleration response is then described simply as not exceeding the maximum trace broadening (in terms of the sensor sensitivity) observed (due to internal noise, vibration, electrical pickup) over the frequency and amplitude range tested.

In potentiometric sensors a mechanical resonance of the slider may manifest itself by complete loss of output signal.

A static calibration at the conclusion of the vibrational acceleration tests is desirable to indicate any possible permanent change in the performance characteristics caused by the tests.

It should be noted that there are two ways of considering acceleration and vibration tests. They can be used to indicate what kind of errors may result if the sensor must make measurements while being subjected to those environments. Such tests can also be used (and this can be part of the same test) to indicate what kind of permanent effects may have occurred in the sensor due to exposure to this environment.

Shock tests, on the other hand, are almost exclusively used to establish the permanent effects on sensor performance (survivability). There is generally no requirement to exactly duplicate the real environment which the sensor may encounter. The shock test is specified to assure the ability of the sensor to survive the assumed shock environment. Shock theory, tests, and data interpretation are covered in great detail in the "Shock and Vibration Handbook" [22].

Shock test parameters and the shock test equipment to be used are usually specified in military specifications and test standards such as MIL-S-901 Navy. Shock test specifications contain the shape of the shock pulse, its amplitude, and its time duration. The axis of the test item along which the shock is to be applied may also be given, as well as the number of shock pulses which are to be applied.

There are three major types of shock test machines. In one the test specimen is mounted on a table structure which is hoisted vertically to a predetermined height and then dropped onto a platform. The material and shape of that platform as well as the material and mass of the table will determine the shape and duration of the shock pulse. The height of drop will control the amplitude of the shock. Half-sine, rectangular, and saw tooth acceleration pulses are most commonly employed.

A second type of machine uses a hydraulic ram with a shaped piston and damping orifice to generate the desired shock pulse and shape. The third system uses a mechanical hammer which is released from a specified height and strikes a plate on the other face on which the test item is mounted. In this setup the plate properties will influence the shock pulse shape, duration, and amplitude.

In shock tests, three successive shocks are usually applied along three orthogonal axes of the sensor to be tested. After these tests also, at least one static calibration is performed to assess the effect of the shock test on the performance characteristics of the sensor.

Test procedures for other environmental parameters listed in tables 17 and 18 tend to be more specialized and less commonly required. Details on those procedures can be obtained from the military documents cited.

6.3.3.4 Electromagnetic Radiation

The increasing use of electronics in the automotive and process industries led to the recognition of problems caused by susceptibility to undesired electromagnetic interference by conduction or radiation. In military vehicles, the need for measurement of the susceptibility of electronic components to electromagnetic sources has recently become more critical as more electronic components are used in vehicle applications. Electronic and electrical equipment may be susceptible to temporary or permanent malfunctions when subjected to electromagnetic sources, either of a transient or steady-state nature.

Electromagnetic interference (EMI) may be either transient, intermittent, or continuous in nature arising from sources such as transmitters or other equipment located either on board or adjacent to the vehicle, or from component parts of the vehicle ignition or electrical power systems [38].

In the process industries, electromagnetic radiation can arise from various sources. This radiation is frequently generated by the small hand-held radio transceivers that are used by maintenance and security personnel. The susceptibility of process control instrumentation to the radiation of the hand-held transceiver is of great concern. There are other sources of electromagnetic radiation of concern, such as fixed radio and television transmitters, vehicle radio transmitters, and various industrial electromagnetic sources [39].

In addition to the continuous forms of electromagnetic energy deliberately generated, there are also spurious radiations caused by devices such as welders, contactors, and motors. These sources can also cause difficulties in the operation of equipment. Methods employed to prevent effects from continuous radiation will normally also reduce the effects from these sources.

The electromagnetic environment is determined by the strength of the electromagnetic field (field strength in volts per meter). The field strength is not easily measured without sophisticated instrumentation and is not readily calculated by classical equations and formulae because surrounding structures or the proximity of other equipment will distort and/or reflect the electromagnetic waves. The most direct method of specifying the EMI environment limits is to measure the actual fields, voltages, currents, and impedances around the component or system of interest under all hazardous conditions. This will require a large enough sample of installations to determine possible variations.

Another approach to setting limits on levels of EMI would be to establish experimentally the maximum levels of electric and magnetic field strength existing with the actual interconnecting wires and field impedance levels expected during operation of the system. One would use sources of maximum power levels expected for on-board transmitters, transient sources, and external transmitters. All of these constitute the ambient level of EMI. Data of this type are being collected in the automotive industry. They may be available later as special reports on EMI characteristics and test limits.

Test methods for measuring the effects of electromagnetic radiation on the instruments of concern are designed to establish repeatability of results at various test sites. However, electromagnetic radiation will be affected and distorted by the proximity of conductive objects, including the walls of any test chamber. There will undoubtedly be some differences in results for tests conducted at various sites. These results must be taken into account when verification testing is conducted.

Caution must be exercised in carrying out the test procedure where high voltages or intense fields may be present. "... present maximum allowable field for human exposure is 10 mW/cm^2 averaged over six min, which is equivalent to about 194 V/m electric field strength in the far field ..."[38].

A few definitions follow:

> Conducted emission- desired or undesired electromagnetic energy which is propagated along a conductor. Such an emission is called conducted interference if it is undesired.
>
> Radiated emission - radiation- and induction-field components in space. (For many test purposes, induction fields are classed together with radiation fields.)
>
> Field strength - This term can be applied to either the electric or the magnetic component of the field, and may be expressed as V/m or A/m. When measurements are made in the far field and in free space, the power density in W/m^2 may be obtained from field strengths approximately as $(V/m)^2/377$ or $(A/m)^2 \times 377$ [38].

Information is available in the literature on design for electromagnetic compatibility [72]. The measurement of electromagnetic interference characteristics and the requirements are discussed in great detail in the literature [38,39,73,74]. Although the first two documents [38,39] were written for two specific industries, automotive and chemical processes, the principles and test methods described are applicable to other areas of use as well.

Three generally used military standards documents for testing of electrical components, MIL-STD-810C [40], MIL-STD-202E [41] and MIL-T-28800B [42], do not specifically address electromagnetic interference.

6.4 Stability, Durability, and Reliability Testing

6.4.1 General Considerations

The operating conditions in which sensors are used, and which influence their performance characteristics, may be categorized into several major areas. These are: operation at laboratory conditions, operation in harsh environments, operation over extended periods of time, and, finally, operation in harsh environments over extended time. Degradation of sensor performance tends to increase in the order in which the areas are listed.

Determination of performance at laboratory ambient conditions is covered in section 6.2, and the effects of environment in section 6.3. The effects of time on sensor performance are addressed in this section. The terms reliability, stability, and durability are similar in that all indicate quantitatively "how long it will work." There is a distinction between the terms which is tacitly accepted by most measurement engineers. "Reliability" is used to show the time to failure of the device (expressed in a variety of ways). "Stability" and "durability" are more concerned with the manner in which the performance of the device deteriorates prior to total failure. Of course, failure itself can also be defined as the point at which performance deteriorates beyond all specified boundaries. Nevertheless, the distinctions in meaning between these concepts are considered useful and the discussion which follows will be based on these.

Durability is too general a term to be useful in specifications and test procedures. The glossary defines stability as "the ability of a sensor to retain its performance characteristics for a relatively long period of time." The definition also states: "Unless otherwise stated, stability is the ability of a sensor to reproduce output readings obtained during its original calibration, at room conditions, for a specified period of time. It is typically expressed as within _____ percent of full-scale output for a period of ____ months."

The implication in this statement is that the output readings obtained during re-calibrations are taken at room temperature as during the original calibration. In a real-world application, such as a military ATE system, one is really concerned whether the sensor continues to operate within established bounds in its operational environment. This suggests the desirability of in-place calibrations, or self-testing sensors.

The next section will discuss test methods and will attempt to clarify this further.

6.4.2 Stability, Durability, and Operating Life

In order to establish the stability, durability, or operating life of sensors, one must re-calibrate them at specified intervals. There are a number of considerations which will dictate the kinds of tests which are to be conducted.

6.4.2.1 Storage Life Tests

While section 6.4.1 describes four operating regimes, actually, there is also a fifth one: non-use storage with zero measurand input. In this case there are two possible situations: storage at "room conditions" (laboratory environment) or at some other conditions, perhaps simulating spare parts storage at an equatorial island base (high temperatures, high humidity, fungus) or in the artic (very low temperatures, low humidity).

This handbook has repeatedly emphasized that the performance characteristics of the sensor, as determined through careful calibrations, indicate the "health" of the sensor, i.e., its ability to properly perform its specified measurement function. Knowledge of the continuing health of the sensor is derived from re-calibrations which are compared to the initial acceptance tests, as well as subsequent ones. Static calibrations are usually sufficient (except in the case of sensors with no response at zero frequency, such as piezoelectric devices). It is also reasonable to perform abbreviated calibrations in many cases; i.e., five point, instead of eleven- or twenty-one point. Engineering judgment will dictate the choice.

For sensors stored at room conditions and zero measurand, calibrations at yearly intervals are probably adequate. This assumes that sensor characteristics have previously been established through extensive qualification tests and thorough acceptance tests. If the temperature and/or humidity environments are significantly different from room conditions, check calibrations should be performed at more frequent intervals, perhaps even monthly when stored at environmental extremes. The check calibrations themselves should be performed at room conditions to provide a proper base of comparison with the initial calibrations. An indication of the changes observed in such tests follows.

A limited investigation was conducted at NBS on the effects of storage at elevated temperatures on the performance of strain gage pressure sensors [43]. Seven types of these sensors were kept at temperatures of 107 °C, and three others at 91 °C, for five weeks, followed by a three-week period at laboratory ambient conditions again. Excitation voltage was applied during the entire test period. Test results at the end of the test program indicated permanent changes of up to 0.5 percent in sensitivity and up to 4.5 percent of full-scale output at zero pressure for the sensors tested. It should be noted the storage temperature in all cases was below the maximum specified operating temperature for the sensors tested. The largest portion of the changes appeared to occur during the first five days of the test, suggesting such temperature "annealing" may be useful prior to high temperature use. These conclusions are valid only for the actual sensors tested and may not apply to other pressure sensor types.

While information should be available from sensor manufacturers on the shelf life of sensors, proprietary considerations often make it difficult to obtain this information. Again, as in the other areas discussed earlier, considerable work remains to be done to explore the shelf life of sensors. Shelf life or storage life, however, is the most benign regime to which a sensor may be subjected, provided storage is at "room conditions."

6.4.2.2 Operating Life Tests at Room Conditions

A more severe regime is sensor operation at room (laboratory ambient) conditions. It is not possible to generalize the effects of operational life on the stability of any sensor. The effects depend on factors like type of measurand, its amplitude and rate of application, the type, operating principle, and construction of the sensor and the amount of time it is energized. Very little work has been done (or at least published in readily accessible form) on what is often called "life-cycling" (operating life) effects on sensor performance.

A limited investigation was conducted at NBS on the effects of a million pressure cycles on the performance characteristics of several types of strain gage pressure sensors [44]. The test sensors were subjected at laboratory ambient conditions to pressure pulses with amplitudes of 80 percent to 90 percent FS at a rate of about once per second until a total of 10^6 cycles had been completed. The three main conclusions from this investigation were: zero pressure output and sensitivity changed more during the first 10^5 cycles than subsequent ones; after 10^6 cycles, the zero pressure output had shifted about 1 percent from its initial value; and linearity and hysteresis changes due to cycling were minor compared to the changes in zero output and sensitivity.

6.4.2.3 Operating Life Tests at Elevated Temperatures

A more extensive investigation was conducted at NBS on a group of bonded wire strain gage pressure sensors [45]. Near full-scale values of pressure were applied five times per second at laboratory ambient conditions until 40 x 10^6 cycles had been completed.

Some of the sensors were also cycled at 66 °C (150 °F). Conclusions drawn from these tests were: The sensitivities of sensors tested at ambient conditions decreased with cycling as well as time; sensitivities increased at the elevated temperatures; and zero pressure outputs decreased with cycling and time at both temperature levels. Changes in hysteresis and linearity were very small overall, although somewhat larger changes in characteristics occurred during the first 10^5 cycles (the first three for four days of testing) than subsequently. Cycling at pressures higher than full scale produced total failures or radical changes in characteristics within the first 10^5 cycles.

It should be noted that the conclusions obtained from those investigations were based on a small number of specimens of a few types of pressure sensors which were subjected to a particular type of durability testing concept. Nevertheless, the test results point to the type of behavior which other sensors might be expected to exhibit and which should be investigated.

Certain general guidelines can be stated although the particular kind of life-cycling (durability) test procedure selected will depend on the particular type of sensor, measurand, use, and environmental conditions. In such life-cycling tests, the measurand should be applied with an amplitude ranging from zero to the full-scale value (or close to it). It should be applied at a rate slow enough not to excite sensor resonances, but at a frequency which results in a reasonably short testing time. Thus a cycling rate of 3 Hz results in an accumulation of about 1.8 million cycles per week of continuous testing. The effects of this cycling are established from static calibrations following ever-increasing periods of cycling, such as after 10 000, 20 000, 50 000, and 100 000 cycles.

Rest periods during which no cycling occurs, followed by static calibrations, will give indications on permanent, versus temporary, changes in performance characteristics. In all cases, control sensors should be used which are not cycled, but only calibrated statically whenever the test sensors are calibrated. This should permit correct assignment of performance changes to the cycling test itself.

Life cycling under specified environmental conditions: temperature, humidity, vibration, etc., singly or in combination, may furnish additional information on the stability and durability of the sensors in the actual operational conditions. Clearly, all tests of this nature are qualification tests and are not to be performed on each individual specimen, since such tests are ultimately destructive in nature.

It should be emphasized that this is an area about which little information exists and much work needs to be done to establish valid sensor evaluation methods.

6.4.3 Re-Calibration Considerations

As stated in section 6.1, the continuing ability of the sensor to make measurements within acceptable limits of error must be checked throughout the operational life of the measurement system. Qualities such as stability, durability, and to some extent, reliability, are established with the aid of re-calibrations of the sensing system. Unfortunately, it is very difficult to specify the intervals at which such re-calibrations are to be performed since a variety of factors needs to be considered.

The real problem with major significance to the overall performance of the measurement system is that knowledge of the sensor's performance, alone, is insufficient. It is necessary to assess repeatedly the performance of the entire measurement system in order to be continuously assured of obtaining meaningful data.

The two major considerations are: How realistically can one re-calibrate the entire measurement system, and how frequently should this be done? The major trade-offs for the latter are availability for service and cost effectiveness. To re-calibrate the system, it must be taken out of service, i.e., the measurement system (whether it is in the UUT or ATE system) is normally not operational while re-calibrations are performed. This lack of service availability time, in itself, raises the operational cost of the UUT or ATE. The process of re-calibration adds costs as well. Those trade-offs require careful study by engineering management.

There are other considerations for meaningful calibration of sensors. The most realistic approach is to apply one or more known values of measurands to the sensing end of the sensor and record the corresponding output at the output end of the entire system. This presents several difficulties, including problems of generating measurands with the proper characteristics, injecting them at the right point of the sensing chain. Of necessity, the sensor and system (or channel) must be taken out of service during calibration. This approach is not widely used, largely because it is uneconomical. However, it is possible, for example, to apply a known pressure to the backside of the diaphragm of a pressure sensor without removing the sensor. Other types of sensors cannot use this approach, notably acceleration or force transducers. An alternative is to dismount the sensor from the UUT, mount it in a portable calibration unit, and apply the measurand in that manner. Inaccessibility of some sensors in the UUT, the possibility of damage to those sensors during dismounting, the lack of suitable portable calibrators for some measurands, and the time involved make this approach unattractive.

"Self-calibrating" sensors with a built-in mechanism to apply the measurand to the sensing element have been developed. The fact that no such sensors are commercially available now suggests that they are not satisfactory. However, the trememdous demand for long-term reliable measurements in complex systems such as ATE did not exist when those self-calibrating sensors were first developed. Perhaps interest in self-calibrating sensors will be renewed for specialized applications. It appears that this field deserves serious investigation and research to develop a variety of self-calibrating sensors to serve ATE needs.

The next best approach to calibration of a measurement system is to employ a substitute signal for the output of the sensor. One can disconnect the sensor and feed in this approach electrical signals which represent the sensor output (corresponding to specified measurands) into the next part of the chain, generally the signal conditioner. This method is relatively easy to carry out, and, in the case of ATE, can take advantage of the ATE software to integrate this kind of check calibration of the measurement chain into the overall ATE test schedule.

This approach, however, cannot check the integrity and quality of the sensor. In the case of strain gage sensors, a compromise measure is frequently used known as "shunt calibration" [46]. In this technique, one or more of the elements of the strain gage bridge are shunted by known resistance values. During previous laboratory calibrations of the sensor, shunt resistance values have been determined which produce signals corresponding to specified measurand values. By shunting the elements during a system calibration, a simulated measurand is generated. This method also lends itself to ATE software implementation, but again, it does not totally assure intrinsic sensor integrity. Similar approaches of known perturbations of electrical parameters can be applied to sensors using other transducing principles, such as differential transformers and variable capacitance devices.

Another largely qualitative approach to overall measurement system calibration can be taken if the sensors in the UUT see a significantly different value of measurand when the UUT is operating than when it is not. For example, a temperature sensor in the cooling system of an engine during operation normally may sense a temperature of 90 °C, and during non-operation the ambient environment of 25 °C. If the system output signals for these two conditions correspond roughly to the calibration values, at least a gross verification of proper system operation exists.

Present approaches to quantitative performance checks of the total measurement system (including the sensor) appear inadequate. This calls for generic investigations of a thorough nature. Past experience shows that it is difficult to find adequate support and resources for this type of research activity. Yet without it, knowledge of measurement system performance, particularly in critical applications such as ATE, can never be adequate to the needs.

6.4.3.1 Re-Calibration Intervals

Despite the limitations of the various approaches to system re-calibration expressed above, it is essential to carry out the task in some manner.

Section 6.4.2, which describes limited life tests performed on some selected sensors, suggests re-calibration at yearly intervals for sensors stored at ambient laboratory conditions and more frequent (monthly) tests if the storage environment departs significantly from laboratory conditions. The Navy's "Metrology Requirements List" [47], for example, in discussing pressure gages (i.e., fully mechanical devices), quotes "... pressure gages that have been treated as follows: for a period up to and including six months, the storage time shall not be considered as part of the calibration interval; that is the date the gage is removed from storage and will be used as the 'date calibrated'." It goes on to indicate that for storage periods from six months to one year, samples of the stored gages shall be check-calibrated to determine the probable status of the entire lot. It is also stated that for storage periods greater than one year, all gages must be re-calibrated. Finally the reference states "...whether a gage requires calibration depends on the use of the gage in the equipment or system in which it is installed." It should be noted that the above discussion does not address sensors with electrical outputs. The same document [47] has a listing of "calibration intervals by type of TMDE, (generic)" where TMDE is "test, measurement and diagnostic equipment." Here are some examples from this listing of devices and their "generic calibration intervals": accelerometers, 12 months; gage, vacuum, electronic, 12 months; manometer, capacitance, 6 months; transducer, pressure, 6 months; transducer, force, 12 months; transducer, vibration, 6 months.

The National Conference of Standards Laboratories has issued a Recommended Practice [48] which addresses the subject of calibration intervals. It cites from MIL-C-45662B "Calibration System Requirements" this passage: "Measurement and test equipment and standards shall be calibrated at intervals established on the basis of stability, purpose, degree of usage, precision, accuracy and skills of personnel utilizing the equipment. Intervals shall be shortened as required, to assure continued accuracy, as evidenced by the results of preceding calibrations and may be lengthened only when results of previous calibrations provide definite indications that such action will not adversely affect the accuracy of the system." The recommended practice continues by outlining five general methods in use today for the establishment of calibration intervals and gives advantages and disadvantages of each. The methods are: fixed interval through engineering intuition, fixed interval through data, variable or floating intervals, interval by use time, and interval by in-use testing. The conclusion states "...there is considerable crossover in these techniques and portions of each may be used in constructing a satisfactory program." This supports the introductory statement of this document that "...establishment of calibration intervals has long been a weak technical link in the calibration chain. At the present time there appears to be no definite single solution to this problem."

If there appears to be no single definite solution what should be done? First, as stated earlier, it seems reasonable to re-calibrate stored sensors at no greater than yearly intervals. Such re-calibrations, although requiring certain resources, generally pose no major problems since sensors in storage can be calibrated individually, as in qualification or acceptance tests. Certainly, they must be re-calibrated immediately prior to issue for installation (or replacement) and the data from this re-calibration compared to the original acceptance calibration (or the previous re-calibration). If discrepancies exist beyond specified limits, the particular sensor should not be issued. Whether it should be tested further, returned to the manufacturer, or discarded will depend on cost-benefit considerations for the particular system.

Second, in the case of system tests of UUTs or acceptance tests of UUTs, the entire ATE measurement chain, including the sensor, should be calibrated (in place, preferably) immediately prior to those tests and immediately after the tests. Comparison of these calibration data with previous system calibrations should generate valid information on the short-term stability of the sensor systems.

Third, for operational applications, in-place calibrations should be performed at those intervals which are selected by the experienced engineering staff directly concerned with the design and operation of the ATE/UUT. Conservatively, the initial (early in the operational life) intervals should be shorter than those considered optimum for the total life of the system. As re-calibration data are gathered and compared, and if the system stability appears to be within specified bounds, the re-calibration intervals may be incrementally lengthened. Experience and expertise are needed to evaluate the data on system performance and decide the best course of action.

In a system where a sensor is used to measure a parameter that is adjusted to a single value or checked to be within a narrow tolerance band as compared to the full output range, a single point calibration may suffice for periodic checks of the installed sensor.

It must be emphasized, again, that the above recommended in-place ("field") system calibrations are difficult to achieve, at best. Much work remains to be done to develop "self-calibration" (or "in-place calibratable") sensors and systems. But without a reasonable continuing assurance that the sensor system performs within specifications, the function and value of the entire ATE system are compromised.

6.4.4 Reliability

The following information is largely extracted from the "Reliability Design Handbook" [50]. Other detailed information on reliability can be found in a series of five handbooks: "Design for Reliability," AMCP 706-196; "Reliability Production," AMCP 706-197; "Reliability Measurement," AMCP 706-198; "Contracting for Reliability," AMCP 706-199; and "Mathematical Appendix and Glossary," AMCP 706-200. These are published by the U.S. Army Material Command [33].

Reliability has been described as "quality in the time dimension." It is classically defined as the probability that an item will perform its purpose satisfactorily for a period of time under a stated set of use conditions. From a functional point of view, in order for an item to be reliable it must do more than meet an initial factory performance or quality specification--it must also operate satisfactorily for an acceptable period of time in the field application for which it is intended.

The classical definition of reliability, stated above, stresses four elements, namely: probability, performance requirements, time, and use conditions. Probability is that quantitative term which expresses the likelihood of an event's occurrence (or non-occurrence) as a value between 0 and 1. Performance requirements are those criteria which clearly describe or define what is considered to be satisfactory operation. Time is the measure of that period during which one can expect satisfactory performance. The use conditions are the environmental conditions under which one expects an item to function.

Determining reliability, therefore, involves the understanding of several concepts which relate to these four definitional elements. Among such concepts is that of a failure rate which can vary as a function of age. A failure rate is a measurement of the number of malfunctions occurring per unit of time. In order to show the variation in failure rate, separate consideration is given to three discrete periods when viewing the failure characteristics of a product or item over its life span (and then considering a large sample of its population). This is illustrated in figure 5.

6.4.4.1 Infant Mortality

Initially, the item population exhibits a high failure rate. This failure rate decreases rapidly during this first period (often called the "infant mortality," "burn-in," or "debugging period"), and stabilizes at an approximate value when the weak units have failed. It may be caused by a number of things: gross built-in flaws due to faulty workmanship or manufacturing deviations from the design intent, transportation damage, and installation errors. This initial failure rate is unusually pronounced in new equipment. Many manufacturers provide a "burn-in" period for their product, prior to delivery, which helps to eliminate a high portion of the initial failures and assists in establishing a higher level of operational reliability. Examples of workmanship deficiencies which contribute to early failures of a system are:

Poor welds or seals
Poor solder joints
Poor connections
Dirt or contamination on surfaces or in materials
Chemical impurities in metal or insulation
Voids, cracks, thin spots in insulation or protective coatings
Incorrect positioning of parts
Missing heat sinks.

Many of these early failures can be prevented by improving the control over the manufacturing process. Sometimes improvements in design or materials are required to increase the tolerance for these manufacturing deviations, but fundamentally these failures reflect the "manufacturability" of the component or product and the control of the manufacturing process. Consequently, these early failures would show up during:

In-process and final tests
Process audits (to uncover potential for failure)
Life tests
Environmental tests.

6.4.4.2 Useful Life

The item population, after having been burned in, reaches its lowest failure rate level, which is normally characterized by a relatively constant failure rate accompanied by negligible or very gradual changes due to wear. This second period is called the useful life period, and is characterized mainly by the occurrence of stress-related failures. The exponential failure distribution is widely used as a mathematical model to approximate this time period. This period varies among hardware types and is the interval usually given for reliability prediction and assessment activities.

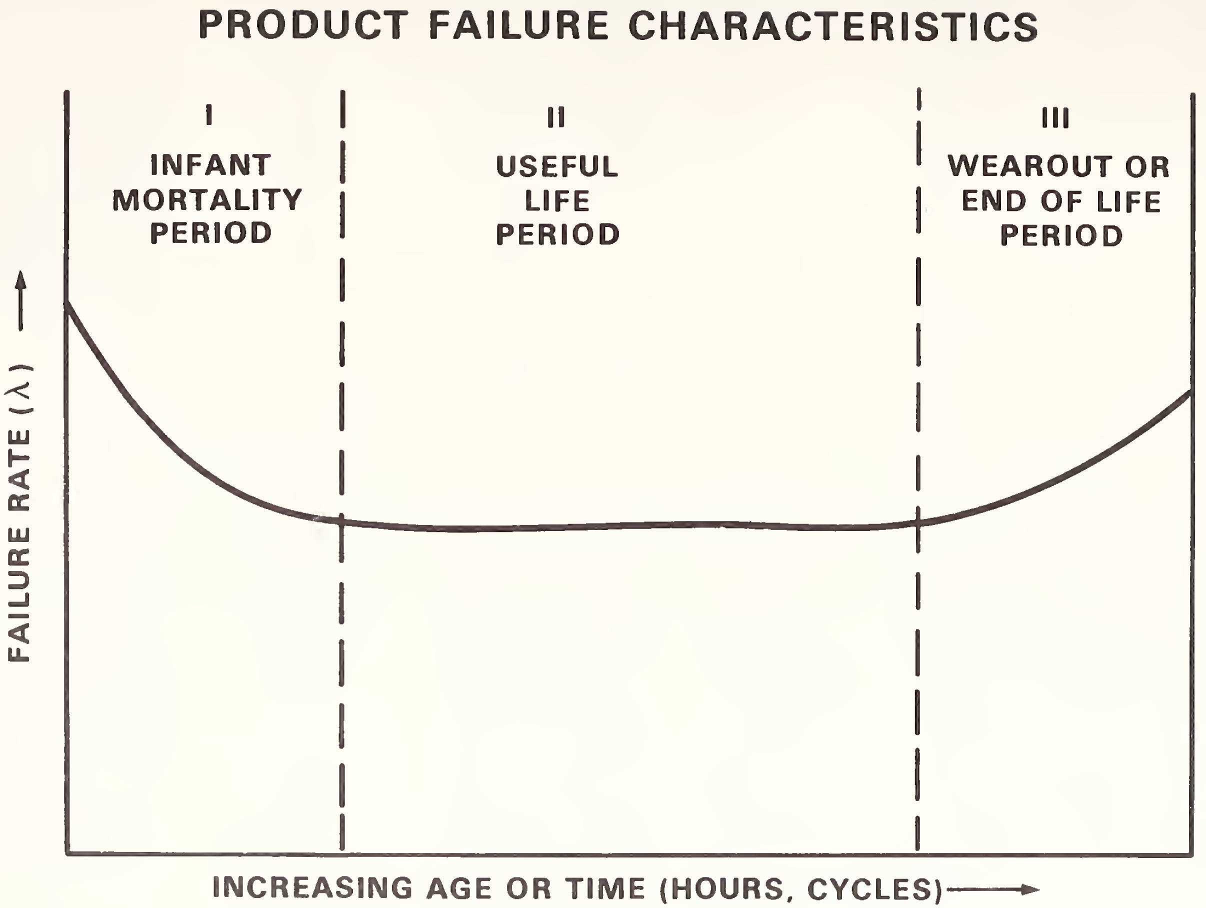

Figure 5 LIFE CHARACTERISTIC CURVE

For electronic devices and components, experience has shown that excessive temperature and voltage levels, either steady state, transient, or changing at rapid rates, are the two most destructive stresses. Humidity, vibration, shock, and altitude also contribute to the failure of these devices.

6.4.4.3 Wearout

The third and final life period occurs when the item population reaches the point where the failure rate starts to increase noticeably. This point is identified as the end of useful life or the start of wearout. Beyond this point on the time axis, the failure rate increases rapidly. When the hardware failure rate due to wearout becomes unacceptably high, replacement or repair of the item should be made. Replacement schedules (of critical short-life components) are based on the recognition of this failure rate.

Wearout failures are due primarily to deterioration of the design strength of the device as a consequence of operation and exposure to environmental fluctuations. Deterioration results from a number of familiar chemical and physical phenomena:

Corrosion or oxidation
Insulation breakdown or leakage
Ionic migration of metals in vacuum or on surfaces
Frictional wear or fatigue
Shrinkage and cracking in plastics.

Optimizing reliability involves the consideration of each and all of these three life periods. Early failures must be eliminated by systematic procedures of controlled screening and burn-in tests. Stress-related failures must be minimized by providing adequate design margin. Wearout must be eliminated by timely preventive replacement of short-life component parts. Thus all major factors which influence (and degrade) a system's operational reliability must be addressed during design (using appropriate techniques described later) to optimize and control system reliability.

6.4.4.4 Failure Rate

During the "useful life" time period, reliability is described by means of the single parameter exponential distribution:

$$R(t) = e^{-\lambda t}$$

where

$R(t)$ is the probability that the item, which has a constant failure rate λ, will operate without failure for the time period, t (usually expressed in hours), under stated operating conditions;
e is the base of the natural logarithms, equal to 2.7182...;
λ is the item failure rate (usually expressed in failures per hour), and is a constant for any given set of stress, temperature, and quality level conditions. It is determined for parts and components from large-scale data collection and/or test programs.

When the values of λ and t are inserted into the above expression, the probability of success (i.e., reliability) is obtained for that time period.

The reciprocal of the failure rate is defined as the mean time between failures (MTBF)

$$\text{MTBF} = 1/\lambda$$

The MTBF is primarily a figure of merit by which one hardware item can be compared to another. It is a measure of the failure rate (λ) during the useful life period. The procedures used to establish failure rates for the constituent electronic parts (resistors, semiconductors, etc.) used in systems and equipment is given in MIL-HDBK-217B [49]. For non-electronic parts, information appears in the "Non-Electronic Reliability Notebook" [75].

6.4.4.5 Reliability Degradation

Reliability estimates prepared in accordance with MIL-HDBK-217B techniques reflect the inherent (or potential) reliability of a system as defined by its engineering documentation, its stress and safety factors and gross environmental application, and manufacturing and quality factors. These estimates are indicative of the upper limit or reliability potential as applied to the useful life period. However, these estimates do not reflect expected performance when operated and maintained in its actual field environment.

The results of numerous data collection efforts have shown that the reliability of fielded equipment and systems is degraded from three to ten times the potential predicted during design. The transition from a paper design to production to field operations introduces degradation factors which constrain the expected reliability.

In order to assess the magnitude of the reliability degradation due to manufacturing, the impact of manufacturing processes (i.e., the process-induced defects, the efficiency of conventional manufacturing and quality control inspection, and the effectiveness of reliability screening techniques) must be considered. In addition to the latent defects attributable to purchased parts and materials, assembly errors can account for substantial degradation. Assembly errors can be brought about by operator learning, motivational, or fatigue factors.

A decrease in reliability may occur at the onset of production. This is primarily due to workmanship errors resulting from unfamiliar operations, process discrepancies, and quality oversights which drive reliability below expected levels. As production continues and skill increases, measured reliability again approaches the inherent value.

Manufacturing and quality control inspections and tests are provided to minimize degradation from these sources and to seek out the more obvious defects. No inspection process can remove all defects which are contained in an item presented for inspection. A certain number of defective items will escape the process, be accepted, and be placed in field operation. More important, these gross defects are overshadowed by unknown numbers of latent defects, the results of weakened parts, which can fail under the proper conditions of stress--usually during field operation. Factory screening tests are designed to apply a stress of given magnitude over a specified duration to remove these kinds of defects. As in the case with conventional inspection processes, screening tests are not 100 percent effective.

Degradation in reliability also occurs as a result of system operation. Wearout, with aging as the dominant failure mechanism, can shorten the useful life. Situations also occur in military systems where the system is operated beyond its design capabilities because of an unusual mission requirement or to avoid a threat. These situations could cause ill effects to the constituent parts of systems. Operational abuses due to rough handling, extended duty cycles, or neglected maintenance can contribute materially to reliability degradation, which eventually results in failure. The degradation can be a result of the interaction of man, machine, and environment. The translation of the factors which influence operational reliability degradation into corrective procedures requires a complete analysis of functions performed by man and machine, plus fatigue and/or stress conditions which could degrade operator performance.

Degradation in inherent reliability can also occur as a result of maintenance activities. Indeed, studies have shown that excessive handling brought about by frequent preventive maintenance or poorly executed corrective maintenance (e.g., installation errors) have degraded system reliability. Several trends in system design have reduced the need to perform adjustments or make continual measurements to verify peak performance. Extensive replacement of analog with digital circuitry, inclusion of more built-in test equipment, and use of fault-tolerant circuitry are indicative of these trends. These factors, along with greater awareness of the cost of maintenance, have brought changes for ease of maintenance whose by-product has been increased system reliability. In spite of these trends, the maintenance technician remains a primary cause of reliability degradation. The effects of poorly trained, poorly supported, or poorly motivated maintenance technicians on reliability degradation require careful assessment and quantification.

6.4.4.6 Reliability Growth

Reliability growth represents the resultant action taken to hasten a hardware item toward its reliability potential either during development or during subsequent manufacturing or operation. During early development, the achieved reliability of a newly fabricated item, or an off-the-board prototype, is much lower than its predicted reliability. This is due to initial design and engineering deficiencies as well as manufacturing flaws. The reliability growth process, when formalized and applied as an engineering discipline, allows management to exercise control, allocate resources, and maintain visibility into activities designed to achieve a mature system prior to full production or field use.

The basic concepts associated with a reliability growth process and its application to newly fabricated hardware involve consideration of <u>hardware test</u>, failure, correction, and retest activities. Specifically, <u>reliability growth</u> is usually an iterative test-fail-correct process. There are three essential elements involved in achieving reliability growth, namely:

(1) Detection and analysis of hardware failures.
(2) Feedback and redesign of problem areas.
(3) Implementation of corrective action and retest.

The rate at which hardware reliability grows is dependent on how rapidly these three elements can be accomplished and, more importantly, how well the corrective action solves the problem identified. During early development and test activities, the achieved reliability (or MTBF) is well below that predicted on the basis of design analyses and analytical predictions. As development and test efforts progress and problem areas become resolved, measured reliability values approach the inherent (design based) value.

6.4.5 Failure Mechanisms

The failure (or deterioration of performance) of sensors can be caused by one or more factors. One of the factors is simply the operating life of the device, another factor is the environment in which the sensor must operate, a third factor (less easily taken into account) is inappropriate selection, or application, of the sensor. In considering the effects of the operating life on the mechanical components of a sensor, fatigue failure and its precursing effects need to be taken into account. Well established engineering practice assigns lower values of maximum allowable stress to those parts which may be subjected to repeated stress. It is generally assumed that fatigue needs to be considered if the repetitions of the stress are of the order of one million cycles or more. Corrosion and defects in the material under stress can materially affect the fatigue life.

One notable effect of repeated stress application, known as "cold working," actually tends to increase the fatigue strength, although the process may also introduce internal strains and minute cracks [51]. Thus it may be possible to increase the fatigue life by subjecting the component to stress cycling at low stress levels. A possible side effect of this is that work hardening may result, which in case of a sensor may result in decreased sensitivity with time and cycling. Repeated stress cycling may also decrease friction and decrease hysteresis of the stressed components.

The environmental factors which affect the life (and contribute to failure) of sensors and similar devices are manifold and are listed in tables 17 and 18. Some examples follow [50].

High temperatures impose a particularly severe stress on most electronic components. They can cause not only catastrophic failure, such as melting of solder joints and burn out of solid-state devices, but also slow progressive deterioration of component performance levels due primarily to chemical degradation effects. It is often stated that excessive temperature is the primary cause of poor reliability in military electronic equipment.

In present day electronic systems design, great emphasis is placed on small size and high component part densities. This generally requires a cooling system to provide a path of low thermal resistance from heat-producing elements to an ultimate heat sink of reasonably low temperature.

Solid-state components are generally rated in terms of maximum junction temperatures, and the thermal resistances from this point to either the case or to free air are usually specified. The specification of maximum ambient temperature for which a component is suitable is generally not a sufficient method for component selection with densely packaged parts since the surface temperatures of a particular component can be greatly influenced by heat radiation or heat conduction effects from other nearby parts. These effects can lead to overheating above specific maximum safe temperatures even though the ambient temperature rating appears not to be exceeded. It is preferable, therefore, to specify thermal environment ratings such as equipment surface temperatures, thermal resistance paths associated with conduction, convection and radiation effects, and cooling provisions such as air temperature, pressure, and velocity. In this manner, the true thermal state of the temperature-sensitive internal elements can be determined.

Low temperatures experienced by electronic equipment can also cause reliability problems. These problems are usually associated with mechanical elements of the system and include mechanical stresses produced by differences in the coefficients of expansion (contraction) of metallic and nonmetallic materials, embrittlement of nonmetallic components, mechanical forces caused by freezing of entrapped moisture, stiffening of liquid constituents, etc. Typical examples include cracking of seams, binding of mechanical linkages, and excessive viscosity of lubricants.

Additional stresses are produced when electronic equipment is exposed to sudden changes of temperature or rapidly changing temperature cycling. These conditions generate large internal mechanical stresses in structural elements particularly, when dissimilar materials are involved. Effects of the thermal shock-induced stresses include cracking of seams, delamination, loss of hermeticity, leakage of fill gases, separation of encapsulating components from components and enclosure surface leading to the creation of voids, and distortion of support members.

A thermal shock test is generally specified to determine the integrity of solder joints since such a test creates large internal forces due to differential expansion effects. Such a test has also been found to be instrumental in creating segregation effects in solder alloys leading to the formulation of lead-rich zones which are susceptible to cracking effects.

Electronic equipment is often subjected to environmental shock and vibration both during normal use and testing. Such environments can cause physical damage to components and structural members when deflections produced cause mechanical stresses which exceed the allowable working stress of the constituent parts.

The natural frequencies of subsystems comprising the equipment are important parameters which must be considered in the design process. A resonant condition can be produced if a natural frequency is within the vibration frequency range. The resonance condition will greatly amplify the deflection of the subsystem and may increase stresses beyond the safe limit.

The vibration environment can be particularly severe for electrical connectors since it may cause relative motion between members of the connector. This motion, in combination with other environmental stresses, can produce fret corrosion which generates wear debris and causes large variations in contact resistance.

Humidity and salt air environments can cause degradation of equipment performance. They promote corrosion effects in metallic components and can foster the creation of galvanic cells, particularly when dissimilar metals are in contact. Another deleterious effect of humidity and salt air atmospheres is the formation of surface films on nonmetallic parts. This causes leakage paths and degrades the insulation and dielectric properties of these materials. Absorption of moisture by insulating materials can also cause a significant increase in volume conductivity and dissipation factor of materials so affected.

Electromagnetic and nuclear radiation can cause disruption of performance levels and, in some cases, permanent damage to exposed equipment. It is important that such effects be considered in determining the required environmental resistance for electronic equipment to achieve a specified reliability goal.

Electromagnetic radiation often produces interference and noise effects within electronic circuitry which can impair the functional performance of the system. Sources of these effects include corona discharges, lightning discharges, sparking, and arcing phenomena. These may be associated with high voltage transmission lines, ignition systems, brush-type motors, and even the equipment itself. Generally, the reduction of interference effects requires incorporation of filtering and shielding features or the specification of less susceptible components and circuitry.

Nuclear radiation can cause permanent damage by alteration of the atomic or molecular structure of dielectric and semiconductor materials. High energy radiation can cause ionization effects which degrade the insulation levels of dielectric materials. The mitigation of nuclear radiation effects typically involves the use of materials and components possessing a higher degree of intrinsic radiation resistance and the incorporation of shielding and hardening techniques.

In addition to the aforementioned stress factors, other environmental factors must be considered in the design to assure adequate environmental resistance for the equipment. These additional factors include:

Sand and dust
Fungus
Acoustic noise
Electric fields
Magnetic fields
Presence of reactive liquids and gases.

The effect of each of these stress factors on the operation and reliability of the materials and components of the ATE equipment being designed must be determined. This entails the identification of material, component, and packaging techniques that afford the necessary protection against such degrading factors.

In the stress identification process preceding the selection of environmental resistance techniques, stresses associated with all life intervals of the equipment must be considered. This includes not only the operational and maintenance environments but also the preoperational environments. Stresses imposed on the parts during manufacturing assembly, inspection, testing, shipping, and installation may have significant impact on the eventual reliability of the equipment. Stresses imposed during the preoperational phase are often overlooked, but they may represent a particularly harsh environment which the equipment must withstand. Often the shock and humidity environments to which commercial and military systems are exposed during shipping and installation are more severe than those it will encounter under normal operating conditions.

6.4.6 Accelerated Life Testing

The preceding sections discussed the factors which tend to influence the stability, durability, and reliability of sensors. They also touched briefly on failure mechanisms and test methods used to establish stability, durability, and reliability of the sensors. It should be clear that the subject is very complex and relatively unexplored; certainly no easy answers exist. Nevertheless, test methods exist in some areas which, by subjecting the sensors to postulated operating conditions (and environments), make an attempt to simulate the operational life of the sensor. One problem common to these methods is that they generally require a testing time close to the real operational life.

When such a test method really simulates the actual operating life of the sensor, it then becomes desirable for economical and logistical reasons to shorten the test period required. This brings in the concept of "accelerated" testing, which is treated in AMCP 706-198, "Development Guide for Reliability" [33]. The following discussion is excerpted from that reference.

"Accelerated" testing is a very loosely defined concept; attempts to make it rigorous generally run into difficulties. Loosely speaking, accelerated testing started when someone said: "Let's shoot the juice to it and see what happens." This means, roughly, "Let's treat it worse than we expect it to be treated in ordinary practice and then see what happens." One difficulty is that treating it worse does not always mean "shooting the juice to it." For example, electrical contacts behave better as voltage and current are increased (up to a point) and some warmth may improve matters for electronic equipment by helping to reduce the moisture problem.

Accelerated testing in this qualitative sense is something that anyone can do and that everyone does. There is a reasonably firm qualitative foundation for much of it. It is in the quantitative interpretation that troubles begin. These qualitative and quantitative uses of accelerated testing can conveniently be put into four classes:

1. Qualitative - to see what kinds of failures are generated and to decide then if a modification is worthwhile,
2. Qualitative - to get a rough, quick idea of whether or not something can stand the "gaf,"
3. Qualitative - to see what happens when the user maltreats the device, as he probably will, and
4. Quantitative - to make a prediction about the life under actual operating conditions.

There is little question that accelerated testing is useful for the three qualitative measures, so it is mainly the quantitative problem to which this chapter is addressed.

Several definitions for "true" acceleration appear in the literature, some of which are not very explicit, although most engineers associate true acceleration with behavior over time. The definition below is chosen for its generality and applicability. Acceleration need not be "true" to be useful even though untrue acceleration is more difficult to analyze, even qualitatively.

Acceleration is true if, and only if, the system under the accelerated conditions passes reasonably through equivalent states and in the same order it does at the usual conditions. In addition to verifying that true acceleration exists, a great deal of effort must be expended in determining the acceleration function. It is virtually always presumed that the acceleration function is a constant.

Some gross failure modes which can be accelerated for mechanical parts are fatigue, corrosion, creep-rupture, stress corrosion, and various combinations of them. In electronics, one does not ordinarily specify the gross failure modes for acceleration, but, rather, specifies the "stresses" which are being increased. Some of these are temperature, supply voltage, power dissipation, vibration, humidity, and corrosive environments. There is a large body of material in the mechanical and metallurgical fields dealing with those gross failure modes. Since the behavior of electronic components is organized differently, there is no organized body of literature which deals with gross failure modes that cut across all components or applies to complex devices such as sensors.

Several accelerated tests are in use. One of them is the constant severity-level method, a traditional type of test in which the severity level remains constant throughout the life of the items on test. It is customary to run tests at several severity levels and to plot a curve of some parameter such as failure rate vs severity level. A sample of several items usually is put on test, and the test stopped when some fraction of the original sample has failed or a specified test time has elapsed. For reliability prediction purposes, the early fraction that fails is most important because only the short-lived items are going to affect the reliability seriously.

Other approaches involve "step-stress" and "progressive-stress" methods. The word "stress" is used in the sense of severity level. In this method, the severity applied to a sample of items is increased in steps or increments until some criterion is met for terminating the test. All steps do not have to be the same size, even though this is a common practice.

The term "step-stress" as used in the literature is ambiguous. It is convenient to classify step-stressing into three categories:

1. Large steps in which the steps are presumed high enough and long enough so that, for a given step, the damage accumulated at all previous steps is negligible.

2. Small steps in which the steps are small enough so that in the analysis one can presume with negligible error that the severity level is steadily increasing. This is the progressive-step case in which the stress increases at a constant rate.

3. Medium steps for which the assumptions for neither small nor large steps are valid. The cumulative damage at previous steps must be

taken into account, but the steps are not small enough that the severity level can be considered to be continuously increasing.

The following terminology is used: large/step-stress, medium/step-stress, and small/step-stress. The size designations are not absolute, but are relative to the kind of analysis that must be performed.

Large/step-stress tests are analyzed as if they were constant-stress tests being run at the severity level of the last step. Parts that are very expensive or otherwise difficult to acquire or test often are treated in this way. Often a sample of only one is used. It is wise to consider the results as "ballpark" figures, since the necessary assumption that the effects of previous steps are negligible is likely to be in error. Preliminary tests often are run in this way and are followed by a more comprehensive set of tests later on.

Small/step-stressing is analyzed in the same way as progressive-stressing, and, in fact, there is really no distinction between them. In many cases, there may be an economic advantage to choosing very small step increments over a continuously increasing stress. For example, if extremely accurate voltage steps are desired, a stepping switch might be used with a voltage divider; otherwise, a slow motor might be used to turn a multi-turn potentiometer.

Less testing time is the major advantage of step-stress tests over constant-stress tests. A direct comparison of the methods requires an assumption of a theory of cumulative damage; for example, metal fatigue is attributed to a variety of such theories. In electronics, a simple linear model is assumed most often because of its simplicity and the lack of knowledge of the actual processes.

A linear model of cumulative damage is a gross approximation. In some circumstances, it consistently underestimates, and in other circumstances consistently overestimates, the correct results. Regardless of these deficiencies, it offers the advantages of being tractable, easily remembered, and widely used. One should use the linear model unless some other, better model is known. But one must remember the arbitrariness of any assumption.

An important parameter in step-stress testing is the ratio of severity step size to the time at each level. This controls the rate of increase of the stress severity and is the parameter that is varied when running several tests on a particular population of items.

For some kinds of items, the maximum useful severity level will be exceeded before the device fails in the proper mode. For example, on thermally stressed transistors there are sometimes eutectic points where melting occurs and the transistor essentially ceases to be a transistor. If this happens, the rate of increasing the stress severity must be decreased. The slope of the steps during the course of the tests also can be modified. The severity level limits (i.e., the level where the device ceases to function in its usual manner) are an important limitation to step-stressing. There are other cases where the failure mode changes so drastically at some level that it is senseless to continue testing above that level.

Another advantage of step-stress testing is the elimination of "switch-on" problems, such as initial transients and failures due to high stress rates. This is because the severity level is low at the beginning and the severity increase is gradual. The severity level need not begin at "zero" (i.e., a level near benign). This can save time and reduce the amount of cumulative damage at severity levels other than the failure level. Some programs concerned with investigating cumulative damage theories may change the severity level only once during a test. For example, the initial part of one test may be at a high severity level and the remainder at a low severity level; a subsequent test reverses the procedure. Not much work of this sort is done in electronics, but metallic fatigue is a field in which these methods of programming stresses have received considerable attention.

In order to compare tests (or field experience) run under different severity level programmings, some model of cumulative damage is necessary. No particular model is required, merely some model. In electronics there are very few theories of cumulative damage, regardless of the part, but in mechanical fatigue, for example, there are many models of cumulative damage. Most often such a model uses "constant stress" test as its basis. The most common conceptual model, in almost any field, for cumulative damage is the so-called linear model. It has one basic assumption, i.e., the rate of doing damage is 1/MtF where MtF is the Median-time-to-Failure. The MtF is for the particular severity level at which damage is accumulating. There are several corollaries to this assumption which often are (but improperly) stated as additional assumptions.

- The rate of doing damage does not depend on the amount of damage already done.
- The order in which the severity levels are applied makes no difference.
- The total damage is the simple sum or integral of the damage done at each stress level.
- The rates of doing damage are independent of each other for different severity levels.
- The Median endurance at constant severity level is unity.

The use of a cumulative damage model does not necessarily mean that the failure modes/mechanisms were the same at each severity level, although such a case may help the validity of the model.

Accelerated life tests can be used in programs operating under tight and critical schedules. If production begins before research and development is completed, some assurance must be obtained quickly that the equipment has an adequate lifetime and that no gross design weakness exists. Conventional life tests often take too long to be used under these conditions.

Accelerated testing also is used when repair parts must be manufactured simultaneously with a short run production program. In this case, failure rate data cannot be provided quickly enough by life testing to influence the analysis of the repair complement.

In some cases (explosives, for example), the earliest times to failure in the storage environment and variations in times to earliest failure must be known with high accuracy. A large sample would have to be kept in storage in a usual life test. This would be very expensive and time consuming. Accelerated testing of critical failure modes can be used to determine the range of variability of the time to failure, with useful accuracy, with a smaller sample than that required for usual life testing. For example, solid rocket propellants are subject to catastrophic failure modes that may result in explosions. The remaining life in a stored lot must be subjected to accelerated aging in order to determine whether some critical failure mode is about to be triggered.

Accelerated tests can be implemented by speeding up the duty cycle or the environmental level, or both. The environments must be cycled from extreme to extreme in order to reproduce in a short time the degradation expected over the period of actual service life. The environmental factor selected for acceleration is determined by the item tested and its failure modes. For example, for many mechanical components, failure is caused by mechanical wear; hence the acceleration is obtained by increasing the frequency and severity of stress.

The failure data at usual environmental levels and those at accelerated environments must correlate in some way with the stresses actually applied. A precise statistical correlation frequently cannot be obtained because much of the theory of accelerated testing is still very crude. In such cases accelerated environmental tests may permit a great deal of intuitive information to be developed.

Statistical correlation often can be obtained with accelerated duty cycle testing. The expected number of cycles of actual service in a given time period often can be estimated. Accelerated testing is performed by increasing the number of cycles in a given time period and measuring the mean-cycles-to-failure. The mean-cycles-between-failures (MCBF) at the accelerated duty cycle frequently can be related to the MCBF at normal duty cycles as a function of the ratio of cycles per time period.

The ideal accelerated test should include the following information:

- An algorithm for converting the reliability data observed at accelerated conditions to reliability data at normal conditions.

- A statistically sound empirical proof of the algorithm.

- A physical model explaining the algorithm.

Unfortunately, most accelerated test techniques do not meet these criteria. They tend to be approximate and require a great deal of engineering judgment in the absence of precise physical models or statistical techniques. Some discussions in the literature are vague and ambiguous; the word "life" may mean the random variable, or may refer to the mean life, or may not mean anything specific. One must beware of using acceleration factors from the literature for specific components. The state-of-the-art in components changes rapidly enough so that failure modes and their acceleration factors can be expected to change in nonapparent ways.

Temperature is the most common method of accelerating a test; usually the scale parameter of the distribution is presumed to follow the Arrhenius law [54]. Voltage can be increased for some kinds of capacitors, and power dissipation can be increased to shorten the life of many electronic components. Mechanical excitation, such as vibration and shock, are sometimes used.

In the parametric approach, the parameters of the failure distribution are presumed to change in a "deterministic fashion" with the "stress." The functional relationship of the "deterministic fashion" is presumed known, and the purpose of the test is to evaluate the parameters in that relationship. The most common situation is the constant failure rate and the Arrhenius temperature law, which describes the rate of increase of chemical reactions with increasing temperature [52].

When a failure distribution has two parameters, it is most common to assume that one of them is independent of the accelerating "stresses." Other assumptions tend to be tractable, even if more realistic. In the s-normal or log normal distributions, the median usually is assumed to be a function of the "stresses," and the other parameter to be a constant.

No matter what distribution is assumed, it is essential that the statistical uncertainty in the results be estimated and clearly stated--because this uncertainty is usually so large as to greatly reduce the impact of the nominal conclusions. In fact, one is often tempted to remark, "I could have guessed that close without the tests!" For example, in some reasonably high temperature tests, the uncertainty in failure rate at operating temperatures might be a factor of 10 or so. At this point it may be useful, in summing up accelerated testing, to cite appropriate remarks from an NBS study of life-cycle testing [53].

"Accelerated testing, in the absence of historical data is inherently risky--by making a use condition or environmental factor more severe than normal, failure mechanisms different from those which would occur normally may be brought on; further, it is difficult to predict the performance at the normal stress level. There should be justification for predicting what the characteristic would be at normal use conditions and environmental factors. Otherwise, predictions are little more than guess work. Justification can take the form of historical data or a quantitatively calculable knowledge of the processes governing the predominant failure mechanisms.

"Because of the risk involved in accelerated testing it is advisable to do normal testing when practical; except if historical data are available. If the product class were rapidly evolving, or the time to complete testing were excessively long, or the cost were prohibitive, the normal test would be considered impractical. A way to reduce clock time while still doing a normal stress test may be to increase the frequency of use (an example where this should work is an appliance such as the vacuum cleaner).

"In summary, where historical data are not available, because of the risk in making accelerated tests, normal tests are advisable wherever practical. Where normal tests are not practical, then accelerated tests should be considered, but accelerated tests will not always be feasible and the specific product class must be considered and evaluated. A necessary condition for making credible accelerated tests is (1) historical data or (2) a calculable knowledge of the main failure mechanisms."

6.4.7 Fail-Safe Considerations in ATE Systems

There are two major, but overlapping, failure problems in relation to ATE systems. One is the failure of a component in the ATE system which will not result in damage to the remainder of that system or affect its performance so that it can no longer perform all, or most, of its ATE functions. The implication here is that the ATE system would continue to operate, although at less than the total effectiveness desired.

The second failure problem is one in which another type of component, such as a sensor monitoring a critical parameter in the UUT, fails. If ATE data are used as inputs to an automatic control system, the UUT itself could conceivably be destroyed or damaged beyond repair. An example might be a rotary speed sensor with a voltage output amplitude proportional to speed. If the sensor output were to drop due to increased temperature or leakage currents, the ATE might not detect anything amiss and an automatic control might feed more power to the rotating device to bring its speed up to "normal."

The answer to both problem areas, of course, is proper planning and execution of fail-safe design practices.

Again, there are two overlapping areas to achieving a reliable fail-safe system: redundancy and part selection. The reliability of a system can be significantly enhanced through the use of redundancy. Redundancy involves designing one or more alternate signal paths into the system through addition of parallel elements. Redundancy has been extensively applied to airborne systems. For example, the electronic multiplexing system may use a redundant design. In such a system, redundant computers control the main switching buses. Normally, one of two computers is active and feeds the two main buses which control all switching functions while the other continuously performs the same function and compares its output with the active computer. If the active computer malfunctions, the standby automatically takes over.

Another example of a redundant configuration is provided in a weapon control system in which two major sensors are used to achieve the same goal. An example is a pulse Doppler search, track, acquisition, and guidance radar with a gimbal-mounted infrared search/acquisition sensor. The infrared system provides a backup to the radar if the latter is inoperable due to malfunctions or jamming. Additionally, it may operate in a dual mode to augment the radar search volume.

Depending on the specific applications, a number of approaches are available to improve reliability through redundant design. These design approaches can be classified on the basis of how the redundant elements are introduced into the circuit to provide a parallel signal path. In general, there are two major classes of redundancy.

> Active redundancy--External components are not required to perform the function of detection, decision, and switching when an element or path in the structure fails.

Standby redundancy--External elements are required to detect, make a decision, and switch to another element or path as a replacement for a failed element or path.

Additional details can be found in the literature [50].

The other approach involves part selection and control from the diversified complement of electronic parts which is available to structure modern military electronic systems. These parts constitute the building blocks from which systems are fashioned and greatly impact hardware reliability. Since the reliability of the end item is dependent upon these building blocks, the importance of selecting and applying the most effective parts cannot be overemphasized.

The task of selecting, specifying, assuring proper design application, and, in general, controlling parts used in complex electronic systems is a major engineering task. Part selection and control is a multi-disciplinary undertaking involving the best efforts of component engineers, failure analysts, and reliability engineers, as well as design engineers. Numerous controls, guidelines, and requirements must be formulated, reviewed, and implemented during the development effort.

Part control activities comprise a large segment of the total effort for part selection, application, and procurement. The effort encompasses tasks for performance, reliability, and other requirements of the evolving design. Other subsections of the handbook provide further details with regard to these control tasks, indicate their importance within the part selection process, and provide appropriate design guidance.

Electronic parts that comprise any electronic equipment constructed for military purposes are under the cognizance of the Military Parts Control Advisory Group, located in the Directorate of Engineering Standardization at the Defense Electronics Supply Center (DESC). This group promotes standardization in part selection and application. By using standard parts in new equipment design and development programs, much time and effort can be saved while obtaining better equipment performance, in addition to simpler and better logistics support. DESC promotes usage of standard parts and manages standardization problems for parts which are initially characterized as nonstandard but whose repetitive usage makes their standardization necessary. Department of Defense standardization managers work closely with the military services and industry in developing an effective standardization program for new systems.

The general rule for part selection is that wherever possible, "standard" devices should be used. "Standard" devices may be defined as those which, by virtue of systematic testing programs and a history of successful use in equipment, have demonstrated their ability to consistently function within certain specific electrical, mechanical, and environmental limits and, as a result, have become the subject of Military (MIL) Specifications. MIL Specifications which thoroughly delineate a part's substance, form, and operating characteristics exist, or are in preparation, for practically every known type of electronic component. Military Standards also cover the subject of testing methods applicable to MIL-specified components. A listing appears in section 8.3.

In addition, Military Standards exist which list by MIL designation those parts or devices which are preferred for use in military equipment. In regard to sensors, there are only a few MIL Standards (see section 8.3), but a larger number of "Civilian" Standards (see section 8.2). Since there are significant gaps in coverage, sensors generally must be subjected to qualification tests tailored to the specific application as outlined below.

In conjunction with part standardization, nonstandard part approval must be considered. Nonstandard part approval is comprised of activities to document and secure authorization to use the part in the system. Military-STD-891 outlines the functions of a Part Advisory Group or a Part Control Board operating under both government and contractor cognizance and which provides the necessary mechanism for securing approval of nonstandard parts.

The qualification of nonstandard parts must include detailed and formal submittal of data to support approval request. This data must be: (1) statistical test data, (2) analytical data for components that are similar to a standard part, or (3) a combination of statistical and analytical data. (Note: Those components that require formal statistical test data for qualification should be identified as critical items.)

The selection process must include design evaluation, reliability history review, construction analysis, failure mode and effects analysis, and cost effectiveness studies as necessary. The control effort should include the development of meaningful procurement specifications which, when completed, reflect a balance between design requirements, quality assurance, and reliability needs consistent with apportionment studies and vendor capabilities.

A well controlled parts program involves establishing a vendor control program, audits of vendor processes, the establishment of source inspection where applicable, and the preparation of associated documentation. The parts control effort includes identifying all critical parts, equipment/components, and other items considered critical from any of the following standpoints:

Mission and safety sensitive (failure impacts mission success
  and personnel safety),
Reliability sensitive (from early reliability studies,
  apportionments, etc.),
Have limited life,
Are high cost items,
Have long procurement lead times,
Require formal statistical qualifications testing.

Planning for critical item control must include controls for special handling, the identification of critical item characteristics to be inspected or measured during incoming inspection, material review procedures, traceability criteria, and periodic audits. All items considered safety critical must be coded. Detailed documentation must be prepared that describes procedures, tests, test results, and efforts to reduce the degree of criticality of each item.

In order to realize fully the benefits of a reliability-oriented design and to assure fail-safe provisions, consideration must be given early in the design process to the required environmental resistance. Whether intrinsic or provided by specifically directed design features, it will singularly determine the ability of the equipment to survive the deleterious stresses imposed by the operational environment. The initial requirement for determining the required environmental resistance is the identification and detailed description of the environments in which the equipment must operate. The next step is the determination of the performance of the components and materials that comprise the equipment when exposed to the degrading stresses of the environments so identified. This had been discussed in much detail in the preceding sections. When such performance is inadequate or marginal, with regard to the equipment reliability goals, corrective measures such as derating, redundancy, protection from adverse environments, or selection of more resistant materials and components are necessary to fulfill the reliability requirements of the equipment.

7. ERROR ASSESSMENT AND ACCURACY

7.1 General Considerations

The primary function of the ATE system is to monitor the health of the UUT. To do this the health of the ATE system itself must be superior to that of the UUT. The quality of performance (continuing health) of the ATE system is established from an assessment of the errors within the system.

Two things must be kept in mind: First, ATE system outputs ultimately require decisions to be made in regard to the health of the UUT. The validity of these decisions depends largely on all the errors inherent in the total ATE system. Second, the errors in the total ATE system include the errors of the sensor and the errors inherent to the remainder of the electronic portion of those systems.

Error analysis for the sensor is discussed in the following sections. Error analysis for the electronic components has similar considerations, based on calibration and test results of those components. Discussion of the latter is outside the scope of the Sensor Handbook.

7.2 Sensor Error Analysis

7.2.1 Straight Line Data Reduction

In order to establish the quality of measurements performed by the sensor, it is necessary to establish its "accuracy" by an error analysis. This analysis is largely based on the reduction of data obtained from sensor calibrations and evaluations.

In the process of data reduction, it is incumbent to extract the maximum amount of useful information from the calibration data of the sensor. This information is generally given in terms of a number of performance parameters, the numerical values of which permit interpretation of measurements performed by the sensor. These values also permit the quantitative comparison of different sensors. Such parameter values, obtained from calibration data, must be the "best" values, that is, those which best represent the actual character of the sensors. "Best" in this connotation requires a preconceived basis of judgment for comparison. As indicated previously, for the vast majority of sensors this basis is the assumed straight-line relationship between sensor output and measurand input.

Thus sensor calibration data are generally reduced so as to obtain the parameters of, and show deviations from, the "best" straight line.

7.2.2 Selection of Straight Line

There are a number of straight lines which may be chosen to represent the sensor's calibration characteristic. ANSI Standard MC6.1-1975 [2] lists five: "end-point" line, "best straight" line, "terminal" line, "theoretical slope" line, and "least squares" line. They are defined in the glossary, section 10. The line most commonly used is the one based on the mathematically rigorous criterion of least squares. It is based on the principle: "The most probable value of an observed quantity is such that the sum of the squares of the deviations of the observations from this value is a minimum" [20]. This is based on the fact that most measurements of physical quantities show a normal distribution with positive and negative deviations from the mean equally likely and very large deviations less likely than small ones.

The "least squares" straight line is the most desirable one to use in reducing data from static calibrations of sensors. The line can be defined unequivocally in terms of the quantities measured. This line is also statistically significant and standard deviations can be assigned to estimates of the slope, intercept, and other parameters derived from it.

Accordingly, the "least squares" straight line is recommended for data reduction. Laboratories that have digital computers or modern desk calculators can frequently obtain all parameters of this line with the use of a standard "least squares" straight line program supplied with these devices.

7.2.3 Calibration Parameters Obtained From Data Reduction

As indicated earlier, the general simplified assumption in data reduction is that the sensor calibration is a straight line, with the customary equation $y = bx + a$, where y represents the electrical output parameter and x the input measurand. Calibration data are normally tabulated and from this the data can readily be reduced.

There are five resulting numerical calibration parameters describing the straight line relation which is assumed to represent the sensor performance for each calibration. They are:

a - the y-intercept (intercept on the output axis)
S_a - the standard deviation of the y-intercept
b - the slope (sensitivity of the transducer)
S_b - the standard deviation of the slope
S_t - the standard deviation of the "deviations of experimental points from the theoretical line" (the "goodness of fit").

In addition two other parameters commonly used to describe performance characteristics may be obtained from the data or from a graph plotted with the aid of the tabular data from one calibration.

Hysteresis - the maximum difference in output, at any measurand value within the specified range, when the value is approached first with increasing and then with decreasing measurand [2].

Linearity - the closeness of a calibration curve to the specified straight line, expressed as the maximum deviation of any calibration point from that line during any one calibration cycle [2].

From the data obtained from three static calibrations performed consecutively, an additional parameter can be derived.

Repeatability - The ability to reproduce output readings when the same measurand value is applied to it consecutively, under the same conditions, and in the same direction [2].

Repeatability is expressed as the maximum difference between corresponding values in the three calibrations. There is no universal agreement as to the particular values selected. Full-scale output is a commonly used one, as is zero measurand output. Derived values are also used, like slope (sensitivity) or the y-intercept. Deviations in full-scale output values are likely to be greatest, and therefore probably the best indicators of repeatability. The total time involved for the three calibration cycles must be reported also, since time has a significant effect on repeatability.

It should be pointed out that modern computers make it relatively easy to represent calibration data by polynomial expressions of varying degrees of complexity. The advantages of obtaining a major conformance ("fit") of such a theoretical curve to the actual calibration points must be weighed carefully against the ellipse of uncertainty which in reality represents each calibration point. It is the author's opinion that the straight-line assumption of sensor characteristics in the vast majority of cases is the most realistic approach. A notable exception to this are flow measurements based on differential pressures where the output corresponding to flow is given by the square root of the differential pressure.

7.2.4 Number of Significant Digits for Reporting Calibration Results

Data reduction of a calibration run ordinarily produces the pertinent parameters which describe an instrument being tested. The number of significant digits which should be used is important in order to neither overspecify nor underspecify a parameter value.

As might be anticipated, computation cannot be expected to lead to values of greater precision than that of the input data. Thus the accuracy of the measuring instruments in the calibration system and, in particular, the precision of the measurements (as measured by the number of significant digits indicated) are the principal factors which limit the precision to which one should properly report derived (i.e., computed) parameters, e.g., the sensitivity.

Using a pressure sensor as an example, the input data in a pressure sensor calibration is ordinarily the pressure applied (in Pa or psi), the output response (in mV/V), and the power supply voltage (in volts). If a temperature correction is needed, the temperature (in °C) is also part of the input data. Thus a number of significant digits to which each measurement (mentioned above) can be reported is of paramount importance in determining the precision to which the computed parameter can be reported.

The rules for handling significant digits in the common arithmetic operations are as follows (according to section 22-2, "Rounding in Statistical Computation," NBS Handbook 91 [20].

1. For addition - record and report to the number of decimal places in the addend with the fewest number of decimal places. Before summing, round more precise addends to 1 decimal place more than this. Round the sum one more place where required.

2. For subtraction - both numbers should be rounded to the same number of places before subtracting. Keep as many decimal places as possible to

avoid error in differences between two nearly equal numbers. Where possible, approximate to more places before subtracting.

3. For multiplication and/or division - if the less precise of two approximate numbers (for division - divisor or dividend) contains n significant digits, the product (or quotient) can be relied on for n significant digits at most. Keep all digits until the final results and then round as indicated.

4. For power and roots - the power (root) of a number is good at best to the same significant number of digits as the number.

The gist of the rules given, as they apply to the statistical parameters presented as a result of a calibration, is that the number of significant digits to be used in the value of any parameter should be no more than that of the least precise value which entered into the calculation of the parameter. There are certain considerations which appear to represent (but do not) exceptions to the rules. An integer such as 10, which is a counting number, is exact and therefore has not two significant digits but an infinite number.

Another consideration which has a two-fold benefit is Berkson's premise with regard to an ordered laboratory experiment [20]. This premise, first described by Joseph Berkson in 1950, can be summarized briefly as follows.

An exception to the normal precision requirement is available in a planned physical experiment where both variables, x (measurand) and y (output voltage), could be expected to have some associated random error in their measurement. If the normal independent variable is given a set of ordered preassigned values called nominal or target values and then set to these target values as well as possible (assuming only randomness and independence of errors), the resultant data will give a valid underlying linear structural relationship where measurement errors are assumed in the y measurements but not in the x measurements. In this procedure, the x measurements are assumed to be without error and therefore precise to as many places as desired. According to this premise, which has had wide acceptance in statistical circles, not only does one not have to consider the random error in the x measurement (measurand), but because, in effect, there is no random error, precision can be added to this measurement to equal that of the next least precise measurement made and used in parameter calculation. Thus the lack of precision of the x measurement does not degrade the precision of the result.

One can thus state the simple rule--parameters derived from a calibration (of a sensor, for example) should be expressed to the same precision (i.e., significant number of digits) as that of the output voltage reading, not more and not less. Thus an accurate output reading voltmeter is most significant.

7.2.5 Expression of Uncertainties of Final Results

Most of the following material was obtained from chapter 23, "Experimental Statistics" by Mary G. Natrella, NBS Handbook 91 [20].

The actual error of a reported value, the magnitude and deviation from the true value, is usually unknowable. Limits to this error can generally be inferred from the precision of the measurement process and from reasonable limits of the possible bias of the measurement process. The bias, or systematic error of a measurement process, is the magnitude and direction of its tendency to measure something other than what was intended; its precision (actually imprecision) refers to the typical closeness of successive independent measurements of a single magnitude generated by repeated application of the process under specified conditions. Its accuracy is determined by the closeness to the true value characteristic of such measurements. Precision and accuracy are inherent characteristics of the measurement process employed.

The uncertainty of a reported value is indicated by giving credible limits to its likely inaccuracy. No single form of expression for these limits is universally satisfactory. Different forms are recommended, depending on the relative magnitudes of imprecision and likely bias. Four distinct cases are possible:

1. Both systematic error and imprecision are negligible in relation to the requirements of the intended and likely uses of the result.

2. Systematic error is not negligible, but imprecision is negligible in relation to the requirements.

3. Neither systematic error nor imprecision are negligible in relation to the requirements.

4. Systematic error is negligible, but imprecision is not negligible in relation to the requirements.

In general, it is recommended that two numerics relatively expressing the imprecision and the bounds to the systematic error to the results should be used whenever (a) the margin is narrow between ability to measure and the accuracy or precision requirements of the situation; or (b) the imprecision and the bounds to the systematic error are nearly equal in indicating possible differences from the true value (case 3).

Also it is desirable that expressions of uncertainty be given in sentence form whenever feasible. Finally, the form "a ± b" should be avoided as much as possible, and never used without an explicit explanation of its connotation.

It is very likely that most practical static calibration situations can be represented by case 3 above, i.e., neither systematic error nor imprecision negligible. In this case, recommendations are that the reported numerical result be qualified by a statement that places bounds on its systematic error and a second statement identifying its measure of imprecision.

In the statements of values, the bounds of systematic error and the measure of imprecision should be stated to no more than two significant figures. Furthermore, the reported numerical result should be stated, at most, to the last place affected by the more precise of the two qualifying statements. It is also desirable to give the qualification in sentence form.

The term "standard error" may be used to signify the standard deviation of the reported value itself, such as the sensitivity and the y-intercept computed from the static calibration data by the method of "least squares." The recommendations above do not exclude, however, the presentation of the type of statement placing bounds on an overall uncertainty, provided separate statements of its imprecision and possible systematic error are included also. Such bounds indicating the overall uncertainty of the repeated value should not be numerically less than the corresponding bounds placed on the systematic error outwardly increased by at least two times (and preferably three times) the standard error. An example of such a statement is "...with an overall uncertainty of ±3 percent, based on a standard error of 0.5 percent and an allowance of ±1.5 percent for systematic error." The uncertainty might alternatively be described as: "...the standard error of this value is less than 0.5 percent, and the systematic error is thought to be less than ±1.5 percent." It is also desirable to state that the standard error was obtained from a "least squares" evaluation of an n-point static calibration.

7.2.6 Sampling Considerations in the Performance Testing of Sensors

The sections above have been concerned with the error analysis of data obtained from one or more calibrations of a single sensor. In qualification testing in particular, but also in certain cases of acceptance testing, one desires to gain some understanding of the performance of a group or class of sensors. While it would seem desirable to evaluate the performance characteristics of every single sensor, this is not practical for at least two reasons: the high expense of testing in terms of personnel, equipment, and time makes such evaluation economically unsound. Furthermore, the performance tests themselves may cause deterioration of the sensor's performance.

Accordingly, it is an established practice to select some sensors from a group for evaluation and to consider their performance characteristics as representative of the entire group. The use of certain statistical principles makes it possible to draw mathematically valid inferences from the experimental data. For any particular performance characteristic, one would like to be able to state numerical limits between which one has a certain confidence (ρ%) that a given proportion (p) of all the values will lie. The limits are based on two factors derived from the numerical values of the particular performance characteristic of a number (sample) of selected sensors. The two factors are $\overline{X}$, the arithmetic mean of the values and S, the standard deviation of these values.

Extensive tables in "Experimental Statistics," NBS Handbook 91 [20] enable one to find for (N), a desired number of samples, the factor K such that the proportion (P) of the values lie within the range $\overline{X} \pm KS$, with a confidence level ρ percent where

$$\overline{X} = \frac{1}{N} \left(\xi_{i=1}^{N} X_L \right) \qquad \text{Arithmetic mean of sample}$$

$$S = \sqrt{\frac{\sum_{i=1}^{N} (\overline{X} - X)^2}{N - 1}} \qquad \text{Standard deviation of sample}$$

It is extremely important to realize that the tables cited and the validity of values derived from them are based on two fundamental assumptions:

(1) The particular characteristic has a normal distribution in the entire group of sensors.

(2) The samples tested are selected in a random manner.

To gain an idea of the numerical values involved, the following is extracted from a table of "Factors for Two-Sided Tolerance Limits for Normal Distribution" [20].

Confidence Level	75%	75%	75%	90%	90%	90%	95%	95%	95%
Proportion of Group P	0.99	0.95	0.90	0.99	0.95	0.90	0.99	0.95	0.90
Number of Samples N					"K"				
2	9.53	7.41	6.30	24.2	18.8	16.0	48.4	37.7	32.0
3	5.43	4.19	3.54	8.97	6.92	5.85	12.9	9.92	8.38
4	4.47	3.43	2.89	6.44	4.94	4.17	8.30	6.37	5.37
5	4.03	3.09	2.60	5.42	4.15	3.49	6.03	5.08	4.28

It is apparent from the table that a considerable shrinking of the limits of the range of values $\overline{X} \pm KS$ occurs when three samples are tested, as compared to two. The improvement possible varies from 1.8 to 3.8 fold, depending on proportion and confidence level selected. The testing of four samples results in a much smaller additional improvement, the total ranging from about 2.2 to 5.8 fold, as compared to the values based on two samples, while adding appreciably to testing time and expense.

It is quite practical to perform static calibration, and similar tests, on three sensors (including data reduction) within one day or less. Four or more sensors may require testing time extending over several days with the added possibility of different laboratory conditions, warm up etc., which would make data comparison less valid.

More important, however, under the present system of procurement of sensors, there is no assurance that the samples received are randomly selected. The numerical validity of the inferences as to the characteristics of the group is therefore doubtful, although this may be offset somewhat by the fact that quality control of the sensors during manufacture may result in a distribution closer to the mean than described by the normal curve.

It is quite feasible for the large-scale user of sensors to assure himself of random sampling by ordering a large number of sensors and then selecting random samples.

In general, it seems that the testing of three sensors is the most practical procedure to establish most performance characteristics. If a particular characteristic contributes only a small error to the measurement, tests on two and sometimes even one unit seem adequate. Experience and judgment help to make these decisions.

If the three sensors tested are known to be, or assumed to be, random samples, the value of K for P = 90 percent (P = 0.90), K = 5.85 appears a reasonable one to use. With this value the computed limits of the particular characteristic can be said to represent the actual limits nine times out of ten for nine out of ten specimens of the group.

7.2.7 Error Band Concept

The discussions to this point have been directed at base line (static or reference) calibrations of sensors. These are the fundamental calibrations to establish sensor performance at laboratory conditions. Actual sensor operation, however, as elaborated earlier, is not normally in such benign circumstances and the performance is expected to be "poorer." Thus the numbers expressing the uncertainty (or error) of a particular characteristic of the sensor are likely to be larger when the conditions of sensor operation are less favorable.

Calibrations yield a number of parameters which measure the quality of performance of the sensor, among them linearity, hysteresis, repeatability, stability, friction error, creep, etc. (see section 3.3 for definitions). It is difficult to compare the qualities of several sensors using values of these individual parameters.

In 1957, the error band concept was developed at an aerospace company [29]. In brief, it postulates that individual tolerances assigned to repeatability, hysteresis, friction error, and linearity could be replaced by a single set of tolerances on the maximum deviation of any data point from a specified performance line which represents the ideal calibration curve of the sensor.

The introduction of error band specifications resulted in higher production yields by sensor manufacturers since more leeway was permitted in the tolerances of individual parameters. In addition, this approach led to interchangeable calibration records. If the error band specified for a given sensor was sufficiently narrow for overall data accuracy requirements, the calibration records of all sensors having an equal or smaller error band were considered interchangeable within error band tolerances. The data obtained from any of the sensors could then be reduced on the basis of the ideal calibration curve and the uncertainties associated with it.

The base line (static) error band can be obtained from the static calibrations discussed in section 6.2.1, in which the measurand is applied in increasing and then decreasing manner. The author of this handbook feels that a more realistic approach would involve the application of the specified measurand amplitudes in a random sequence during the calibrations and believes this to be a subject worthy of experimental investigation.

For sensor operation under other than laboratory conditions, the error band concept is logically extended to describe the deviations of data points from the ideal line or curve when the sensor is calibrated at the specified environment or following a specified exposure or cycling, etc. Thus the error band is a very useful and realistic concept since it focuses attention on the overall quality of the data obtained from the sensor as a measuring device, i.e., its ultimate quality of performance.

8. SENSOR-RELATED STANDARDS DOCUMENTS

8.1 Introduction

The aim of standards documents is to enhance communications and understanding concerning particular items among the community making or using those items. There are several groups of standards extant in the field of sensors and their applications. These standards fall into two major subdivisions: voluntary standards and mandatory standards. The former are generally promulgated by professional or trade associations, the latter by governmental bodies.

Standards are generally not of a static nature, that is, they are supposed to be reviewed and revised after specified intervals of time. New standards are being worked on as well, consequently, there is a continuing state of flux and a completely up-to-date listing of standards documents, even in a restricted field, is difficult to achieve. The field of sensors is no exception. It is felt, however, that a listing of such documents applicable to sensors would be of considerable benefit in the planning, design, use, and testing of ATE systems. A quotation from the preface to a sensor standard by the Instrument Society of America outlines quite clearly the aims of such a document.

"This standard is intended as a guide for technical personnel at user facilities as well as by manufacturers' technical and sales personnel whose duties include specifying, calibrating, testing or showing performance characteristics of pressure transducers. By basing users' specifications as well as technical advertising and reference literature on this Standard, or by referencing portions thereof, as applicable, a clear understanding of the users' needs or of the transducers' performance capabilities, and of the methods used for evaluating or proving performance, will be provided. Adhering to the specification outline, terminology and procedures shown will not only result in simple, but also complete specifications; it will also reduce design time, procurement lead time, and labor, as well as material costs. Of major importance will be the reduction of qualification tests resulting from use of a commonly accepted test procedure and uniform data presentation" [54].

Government standardization documents are almost always of a mandatory nature and are frequently used as regulatory documents. The two major subdivisions are federal (civilian) and military documents, although some overlaps exist. No federal standards pertaining to sensors with electrical output were located. As expected considerable numbers of military documents exist. They fall into several classes and it seems useful to define the types of standards documents which exist. The definitions which follow are extracted from Defense Standardization Manual DoD 4120.3-M [55].

Specifications

Specifications are documents prepared specifically to support procurement and cover items which vary in complexity from paper clips to missile weapon systems. They establish requirements in terms of complete design details or in terms of performance, but in most instances in terms of both design and performance. Specifications may cover a single item, such as a camera, or thousands of items, such as bolts, and for each single style there may be several finishes and hundreds of sizes. When invoked, specifications should be tailored to their application consistent with basic program requirements.

Standards

Standards are documents that establish engineering and technical requirements for processes, procedures, practices, and methods that have been adopted as standard. They are prepared to provide the designer with the descriptions and the data normally required for selection and application. Their purpose is to control variety. They may cover materials, items, features of items, engineering practices, processes, codes, symbols, type designations, definitions, nomenclature, test, inspection, packaging and preservation methods, items, parts and components of equipment. Standards represent the best solution(s) for recurring design, engineering, and logistics problems. It is intended that they be up-to-date records of the decisions and recommendations of experts in each field or area. When applied by design and procuring agencies, standards should be tailored to the application consistent with basic program requirements.

Standard and Specification Relationship

Standards function in procurement through the medium of specifications. Thus they are used to standardize one or more features of an item such as size, value, or detail of configuration. In equipment specifications, they are referenced to standardize on those design requirements which are essential to achieving the design objectives, e.g., interchangeability, compatibility, reliability, and maintainability. Standards disclose or describe the technical features of an item in terms of what it is and what it will do. In contrast, the specification for the same item describes it in terms of requirements for procurement.

Federal and Military Standards and Specifications

Federal standards and specifications are developed when the document will be used by two or more federal agencies, at least one of which is an agency other than the Department of Defense. Military standards and specifications cover items or services which are intrinsically military in character, commercial items which meet special requirements of the military, or commercial items with no present or known potential use by federal agencies other than military. Where requirements warrant it, there may be both federal and military specifications and standards covering the same items or services.

Military specifications and standards are issued as either coordinated or limited coordination documents. Coordinated specifications and standards are used to cover items or services required by more than one military department. Limited coordination documents cover items or services of interest to a single department, or those which are prepared by a department or activity to meet an immediate procurement need where urgency does not permit coordination to be effected.

Handbooks

A handbook is a reference document which brings together procedural and technical or design information related to commodities, processes, practices, and services. A handbook may serve as a supplement to specifications or standards to provide general design and engineering data. The use of handbooks as references is optional.

8.2 Voluntary Standards Listing

Standards on sensors (transducers) and related subjects promulgated by professional societies or trade organizations are listed below. They are arranged by the organization which sponsored the work or which issued the standards. Prospective users are urged to contact the listed organization to obtain the most up-to-date version of any given standard or to obtain information on other pertinent documents.

There is some lack of uniformity in the designation of ANSI Standards. All ANSI Standards are actually prepared by other organizations. Some are initially prepared under ANSI auspices and, when issued, carry the ANSI designation only. Others are issued as standards by other standards organizations, then accepted by ANSI, issued also (later) as ANSI Standards, and may carry dual designations. Some ASTM Standards may also carry multiple designations.

Voluntary standards concerned with sensors (transducers) were among those compiled in a very comprehensive column: "Standards and Practices for Instrumentation," Sixth Edition, 1980, published by the Instrument Society of America, Research Triangle Park, NC 27709. The following sensor-related standard titles and abstracts were taken, with permission, from this volume. They are arranged, in alphabetical order, by the organization which developed or published the document. Most of these organizations have active committees working on additional standards documents. No efforts were made to list these since such information becomes rapidly obsolete.

It should be noted that the completeness and applicability of these documents varies widely. They were developed for a wide variety of uses by a variety of organizations. Constraints on time and other resources preclude attempts to critically evaluate these documents in this handbook.

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)
(Formerly United States of America Standards Institute - USASI)

The following publications have been approved as American National Standards and are available from the American National Standards Institute, Inc., 1430 Broadway, New York, NY 10018. Many standards approved by ANSI are published by sponsoring organizations. These standards may be found listed under the sponsoring organization, but the ANSI number is indicated. These are available from either ANSI or the sponsoring organization.

ANSI: C39.3-1976, Specifications for Light-weight Shock-Testing Mechanism for Electrical Indicating Instruments, 24 pp, $5.50.

> Describes and specifies the design and construction of a shock testing mechanism for testing electrical indicating instruments. Includes general design, theory of operation, use, construction, mounting of mechanism, calibration curves, and maintenance. (Sponsored by Electrical and Electronics Standards Board)

ANSI: C39.4-1966 (R1973), American Standard Specifications for Automatic Null-balancing Electrical Measuring Instruments, 2nd edition, 26 pp, $5.50.

> Provides classifications, definitions, general requirements, test conditions and procedures for instruments of the dc potentiometer and dc bridge types. Performance guides are provided for three types of operating conditions: reference, rated, and extreme. (Sponsored by Electrical and Electronics Standards Board)

ANSI: C39.5-1974, American Standard Safety Requirements for Electrical and Electronic Measuring and Controlling Instrumentation, 13 pp, $3.75.

> Provides maintenance classification, general and particular test requirements to assure safe electrical operation of measuring and controlling instrumentation. (Sponsored by Electrical and Electronics Standards Board)

ANSI: C39.6-969, Requirements for Automatic Digital Voltmeters and Ratio Meters, 20 pp, $5.50.

> Provides classifications, definitions, detailed reference standards, test conditions, procedures for instruments intended to indicate dc voltages and voltage ratios in decimal units. (Sponsored by Electrical and Electronics Standards Board)

ANSI: C42.100-1977 (IEEE Std. 100-1977) Standard Dictionary of Electrical and Electronics Terms, 882 pp, $37.50.

> Consolidates and supersedes all previous C42 Series Standards. Defines 20 000 technical words from every area of electrical and electronics engineering. (Sponsored by IEEE)

ANSI: C57.13-1978, Requirements for Instrument Transformers, 68 pp, $7.00.

Applies to current and potential instrument transformers, including general requirements, terminology; and miscellaneous measurement devices. (Sponsored by Electrical and Electronics Standards Board)

ANSI: C83.17-1970, Methods of Definitions and Measurement for Piezoelectric Vibrators, 18 pp, $4.00.

Defines piezoelectric vibrator and equivalent circuit and provides methods for measuring electrical parameters of the equivalent circuit. (Sponsored by IEEE)

ANSI: MC1.1-1975, IEEE Standard Digital Interface for Programmable Instrumentation, 80 pp, $10.00.

This standard applies to interface systems used to interconnect both programmable and nonprogrammable electronic measuring apparatus with other apparatus and accessories necessary to assemble instrumentation systems.

ANSI: S1.2-1962 (R 1976), Method for Physical Measurement of Sound, 23 pp, $5.50.

Covers methods for measuring and reporting the sound presure levels and sound powers generated by a source of sound using a sound-level meter and octave-band filter set as minimum equipment. (Sponsored by Acoustical Society of America)

ANSI: S1.6-1967 (R 1976), Preferred Frequencies and Band Numbers for Acoustical Measurements, 11 pp, $3.25.

Provides guide to the design of new acoustical equipment and to the selection of frequencies to make comparison of the results of acoustical measurements most convenient. (Sponsored by Acoustical Society of America)

ANSI: S1.8-1969 (R1974), Preferred Reference Quantities for Acoustical Levels, 10 pp, $3.75

Concerned with the reference quantities and the definitions of some levels for acoustics, electroacoustics and mechanical vibrations. Purpose to to provide a preferred reference quantity of convenient magnitude for a given kind of acoustical level. (Sponsored by Acoustical Society of America and ASME)

ANSI: S1.10-1966 (R 1976), American Standards Methods for Calibration of Microphones, 33 pp, $7.00.

Methods are described for performing absolute and comparison calibrations of laboratory standard microphones. Absolute calibration is based on reciprocity; pressure, free field, and random field calibration are desired.

ANSI: S1.13-1971 (R 1976), Methods for the Measurement of Sound Pressure Levels, 34 pp, $6.00.

General recommendations to assist in the development of noise measurement techniques that are satisfactory for use under various environmental conditions. Intended to assist in the preparation of test codes for: 1) determining compliance with a specification, ordinance, or acoustical criterion; and 2) obtaining information to assess the effects of noise on people or equipment. (Sponsored by Acoustical Society of America)

ANSI: S1.20-1972, Procedures for Calibration of Underwater Electroacoustic Transducers, 40 pp, $7.00.

Establishes measurement procedures for calibrating underwater electroacoustic transducers and describes forms for presenting the resultant data, determining the sound power level produced by a source. Contains test room requirements, source location and operating conditions, instrumentation and techniques. For measurements that can be used in test codes for particular types of equipment. (Sponsored by Acoustical Society of America)

ANSI: S2.2-1959 (R 1976), Calibration of Shock and Vibration Pickups, 33 pp, $5.50.

Covers definitions of letter symbols and technical terms, characteristics to be measured, and methods for the calibration of acceleration, velocity, and displacement pickups. (Sponsored by Acoustical Society of America and ASME)

ANSI: S2.4-1960 (R 1976), Method for Specifying the Characteristics of Auxiliary Equipment for Shock and Vibration Measurements, 11 pp, $2.75.

Provides a uniform terminology and format for the presentation of the performance and other characteristics of auxiliary equipment for shock and vibration measurement. (Sponsored by ASME and Acoustical Society of America)

ANSI: S2.10-1971 (R 1976), Methods for Analysis and Presentation of Shock and Vibration Data, 28 pp, $6.50.

Designed to acquaint the user with general principles of the analysis and presentation of shock and vibration data and to describe concisely several methods of reducing data to forms that can be applied and used in subsequent analyses. (Sponsored by Acoustical Society of America and ASME)

ANSI: S2.11-1969 (R 1973), Selection of Calibration and Tests for Electrical Transducers Used for Measuring Shock and Vibration, 19 pp, $4.75.

Includes considerations relevant to commonly employed electromechanical shock and vibration measurement transducers, but not to those transducers primarly designed for measurement of acoustic or pressure phenomena. (Sponsored by Acoustical Society of America and ASME)

ANSI: Y32.2-1975, Graphical Symbols for Electrical and Electronics Diagrams, 111 pp, $8.00.

Provides graphical symbols for electrical and electronic devices suitable for all drafting purposes. (Sponsored by IEEE and ASME)

ANSI: Z24.21-1957 (R 1971), Method for Specifying the Characteristics of Pickups for Shock and Vibration Measurement, 19 pp, $4.50.

Applies to pickups that, over a specified amplitude and frequency range, are capable of producing outputs which are known functions of the linear or angular accelerations, velocities, or displacements of objects whose motions are being measured. (Sponsored by Acoustical Society of America)

AMERICAN PETROLEUM INSTITUTE (API)

The following API Publications, Recommended Practices, Standards, and Bulletins are available from the American Petroleum Institute,
1801 K Street, N.W., Washington, DC 20006.

API: Manual of Petroleum Measurement Standards: Measurement of Liquid Hydrocarbons by Turbine Meter Systems, 1970, chapter 5.3, $5.00.

Covers the design, installation, operation, and proving procedures for turbine meter systems. Also presents informational material on the application of statistical methods to metering systems, troubleshooting charts, explanation of electronic readout devices, and glossary of terms.

API: Std. 2543 (ASTM D1036-64), Method of Measuring the Temperature of Petroleum and Petroleum Products, 1965, (ANSI. Z11.172-1971) $1.00.

Describes the procedure and apparatus used in the determination of temperatures of petroleum liquids.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

The following ASTM Standards are available from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103. Joint ASTM-API Standards are available from either organization.

ASTM: Index to Standards; The 1979 Annual Book of ASTM Standards, Part 48, 1979, 292 pp, $5.00.

This book is a key reference volume. It lists by number designation and cross indexed title every one of over 5500 ASTM Standards. The index refers the reader to the exact part of the 48 Part Annual Book of ASTM Standards where a particular standard may be found.

ASTM: D1085-65 (1975) - (API: STD 2545), Standard Method of Gaging Petroleum Products, 39 pp, $2.00. Published as reprint only.

Describes the procedure for gaging crude petroleum and its liquid products in various types of tanks, containers, and carriers.

ASTM: D1142-63 (1975), Standard Methods of Test for Water Vapor Content of Gaseous Fuels by Measurement of Dew-Point Temperature, 13 pp, $4.00.

Covers the determination of the water vapor content of gaseous fuels by measurement of the dew-point temperature and the calculation therefrom of the water vapor content.

ASTM: D1589-60 (1974) Standard Methods of Test for Dissolved Oxygen in Waste Water, 6 pp, $1.75.

Covers four methods of determination of dissolved oxygen in waste water in the presence of certain interfering substances. Includes a description of the use of the polarograph in determination of dissolved oxygen in wastes after dilution with natural water by a factor of 4 to 100.

ASTM: E177-71, Standard Recommended Practice for Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material, 1971, 18 pp, $4.00.

The purpose of this recommended practice is to outline some general concepts regarding the terms "precision" and "accuracy", to provide some standard usages for ASTM committees in reference to precision and accuracy, and to illustrate some important features of the experimental determination of precision.

ASTM: E220-72E, Standard Method for Calibration of Thermocouples by Comparison Techniques, 1972, 18 pp, $1.75.

Covers the techniques of thermocuple calibration based on the comparisons of thermocouple indications with those of a standard thermometer, rather than those using fixed temperatures. Method applies to common types of thermocouples which can be exposed to a clean oxidizing atmosphere.

ASTM: E230-72, Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples, 1972, 100 pp, $7.00.

Consists of temperature-emf tables for thermocouple types B, E, J, K, R, S, and T,; standard and special limits of error and upper temperature limits. All intervals are 1°.

ASTM: E235-76, Standard Specification for Thermocouples, Sheathed, Type K, for Nuclear or for Other High Reliability Applications, 1976, 7 pp, $4.00.

Presents the material, operating, and environmental requirements of two-wire thermocouples intended for nuclear service. Provisions for temperatures up to 900 °C (1650 °F) are covered.

ASTM: E251-67 (1974) - (ANSI: Z168.7-1969), Standard Methods of Test for Performance Characteristics of Bonded Resistance Strain Gages, 1967, 7 pp, $4.00.

> Describes procedures for determining: gage factor at a reference temperature; variation of gage factor with temperature; transverse sensitivity; temperature sensitivity.

ASTM: E344-74, Standard Definitions of Terms Relating to Temperatuare Measurement, 1974, 4 pp, $1.75.

ASTM: E380-76, Standard for Metric Practice, 1976, 37 pp, $4.00.

> Gives guidance for application of the International System of Units (SI). Includes information on SI, a limited list of non-SI units recognized for use with SI, a list of conversion factors from non-SI units recognized for use with SI units, and general guidance on proper style and usage.

AMERICAN SOCIETY OF HEATING, REFRIGERATING, AND AIR CONDITIONING ENGINEERS, INC. (ASHRAE)

The following ASHRAE Standards may be obtained from the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.,
345 East 47th Street, New York, NY 10017.

ASHRAE: Std. 41.1-74, Part I, Standard Measurements Guide: Section on Temperature Measurements, 1974, 18 pp, $10.00.

> Provides methods for accurate temperature measurement for the particular needs of heating, refrigeration, and air conditioning. The rates of heat flow, both to and from moving volatile and non-volatile fluids, in the range of -40 to 400 °F are covered. The use of thermometers, thermocouples, and thermistors and the effect of changes in enthalpy are discussed.

AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME)

The following ASME and ANSI Standards may be obtained from the American Society of Mechanical Engineers, 345 East 47th Street,
New York, NY 10017.

ASME: PTC 9, Displacement Compressors, Vacuum Pumps, and Blowers, 1970, 41 pp, $8.00.

> Describes tests for determining the performance of positive displacement, compressors, blowers, and vacuum pumps whether reciprocating or rotating.

ASME: PTC 19.2, Instruments and Apparatus: Pressure Measurement, 1964, 58 pp, $9.00.

Discusses the technology of pressure measurement: general considerations and definitions, pressure connections, liquid-level gages, deadweight gages and testers, elastic gages, and low-pressure measurement.

ASME: PTC 19.3-1974, Instruments and Apparatus: Temperature Measurement, 1974, 118 pp, $16.00.

Presents a revision, expansion, and consolidation of all earlier pamphlets on temperature measurement instruments, with particular emphasis on basic sources of errors and means of coping with them.

ASME: PTC 19.5, Interim Supplement on Instruments and Apparatus: Application, Part II, Fluid Meters, Sixth Edition, 1971, 140 pp, $14.00.

Presents the recommended conditions, procedures and data for measuring the flow of fluids, particularly with the three principal differential presssure meters: the orfice, the flow nozzle, and the venturi tube.

ASME: PTC 19.6, Electrical Measurements in Power Circuits, 1965, 40 pp, $7.00.

The methods given include measurements made with either indicating or integrating instruments of power voltage and current in direct-current and alternating current single-phase and poly-phase rotating machinery, transformers, induction apparatus, arc and resistance heating equipment, and mercury arc rectifiers.

ASME: PTC 19.7, Measurement of Shaft Horsepower, 1961, 29 pp, $5.00.

Shows how measurement of shaft horsepower of rotating machines can be accomplished either by the direct method of utilizing dynamometers or the indirect method of using calibrated motors or generators, heat balance, or heat exchangers.

ASME: PTC 19.13, Measurement of Rotary Speed, 1961, 17 pp, $5.00.

Covers commonly used instruments and methods, and discusses characteristics and limitations of commercially available instruments used for testing rotating machinery, turbine, blower, or electric motor.

The following Standards, identified by their ANSI number are ANSI approved, but published by ASME. They are available from either ASME or ANSI.

ANSI: B88.1-1972 (R1979), Guide for Dynamic Calibration of Pressure Transducers, 1972, 20 pp, $5.00.

The intent of this document is to provide the user with a comprehensive guide to current techniques and to identify possible pitfalls associated with the dynamic calibration of pressure transducers.

ANSI: C85.1-1963, Terminology for Automatic Control, 1963, 65 pp, \$5.25 (includes supplements C85.1a-1966 and C85.1b-1972). (Individual supplements \$1.50 each)

Terminology pertaining to systems such as: automatic process control, feedback control, regulating, and other related systems not requiring human intervention as a part of the regulating procedure.

AMERICAN VACUUM SOCIETY (AVS)

The following tentative Standards are available from the American Vacuum Society, 335 East 45th Street, New York, NY 10017.

AVS: 6.2-1969, Procedure for Calibrating Vacuum Gages of the Thermal Conductivity Type, 1969, 4 pp, \$1.00.

Procedures are given and apparatus described for calibrating vacuum gages of the thermal conductivity type of direct comparison with measurements made with an absolute reference instrument such as the McLeod gage. The pressure range considered is of the order of 10^{-4} to several Torr.

AVS: 6.4-1969, Procedure for Calibrating Hot Filament Ionization Gauges Against a Reference Manometer in the Range of 10^{-2}-10^{-5} Torr, 1969, 5 pp, \$1.00.

Procedures are given for the calibration of hot cathode ionization gauges and gauge tubes by direct comparison against a McLeod gauge or other absolute manometer in the pressure range of 10^{-2}-10^{-5} Torr.

ELECTRONIC INDUSTRIES ASSOCIATION (EIA)

The following EIA Standards are available from the Electronics Industries Association, 2001 Eye Street, N.W., Washington, DC 20006. In addition, EIA and NEMA have jointly prepared several standards. The joint standards may also be listed under EEI or NEMA and may be ordered from any of the three.

EIA: RS-186-E, (ANSI RS-186-E-78), Standard Test Methods for Passive Electronic Component Parts, \$3.00.

Establishes uniform methods for testing electronic component parts. The methods provide a number of test conditions of varying degrees of severity so that appropriate test conditions may be selected for any component. Contains index of individual test methods.

EIA: RS-232-C, Interface Between Data Terminal Equipment and Data Communication Equipment Employing Serial Binary Data Interchange, \$6.90.

Applicable to the interconnection of data terminal equipment (DEC) employing serial binary data interchange. It defines Electrical Signal Characteristics, Interface Mechanical Characteristics, Functional Description of Interchange Circuits and Solid Interfaces for Selected Communication System Configurations. Included are thirteen specific interface configurations intended to meet the needs of fifteen defined system applications. (A companion document to RS-232-C is Industrial Electronics Bulletin No. 9, $2.60. It provides the application notes to RS-232-C.)

EIA: RS-253 (Also NEMA: SK 56-1961), Standard Temperatures for Electrical Measurement and Rating Specification - Semiconductor Devices, 1961, 2 pp, $2.00.

To provide the specification writer with a list of temperatures in common usage, and for which testing equipment will be more readily available; and to reduce the number of temperatures at which semiconductor device electrical measurements and ratings are specified to a minimum consistent with electronic equipment requirements, thus minimizing the diversity of equipment required for environmental testing.

EIA: RS-275-A (ANSI: C83.68-1972), Thermistor Definitions and Test Methods, 1972, $3.50.

Covers definitions of terms and test methods for measurement of the performance characteristics of thermistors. The following are defined: Zero Power Temperature Coefficient, Maximum Operating Temperature, Dissipation Constant, Zero Power Resistance Temperature Characteristic, Temperature Wattage Characteristic, Current-Time Characteristic, Resistance Ratio, Beta, Stability, and Maximum Power.

EIA: RS-309 (ANSI: C83.27-1968)(R 1977), General Specification for Thermistors, Insulated and Non-Insulated, 1972, 12 pp, $4.70.

Covers insulated and non-insulated thermistor disks and rods with leads.

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)

Publications of the former American Institute of Electrical Engineers (AIEE) and Institute of Radio Engineers (IRE) are identified by the IEEE number. All of these publications are available from the Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, NY 10017.

IEEE: STD 85-1973, Test Procedure for Airborne Noise Measurements on Rotating Electric Machinery, 34 pp, $5.00.

Outlines practical techniques and procedures which can be followed for conducting and reporting tests on rotating electrical machines of all sizes to determine the airborne noise characteristics under steady-state conditions.

IEEE: STD 118-1978, Master Test Code for Resistance Measurement, 31 pp, $6.00.

Provides instructions for those measurements of electric resistance which are commonly needed in determining the performance characteristics of electric machinery and equipment.

IEEE: STD 120-1955 (REAFF 1972), Master Test Code for Electrical Measurements in Power Circuits, 40 pp, $3.60.

Gives instructions for those measurements of electrical quantities which are commonly needed in determining the performance characteristics of electric machinery and equipment.

IEEE: STD 121-1959, Recommended Guide for the Measurement of Rotary Speed, 12 pp, $3.00.

Describes the instruments and methods commonly used for the measurement of rotary speed or slip and gives information regarding the characteristics and limitations of commercially-available instruments ordinarily employed in connection with the testing of electric machinery.

IEEE: STD 151-1965 (REAFF 1971), Terms of Audio and Electroacoustics, 2nd edition, 12 pp, $3.00.

Contains definitions for 174 terms used widely in audio and electroacoustic techniques.

IEEE: STD 162-1963 (REAFF 1972), Definitions of Terms for Electronic Digital Computers, 2nd edition, 12 pp, $3.00.

Contains nearly all important terms related to electronic digital computers. Analog and programming terms are not included because they are covered in other standards.

IEEE: STD 165-1977, Definitions of Terms for Analog Computers, 12 pp, $5.00.

Contains definitions for 172 terms common to analog computing techniques and associated hardware.

IEEE: STD 169-1955, Definitions of Industrial Electronics Terms, 4 pp, $3.00.

Defines 76 terms for techniques and equipment used in dielectric and induction heating.

IEEE: STD 170-1964, 170, Definitions of Terms for Modulation Systems, 2nd edition, 8 pp, $3.00.

Contains 75 items important in modulation systems, including those terms on the borderline of information theory.

IEEE: STD 196-1951, Definitions of Terms for Transducers, 4 pp, $3.00.

Defines 32 terms related to theory and devices for converting or transmitting energy.

IEEE: STD 216-1960 (REAFF 1971), Definitions of Semiconductor Terms, 4 pp, $3.00.

Provides definitions of important terms relating to the physical aspects of semiconductor materials and basic components developed from them.

IEEE: STD 221-1962 (REAFF 1971), Definitions of Terms for Thermoelectric Devices, 8 pp, $3.00.

Defines 55 terms related to thermoelectric effects and the application and evaluation of them in devices.

IEEE: STD 223-1966, Standard Definitions of Terms for Thyristors, 6 pp, $3.00.

Includes classes of thyristors, physical structure nomenclature and electrical characteristic terms.

IEEE: STD 251-1963 (REAFF), Proposed Test Procedure for Direct-Current Tachometer Generators, 1963, Reaffirmed 1972, 12 pp, $3.00.

Covers instructions for conducting and reporting the more generally applicable and acceptable tests to determine the performance characteristics of direct-current tachometer generators.

IEEE: STD 337-1972 (REAFF 1978), Specification Format Guide and Test Procedure for Linear, Single-Axis, Pendulous, Analog Torque Balance Accelerometer, 47 pp, $10.00.

Defines the requirements for a linear, single-axis, pendulous, analog torque balance accelerometer. The instrument is equipped with a permanent magnet torquer and is used as a sensing element to provide an electrical signal proportional to acceleration.

The following ANSI-approved Standards are published by IEEE and are available from either IEEE or ANSI. They are identified below by their ANSI number with the IEEE number (if available) in parentheses.

ANSI: C83.23 (IEEE: STD 178), Method for the Determination of the Elastic, Piezoelectric and Dielectric Constant of Piezoelectric Crystals, 1960, 16 pp, $3.50.

Provides equations, diagrams, and charts for calculating important parameters for piezoelectric crystals.

ANSI: C83.24 (IEEE: STD 179), Measurement of Piezoelectric Ceramics, 1962, Reaffirmed 1971, 11 pp, $3.50.

Covers definitions, relations, and measurement methods developed for piezoelectric crystals in general, including ferroelectric ceramics. Includes measurement methods, signal response, pyroelectric effects, and aging.

ANSI: C83.3 (IEEE: STD 176), Piezoelectric Crystals, 1972, 20 pp, $4.00.

Defines areas for piezoelectric crystals, specifies, orientation of crystal plates; provides symbols, units, and relations for piezoelectric components.

INSTRUMENT SOCIETY OF AMERICA (ISA)

The following ISA Standards and Recommended Practices are available from the Instrument Society of America, 67 Alexander Drive, P.O. Box 12277, Research Triangle Park, NC 27709. The price given for each Standard is the non-member, single-copy price. ISA members are entitled to a reduced price and bulk-quantity discount prices are provided on request.

ISA-RP2.1, Manometer Tables, 1962 (R1978), 31 pp, $9.00.

Presents abbreviations and fundamental conversion factors commonly used in manometry, recommended definitions of pressure in terms of a column of mercury and water, and for a large number of liquids, tables of pressure indicated by, or equivalent to, heights of columns at various temperatures.

ISA-S5.1 (ANSI Y32.20-1975), Instrumentation Symbols and Identification, 1973, 54 pp, $10.00.

Establishes a uniform means of designating instruments and instrumentation systems used for measurement and control. The differing established procedural needs of various organizations are recognized, where not inconsistent with the objectives of the Standard, by providing alternative symbolism methods. A number of options are provided for adding information or simplifying the symbolism, if desired.

ISA-RP25.1, Materials for Instruments in Radiation Service, 1957, 15 pp, $9.00.

Intended to serve as a guide to the selection of materials for use in intense radiation fields such as those encountered in and around nuclear reactors.

ISA-S26 (ANSI MC4.1-1975), Dynamic Response Testing of Process Control Instrumentation, 1968, 26 pp, $9.00.

Incorporating four revised ISA recommended practices, the standard establishes the basis for dynamic response testing of measurement and control equipment with pneumatic output and electric output, and for closed loop actuators for externally actuated control values and other final control elements. Pulse testing techniques as well as methods for sine wave, step, and pulse-type signals are included.

ISA-RP31.1 (ANSI ISA RP 31.1-1977), Specifications, Installation, and Calibration of Turbine Flowmeters, 1972, 23 pp, $9.00.

Establishes minimum ordering information, recommended acceptance and qualification test methods including calibration techniques, uniform terminology and drawing symbols, and recommended installation techniques for volumetric turbine flow transducers having an electrical output.

ISA-S37.1 (ANSI: MC6.1-1975), Electrical Transducer Nomenclature and Terminology, 1975, 15 pp, $9.00.

Establishes uniform nomenclature for transducers and uniform simplified terminology for transducer characteristics.

ISA-RP37.2, Guide for Specifications and Tests for Piezoelectric Acceleration Transducers for Aero-Space Testing, 1964, 19 pp, $9.00.

Covers piezoelectric acceleration transducers, primarily those used in Aero-Space test instrumentation. Terminology used in this document follows ISA-537.1, Electrical Transducer Nomenclature and terminology, except that additional terms considered applicable to piezoelectric vibration transducers are defined.

ISA-S37.3 (ANSI: MC6.2-1975), Specifications and Tests for Strain Gage Pressure Transducers, 1976, 20 pp, $9.00.

Establishes for strain gage pressure transducers: uniform minimum specifications for design and performance characteristics; uniform acceptance and qualification test methods, including calibration techniques; uniform presentation of minimum test data; and a drawing symbol for use in electrical schematics.

ISA-S37.5 (ANSI: MC6.3-1975), Specifications and Tests for Strain Gage Linear Acceleration Transducers, 1976, 18 pp, $9.00.

Establishes uniform minimum specifications for design and performance characteristics, uniform acceptance and qualification test methods including calibration techniques, uniform presentation of minimum test data, and a drawing symbol for use in electrical schematics for strain gage linear acceleration transducers.

ISA-S37.6 (ANSI: MC6.5-1976), Specifications and Tests of Potentiometric Pressure Transducers, 1976, 26 pp, $9.00.

Establishes for potentiometric pressure transducers: uniform minimum specifications for design and performance characteristics; uniform acceptance and qualification test methods, including calibration techniques; uniform presentation of minimum test data; and a drawing symbol for use in electrical schematics.

ISA-S37.8 (ANSI ISA S37.8-1977), Specifications and Tests for Strain Gage Force Transducers, 1977, 16 pp, $9.00.

Outlines uniform general specifications, acceptance and qualification methods, methods for data presentation, and includes a drawing symbol used in electrical schematics for tension, compression, and combination tension/compression transducers.

ISA-S37.10 (ANSI: MC6.4-1975), Specifications and Tests for Piezoelectric Pressure and Sound-Pressure Transducers, 1976, 25 pp, $9.00.

> Establishes uniform specifications for describing design and performance characteristics, acceptance and qualification test methods and calibration techniques, and procedures for presenting test data for piezoelectric (including ferro-electric) pressure and sound-pressure transducers.

ISA-S37.12 (ANSI ISA S37.12-1977), Specifications and Tests for Potentiometric Displacement Transducers, 1977, 21 pp, $9.00.

> Establishes uniform specifications for potentiometric displacement transducers for design and performance characteristics, acceptance and qualification test methods and calibration test methods and calibration techniques; uniform presentation of minimum test data and a drawing symbol for use in electrical schematics.

ISA-S50.1 (ANSI: MC12.1-1975), Compatibility of Analog Signals for Electronic Industrial Process Instruments, 1975, 11 pp, $5.00.

> This Standard applies to analog dc signals used in process control and monitoring systems to transmit information between subsystems or separated elements of systems. Its purpose is to provide for compatibility between the several subsystems or separated elements of given systems.

ISA-S51.1 (ANSI/ISA-551.1-1979), Process Instrumentation Terminology, 1979, 41 pp, $9.00.

> Intended to include all specialized terms used to describe the use and performance of the instrumentation and instrument systems used for measurement, control, or both in the process industries.

ISA-RP52.1, Recommended Environments for Standard Laboratoaries, 1975, 20 pp, $9.00.

> Recommendations for three levels of standardization are presented - from the more general National Bureau of Standards, through commercial, industrial and government laboratories. Requirements for nine environmental factors are discussed.

The following Standard, identified by its ANSI number was sponsored and published by ISA, approved by ANSI and is available from either ISA or ANSI.

MC96.1-1975, Temperature Measurement Thermocouples, 42 pp, $9.,00.

> Covers coding of thermocouple wire and extension wire; coding of insulated duplex thermocouple extension wires; terminology, limits of error and wire sizes for thermocouples and thermocouple extension wires; temperature EMF tables for thermocouples; plus appendixes that cover fabrication, checking procedures, selection, and installation.

NATIONAL BUREAU OF STANDARDS (NBS)
U.S. DEPARTMENT OF COMMERCE

The National Bureau of Standards had consolidated the Standards Application and Analysis Division which has two units of interest to those concerned with engineering standards.

Standards Development Services (SDS)

Administers the Department of Commerce Voluntary Products program as set forth in NBS Policy Bulletin No. 4 (November 29, 1971). Basically this program is now operated as a supplement to the activities of the private sector standards-writing bodies. It is the process of transferring, where appropriate, the responsibility for the continued maintenance of older NBS Standards on industrial products to private sector organizations.

Standards Information Services (SIS)

NBS-SIS maintains a reference collection of engineering and related standards which includes over 200 000 standards, specifications, test methods, codes, and recommended practices issued by U.S. technical societies, professional organizations, and trade associations, state and federal agencies, foreign national standards bodies, and international organizations.

NBS-SIS also functions as a referral activity by directing inquiries to appropriate standards-issuing organizations.

For requests for lists of Standards, together with names of organizations where copies of the Standards can be obtained, write to:
Standards Information Services, Room B162, National Bureau of Standards,
Washington, DC 20234, or call (301) 921-3272.

The following NBS Publications may be ordered by SD Catalog Number from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402. Add 25% to SD prices for foreign mailings.

An Index of U.S. Voluntary Engineering Standards, Supplement 1, 1972, to NBS Special Publication 329. Price $8.25; SD catalog number C13.10:329 Supplement 1; Supplement 2, 1975 to NBS Special Publication 329. Price $9.35; SD catalog number SN003-003-01362J.

Index of International Standards NBS Special Publication 390, 1974. Price $7.25; SD catalog number COM 74-56352.

Directory of U.S. Standardization Activities NBS Special Publication 417, Price $6.75; SD catalog number SN 003-003-01395-1.

Order by COM Number from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

An Index of U.S. Voluntary Engineering Standards, NBS Special Publication 329, 1971. Price $26.25 Domestic; $52.50 Foreign. COM 71-50172.

World Index of Plastics Standards, NBS Special Publication 352, 1971, Price $11.75 Domestic; $14.25 Foreign COM 75-10291.

An Index of State Specifications and Standards, NBS Special Publication 375, 1973 Price: $10.75 Domestic; $13.25 Foreign. COM 73-50839.

Tabulation of Voluntary Standards and Certification Programs for Consumer Products, under revision.

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION (NEMA)

The following NEMA Standards publications are available from the National Electrical Manufacturers Association, 155 East 44th Street, New York, NY 10017. In addition, NEMA, EIA, and EEI have jointly prepared several standards, which may be ordered from any of the three organizations. (Remittance required with all orders.)

NEMA: EI 2-1966, Instrument Transformers, 2nd edition 1966, 12 pp, $1.25.

Covers all instrument transformers except bushing current transformers which are mounted inside circuit breakers and power switchgear assemblies; supplements ANSI: C57.13 and NEMA: E121-1973, $1.25.

NEMA: EI 21-1973, Instrument Transformers for Metering Purposes, 15 KV and less, 1973, 20 pp, $1.75.

Covers general requirements, ratings, accuracy classifications, burdens and pertinent dimensions applicable to dry-type instrument current and potential transformers for metering purposes on circuits up to and including 15 KV.

NEMA: II 2-1972, Electrical Indicating Instrument-Relays, 1972, 63 pp, $5.50.

Developed to meet the need for Standards for electrical-indicating instrument-relays, which are known colloquially as "meter-relays." The term "instrument-relay," therefore, is used herein to conform to American National Standards and International standards practice. Contains definitions, general requirements, and test procedures.

NATIONAL FLUID POWER ASSOCIATION (NFLDP)

The following NFPA and ANSI Standards are available from the National Fluid Power Association, 3333 N. Mayfair Road, Milwaukee, WI 53222. Note: the acronym NFLSP is used above and in the index section to distinguish from the National Fire Protection Association.

NFPA: T2.9.6 (ANSI: B93.28-1973), Standard Method for Calibration of Liquid Automatic Particle Counters Using "AC" Fine Dust Test, 1973, 15 pp, $7.50.

> Provides procedures for calibration of a liquid automatic particle counter which is used for determination of particle size distribution of contaminants encountered in hydraulic fluid power applications.

NFPA: STD T3.9.12-1975, Recommended Standard Method of Measuring Sound Generated by Hydraulic Fluid Power Pumps, 8 pp, $5.50.

> Establishes a uniform basis for measuring, reporting, and comparing the sound levels of hydraulic fluid power pumps.

NFPA: STD T3.9.14-R 1976, Recommended Standard Method of Measuring Sound Generated by Hydraulic Fluid Power Motors, 9 pp, $5.50.

> Establishes a uniform basis for measuring, reporting, and comparing the levels of sound generated by hydraulic fluid power rotary motors.

RANGE COMMANDERS COUNCIL (RCC)

The following IRIG and RCC Standards have been prepared and published by the Range Commanders Council for use by governmental agencies, and industries under contract to them, for use in the fields of missiles, rockets, and associated equipment. Limited copies are available to authorized non-government agencies from the Secretariat, Range Commanders Council, STEWS-SA-R, White Sands Missile Range, NM 88002. Authorization is identified by the supporting governmental service for its associate agencies and industries.

RCC: 106-77, Telemetry Standards, Revised 1977, 90 pp.

> These current Standards provide development and coordination agencies with the necessary criteria on which to base equipment design and modification. The ultimate purpose is to ensure efficient spectrum and interference-free operation of the radio link for telemetry systems at the RCC member ranges.

RCC: 118-73, Test Methods for Telemetry Systems and Subsystems, 1975, 336 pp.

Developed by the Telemetry Group and the Inter-Range Instrumentation Group. Complements RCC Document 106-77, "Telemetry Standards," by defining standard test methods for telemetry ground systems and related subsystems. Utilization of the methods as described in this document will enable the exchange of test results which are derived and expressed in a common manner.

RCC: 119-71, Error Analysis and Methods for Estimating Errors in Position, Velocity, and Acceleration Data, 1971, 122 pp.

Developed by the Data Reduction and Computing Working Group and the Inter-Range Instrumentation Group. Mathematical models, methods, and techniques which are useful and appropriate for estimating the accuracy of position (in some coordinate systems); velocity, and acceleration data are presented in this document. The development and use of the techniques discussed have evolved through the years and in some cases out of work not related to missile testing.

IRIG: 126-73, Physical Constants and Conversion Factors, 1973, 24 pp.

Prepared by the Data Reduction and Computing Working Group and the Inter-Range Instrument Group. The objective is to present a compilation of the more commonly used physical constants, mathematical constants, unit conversion factors, and other fixed numerical values as may be required at the various member installations for data processing.

SCIENTIFIC APPARATUS MAKERS ASSOCIATION (SAMA)

The following SAMA and ANSI publications are available without charge from the Scientific Apparatus Makers Association; 1140 Connecticut Avenue, N.W., Washington, DC 20036.

SAMA: MTI 1 and 2, Load Cell Terminology and Recommended Test Procedures, second edition, 1964, 16 pp.

Provides recommended terminology and definitions for hydraulic, pneumatic, and mechanical load cells used for measurement of weight and force. Also provides recommended general purpose test procedures for qualification and acceptance testing of these types of load cells.

The following SAMA publications are available from: Scientific Apparatus Makers Association, Process Measurement and Control Section, 370 Lexington Avenue, New York, NY 10017.

SAMA: PMC 5-10, Resistance Thermometers, 2nd edition, 1963, 6 pp, $1.00.

Establishes uniformity of terminology (including symbols), definitions, and dimensions for resistance thermometers.

SAMA: PMC 8-10, Thermocouple Thermometers (Pyrometers), 2nd edition, 1963, 11 pp, $1.00.

Establishes uniformity of terminology (including symbols), definitions for thermocouple thermometers.

SAMA: PMC 8-10, Thermocouples-Thermometers (pyrometers), 2nd Edition, 1963, 11 pp, $1.00.

Establishes uniformity of terminology (including symbols), definitions, and dimensions for thermocouple thermometers.

SAMA: PMC 17-10, Bushings and Wells for Temperature Sensing Elements, 1963, 6 pp, $1.00.

Establishes uniformity of terminolgy (including symbols), definitions for bushings and wells. Also establishes a series of preferred sizes with dimensions and tolerances such that bushings and wells of the same nominal dimensions are completely interchangeable. Dimensions given in this Standard provide bushings and wells suitable for bimetallic thermometers, resistance thermometers, filled system thermometers and thermocouple thermometers in accordance with other SAMA Standards.

SAMA: PMC 20.1-1973, Process Measurement and Control Terminology, 1973, 44 pp, $2.00.

Applies to terminology associated with industrial process instrumentation used in industries such as chemical, petroleum, metallurgical, power, food, textile and paper. It includes terms relating to measurement and control, and the static and dynamic performance of indicators, recorders, controllers, indicating controllers, recording controllers, transmitters and transducers.

SAMA: PMC 21-4-1966, Temperature-Resistance Values for Resistance Thermometer Elements of Platinum, Nickel and Copper, 1966, 14 pp, $2.00.

Purpose is to establish standard temperature resistance values for platinum, nickel, and copper resistance thermometer elements.

SAMA: PMC 22-111-1966, Functional Diagramming of Instrument and Control Systems, 1966, 20 pp, $2.00.

Presents both symbols and diagramming format for use in representing measuring, controlling, and computing systems as used in industrial practice. The purpose is to establish uniformity of symbols and practices in diagramming such systems in their basic functional form, exclusive of their operating media or specific equipment detail.

SOCIETY OF AUTOMOTIVE ENGINEERS INC. (SAE)

The following and numerous other SAE publications are available from the Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096.

Aerospace Information Reports (AIR)

SAE: AIR 46, Preparation and Use of Chromel-Alumel Thermocouples for Turbojet Engines, 1956, 50 pp, $5.00.

Reviews the precautions which must be taken and the corrections which must be evaluated and applied if the experimental error in measuring the temperature of a hot gas stream with a thermocouple is to be kept at a practicable minimum.

SAE: AIR 65, Thermoelectric Circuits and The Performance of Several Aircraft Engine Thermocouples, 1958, 36 pp, $3.50.

Covers theory of thermoelectric circuits; thermocouple corrections for radiation, conductions, velocity and response rate; and thermocouple materials. Also included is a section on nomenclature and performance charts.

Aerospace Standards (AS)

SAE: AS 407B, Fuel Flowmeters, 3rd edition, 1960, 7 pp, $1.50.

Specifices minimum requirements for fuel flowmeters for use primarily in reciprocating engine powered civil transport aircraft, the operating of which may subject the instruments to specified environmental conditions. Covers two basic types: Type I - measures rate of flow of fuel used; and Type II - totalizes amount of fuel consumed or remaining.

SAE: AS 428, Exhaust Gas Temperature Instruments, 1966, 11 pp, $2.25.

Establishes essential minimum safe performance standards for electrical-servo, null-balance-type exhaust gas indicating instruments for use in turbine-powered subsonic aircraft. Covers a null balance system actuated by vary-emf output of a chromel-alumel thermocouple.

SAE: AS 431A, True Mass Fuel Flow Instruments, 2nd edition, 1962, 12 pp, $2.25.

Establishes essential minimum safe performance standards for true mass fuel flow instruments for use in turbine powered subsonic transport aircraft. Covers three basic types of true mass flow indicating instruments as follows: Type - rate indication. Type II - integration. Type III - rate indication and integration. Each may consist of an indicator, transmitter and other auxiliary items such as a power supply or amplifier as required.

SAE: AS 432A, Tachometer Instruments, 2nd edition, 1963, 12 pp, $2.25.

Establishes essential minimum safe performance standards for tachometer instruments 0-110% rpm and 0-120% rpm indicators and generators for remote indication of engine speed.

SAE: AS 793, Total Temperature Measuring Instruments (Turbine Powered Subsonic Aircraft), 1966, 9 pp, $2.25.

Establishes essential minimum safe performance requirements for the subject instrument, operation of which may subject it to environmental conditions specified. Covers three basic types of total-temperature-measuring instruments: Type I - flush-type total-temperature sensor, and Types II and III - probe-type total-temperature sensors (electrically heated and unheated, respectively).

SAE: ARP 175, Temperature Measurement, Well Insert Type, 1948, 4 pp, $1.50.

Covers the detail installation requirements and the temperature response characteristics of various types of temperature responsive elements intended for well-type installation in aircraft engine cylinder heads. May also be applied to temperature measuring applications other than air-cooled aircraft engine cylinder heads.

SAE: ARP 427, Pressure Ratio Instruments, 1958, 12 pp, $1.50.

Recommends requirements for electrical pressure ratio indicating instruments for use in aircraft. Covers two unit-pressure ratio instruments each of which consists of a transducer and an indicator. The transducer computes the ratio of two pressures and converts this ratio to synchro-electrical signal which is transmitted to the indicator.

SAE: ARP 464, Thermocouple Mount, 1958, 1 pg, $1.50.

Dimensional drawing with tolerances.

SAE: ARP 465A, Flange - Thermocouple, 1971, 4 pp, $1.50.

Supersedes and cancels ARP 465 and ARP 466, issued 2-15-58. Flanges described in this ARP are used for mounting temperature sensing probes in gas turbine engines. The probes are welded or brazed to the flange for positive support. The flanges are bolted or secured by nuts and studs to mounting bosses located on the engine case.

SAE: ARP 485, Nomenclature for Temperature Measuring Devices, 1957, 8 pp, $1.50.

Establishes the nomenclature and related terminology of temperature measuring devices as applied to aircraft, gas-reaction-type power plants for use by: (a) power plant manufacturers, (b) airframe manufacturers, (c) procurement organizations, (d) equipment organization, (e) service and maintenance personnel, and (f) other interested organizations.

Surface Vehicle Documents (J)

The SAE surface vehicle (J) documents can be purchased for prices listed. A lower case "a," "b," etc., appended to the (J) document number indicates successive revisions of that document.

SAE: J211b, Instrumentation for Impact Tests, 1976, 2 pp, $2.00.

Provides guidelines for instrumentation used in motor vehicle and motor vehicle component impact tests. It is intended to supplement impact test procedures such as those described in SAE J850, J944, J117, etc.

SAE: J254, Instrumentation and Techniques for Exhaust Gas Emissions Measurement, 1976, 11 pp, $3.50.

Establishes uniform laboratory techniques for the continuous and grab sample measurement of various constituents in the exhaust gas of the gasoline engines installed in passenger cars and light trucks. The report concentrates on the measurement of the following components in exhaust gas: hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), and oxygen (O_2).

SAE: J390, Dual Dimensioning, 1976, 8 pp, $3.50.

Establishes a uniform method of combining U.S. customary (inch) units and metric units of measure on the same engineering drawing. In this document "metric units" means the International System of Units (abbreviated SI) as described in ISO Recommendation R 1000, which includes certain units in addition to the formal SI.

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS (SNAME)

The following ship testing codes are available from The Society of Naval Architects and Marine Engineers, 74 Trinity Place, New York, NY 10006.

SNAME: Code C-1, Code for Shipboard Vibration Measurements, 1975.

> Establishes standard procedures for gathering and interpreting data on hull vibrations in single-screw commercial ships. These data are needed to compare the vibration characteristics of different ships of a given class, to establish vibration reference levels, and to provide a basis for the improvement of individual ships.

SNAME: Code C-2, Code for Sea Trials, 1973.

> Includes a section which describes the instruments and apparatus commonly used for making measurements of the performance of various items of machinery in ships' trials.

SNAME: T&R Bulletin 3-23, Guide for Centralized Control and Automation of Ship's Steam Propulsion Plant, 1970, 54 pp.

> Gives technical guidance in establishing the desired degree and methods for employing centralized control and for automating a ship's steam propulsion plant.

INTERNATIONAL STANDARDIZATION

Standards of two international organizations are available from the American National Standards Institute (ANSI), 1430 Broadway, New York, NY 10018. ANSI also has an office in Europe: American National Standards Institute, 16 Chemin de la Voie Creuse, 1211 Geneva, Switzerland. ISO and IEC Standards are also available from their respective Secretarial Headquarters. The number of instrumentation-related international standards is so extensive that only representative titles are listed in this section. In addition the listing has been limited to reference number, title and price (ANSI price as of 1976). Additional information on individual standards or a complete listing of international standards from the following organizations may be obtained from ANSI.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) - The American National Standards Institute is the Member Body representing the United States in the International Organization for Standardization (ISO). Fifty-six national standards bodies comprise the world membership and cooperate in formulating the technical program in which each member maintains a status as a participant or observer in accordance with the interest of the member in the specific standard under consideration.

INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC) - The American National Standards Institute has administrative and technical affiliation with the U.S. National Committee of the IEC. This committee, in turn, represents the U.S. in the IEC. The IEC holds the international responsibility for the coordination and unification of all national electrotechnical standards and it is affiliated with the ISO. It also acts as the coordinating body for the activities of other international organizations whose responsibilities relate to or overlap the electrotechnical field.

In addition to the national organizations listed above, two other international organizations actively participate in standardizing activities in the area of automatic control through cooperation with their member societies. They are: Secretariat, International Federation of Automatic Control (IFAC), Postfach 1139, D-4000 Duesseldorf 1, FRG, (West Germany); and Secretariat, International Federation for Information, Processing (IFIP), 3, rue du Marche, 1204-Geneva, Switzerland.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

The following Standards are available from ANSI, 1430 Broadway, New York, NY 10018. In the titles, the number in parentheses refers to a similar ANSI Standard.

Note: Prices given are approximate and may change at anytime due to international currency fluctuation.

ISO: 31/I-1978, Quantities and Units of Space and Time, $18.90.

ISO: 31/II-1978, Quantities and Units of Periodic and Related Phenomena, $10.50.

ISO: 31/III-1978, Quantities and Units of Mechanics, $23.10.

ISO: 31/IV-1978, Quantities and Units of Heat, $18.90.

ISO: 31/V-1965, Quantities and Units of Electricity and Magnetism, $21.00.

ISO: 31/VI-1973, Quantities and Units of Light and Related Electromagnetic Radiations, $14.70.

ISO: 31/VII-1978, Quantities and Units of Acoustics, $18.90.

ISO: 31/VIII-1973, Quantities and Units of Physical Chemistry and Molecular Physics, $18.90.

ISO: 31/IX-1973, Quantities and Units of Atomic and Nuclear Physics, $16.80.

ISP: 31/X-1973, Quantities and Units of Nuclear Reactions and Ionizing Radiations, $21.00.

ISO: 31/XI-1978, Mathematical Signs and Symbols for Use in the Physical Sciences and Technology, $31.50.

ISO: R1680-1970, Test Code for the Measurement of the Airborne Noise Emitted by Rotating Electrical Machinery, $23.10.

ISO: R2186-1973, Fluid Flow in Closed Conduits - Connections for Pressure Signal Transmissions Between Primary and Secondary Elements, $35.70.

INTERNATIONAL ELECTROTECHNICAL COMMISSION (IEC)

The following Standards are available from ANSI. An asterisk (*) following the year of publication indicates that later amendments or supplements are included. In the titles, the number in parentheses refers to a similar ANSI Standard.

Note: Prices given are approximate and may change at any time due to international currency fluctuations.

IEC: 27-1 (1971)* Letter Symbols to be Used in Electrical Technology, Part I: General, $73.50.

IEC: 27-2 (1972)* Letter Symbols to be Used in Electrical Technology, Part II: Telecommunications and Electronics, $51.10.

IEC: 38 (1975) Standard Voltages, $17.50.

IEC: 50-00 (1975), International Electrotechnical Vocabulary, General Index, $63.00.

IEC: 50-08 (1960), Electro-Acoustics, $24.50.

IEC: 50-12 (1955), Transductions, $7.00.

NOTE: IEC: 68, Basic Environmental Testing Procedures.

> Describes a standard general procedure for climatic and mechanical robustness tests, designed to assess the durability, under various conditions of use, transport, and storage, of components used in equipment for telecommunication and in electronic equipment employing similar techniques. This publication is issued in two parts, viz.

IEC: 68-1 (1978)* Part I, General $28.00.

General description of the framework of the test procedure and how it is to be used.

IEC: 68-2, Part 2. Tests.

This part describes the different tests in detail. Each test is identified by a letter of the alphabet and is issued in the form of a separate booklet.

IEC: 68-2-1 (1974), Test A: Cold, $39.20.

IEC: 68-2-2 (1974), Tet B: Dry Heat, $51.45.

IEC: 68-2-3 (1969), Test C: Damp Heat, Steady Heat, $8.00.

IEC: 68-2-4 (1960), Test D: Accelerated Damp Heat, $5.60.

IEC: 69-2-6 (1970), Test Fc: Vibration, (Sinusoidal), $23.10.
IEC: 68-2-7 (1968), Test Ga: Acceleration, Steady State, $7.35.

IEC: 68-2-13 (1966), Test M: Low Air Pressure, $4.90.

IEC: 68-2-14 (1974), Test N: Change of Temperature, $28.00.

IEC: 68-2-17 (1978), Test Q: Sealing, $50.40.

IEC: 68-2-27 (1972), Test Ea: Shock (includes supplement), $24.15.

IEC: 68-2-28 (1968), Guidance for Damp Heat Tests, $7.35.

IEC: 68-2-29 (1968), Test Eb: Bump, $14.00.

IEC: 68-2-30 (1969), Test Db: Damp Heat, Cyclic (12+ 12-Hour Cycle), $6.30.

IEC: 68-2-31 (1969), Test Ec: Drop and Topple, Primarily for Equipment-Type Specimens, $3.50.

IEC: 68-2-32 (1975), Test Ed: Free Fall, $11.20.

IEC: 68-2-33 (1971), Guidance on Change of Temperature Tests, $14.70.

NOTE: All above tests should be used in conjunction with 68-1.

IEC: 160 (1963), Standard Atmospheric Conditions for Test Purposes, $7.00.

IEC: 164 (1964), Recommendations in the Field of Quantities and Units Used in Electricity, $13.50.

IEC: 184 (1965), Methods for Specifying the Characteristics of Electro-Mechanical Transducers for Shock and Vibration Measurements, $21.00.

IEC: 185 (1966), Current Transducers, $48.30.

IEC: 190 (1966), Non-Wirewound Potentiometers Type 2, $31.50.

IEC: 222 (1966), Methods for Specifying the Characteristics of Auxiliary Equipment for Shock and Vibration Measurement, $14.00.

IEC: 271 (1974) Preliminary List of Basic Terms and Definitions for the Reliability of Electronic Equipment and the Components Used Thereof, $60.20.

IEC: 272 (1968) Preliminary Reliability Considerations, $3.50.

IEC: 351 (1971) Expression of the Functional Performance of Electronic Measuring Equipment, $25.20.

IEC: 605 (1978) Equipment Reliability Testing, Part 1, General Requirements, $47.60.

8.3 Government Standards

The documents listed below are standards documents developed and issued by agencies of the United States government. The Office of Standards Information of the National Bureau of Standards has a "Visual Search Microfilm File" which contains copies of more than 100 000 standards and specification documents. A file search of documents considered pertinent to this handbook was made and the information summarized below.

In addition, for military standards documents, the "Index of Specifications and Standards" July 1, 1978 edition, put out by the Department of Defense, was checked for pertinent references. The supplement of November 1, 1979 to this index was also checked. It is possible that some documents may have been left out or that some will be superseded by the time this handbook appears in print.

It should be noted that the search was confined to material bearing on sensors with electrical output and test methods for such components. Gages and mechanical indicators generally are not listed. In case of doubt on the applicability of a particular document, however, we normally chose to include it.

8.3.1 Civilian Standards Listings

GG-G76D, 4 December 1975

Gages, Pressure and Vacuum, Dial Indicating (for Air, Steam, Oil, Water, Ammonia, Chloro-Fluoro Hydrocarbon Gases, and Compressed Gases). ...covers dial gages which indicate pressure or vacuum on a graduated dial by means of a pointer, utilizing an elastic element (Bourdon Tube or cell) and actuating linkage, as required, for measuring pressure or vacuum.

8.3.2 Military Standards Listings (Standards, Specifications, and Handbooks)

MIL-STD-105D, 29 April 1963

Sampling Procedures and Tables for Inspection by Attributes ...establishes sampling plans and procedures for inspection by attributes...intended primarily for a continuing series of lots or batches. (Inspection by attributes is inspection whereby either the unit of product is classified as defective or nondefective, or the number of defects in the unit of product is counted with respect to a given requirement or set of requirements).

MIL-STD-198E, 4 August 1966

Definitions of and Basic Requirements for Enclosures for Electric and Electronic Equipment Enclosures ...establishes definitions and basic requirements for equipment. The use of these definitions for parts intended for mounting in enclosures is also described.

MIL-STD-109B, 4 April 1969

Quality Assurance Terms and Definitions ...provides a standardized interpretation of quality assurance terms and definitions to be applied throughout the determination of product quality.

MIL-STD-143B, 12 November 1969

Standards and Specifications, Order of Precedence for the Selection of ...sets forth the order of precedence for the selection of standards and specifications to identify and describe items, materials, and processes used by design activities in the design and construction of military material for the DoD. Requirements for approval of standards and specifications by the Government Command or agency concerned prior to use are excluded from the coverage of this standard. Requirements for approval or release, if any, or the use of documents stating applicability of standards and specifications for special applications are subject to contract provisions.

MIL-STD-167-1, 1 May 1974

Mechanical Vibrations of Shipboard Equipment (Type I - Environmental and Type II - Internally Excited) ...covers the requirements of Naval equipment including machinery as regards both internally excited vibrations and externally imposed vibrations. In some special machinery, equipment, or installations, such as antennas, large machinery items, and certain unique designs it may be necessary to deviate from this standard. In those cases, special modifications shall be subject to approval by the command or agency concerned. All other deviations from, or waivers of this standard, are prohibited.

MIL-HDBK-172A, 11 March 1964

Electronic Test Equipment (Volume I - Unclassified and Volume II - Classified) ...contains information on electronic test equipment of the Army, Navy, and Air Force used in calibration, adjustment, maintenance, and repair of communication, radar, countermeasures, meteorological, photographic, power, and other technical equipment employed for military purposes. ...presents data and information on technical physical, operational, and logistical characteristics of electronic test equipment. ...primarily for use by standardization, design, development, and procurement activities, and technical planning and coordinating use and maintenance of equipment.

MIL-STD-188C, 24 September 1969

Military Communication System Technical Standards ...provide technical design standards for military communications systems. These provide the basic technical parameters of communications equipment and systems. The parameters have been chosen for future state-of-the-art values wherever these can be determined with reasonable accuracy as well as to define the minimum acceptable performance values for interim use. The standards are to be used in development of new equipment as well as procurement of production models of standard equipment.

MIL-STD-202E, 16 April 1973

Test Methods for Electronic and Electrical Component Parts ...establishes uniform methods for testing electronic and electrical component parts, including environmental test, physical, and electrical test. ...includes capacitors, resistors, switches, relays, transformers, and jacks. ...intended for small parts (transformers over 300 lbs or rms test voltages over 50 000 V are excluded).

MIL-STD-210B, 15 December 1973

Climatic Extremes for Military Equipment ...(a) establishes uniform climatic design criteria for that military material which is intended for world-wide usage (excluding the air, land, and ice shelf areas south of 60° S). ...does not apply in design of material to be used only in specific areas or environments. ...(b) provide sets of climatic design conditions for land, sea, and air in which military materiel may be required to operate. ...also provides separate sets (land and sea) of climatic design conditions which materiel exposed to nature may be required to withstand without damage. (c) If equipment failure due to weather extremes...could endanger life of personnel, the design criteria should be established so as to result in a percentage of inoperability which is as close to zero as possible.

MIL-HDBK-235-1, 23 June 1972

Electromagnetic (Radiated) Environment Considerations for Design and Procurement of Electrical and Electronic Equipment. Part I. ...to provide guidance and establish a uniform approach for the protection of Navy electronics from adverse effects of the electromagnetic environment. Examples of systems, subsystems and equipments for which this handbook may be applicable are: (a) aerospace and weapons, (b) ordnance, (c) support and checkout equipment and instrumentation for (a), (b), and (d). Any other electronic equipment which may be subjected to high intensity electromagnetic environments.

Purpose: provides (a) information on electromagnetic environments for design and procurement of equipment exposed to electromagnetic radiation, (b) information for use in tailoring the radiated susceptibility requirement R503 of MIL-STD-461 and MIL-E-6051.

Part I- ...general information; Part 2- ...describes electromagnetic levels encountered from friendly emitters; Part 3- ...levels from hostile emitters. Table I furnishes an index of locations from which electromagnetic radiation environment levels are provided in Parts 2 and 3.

MIL-HDBK-217B, 20 September 1974

Reliability Prediction of Electronic Equipment. ...provides two methods of reliability prediction: (1) Parts Stress Analysis and (2) Parts Count. Mathematical expressions for part failure rates are provided for use in computer programming. Tables are used for base failure rates. ...is oriented toward reliability prediction of military electronic equipment; ...provides a common basis for prediction and comparing predictions on military contracts and proposals. It is not a complete guide to reliability engineering.

MIL-HDBK-251, 19 January 1978

Reliability/Design - Thermal Applications. ...recommends and presents electronic parts stress analysis methods which lead to the selection of maximum safe temperatures for parts so that the ensuing thermal design is consistent with the required equipment reliability.

MIL-STD-415D, 1 October 1969

Test Provisions for Electronic Systems and Associated Equipment, Design Criteria for. ...establishes design criteria for test provisions that permit the functional and static parameters of electronic systems and associated equipment to be monitored, evaluated, or isolated. These test provisions consist of the following: (a) external test receptacles for connecting automatic; semi-automatic, or manual checkout equipment or automatic monitoring equipment, (b) a built-in test capability, and (c) test points.

MIL-STD-441, 20 June 1958

Reliability of Military Electronic Equipment. Superseded by MIL-STD-785

MIL-STD-454F, 15 March 1978

Standard General Requirements for Electronic Equipment. ...covers the common requirements to be used in military specifications for electronic equipment.

MIL-STD-461A, 1 August 1968

Electromagnetic Interference Characteristics, Requirements for Equipment. ...covers the requirements and test limits for the measurement and determination of the electromagnetic interference characteristic (emission and susceptibility) of electronic, electrical, and electromechanical equipment, subsystems, and systems. The requirements shall be applied for general or multi-service procurements and single service procurements as specified in the individual equipment specifications.

MIL-STD-462, 31 July 1967

Electromagnetic Interference Characteristics, Measurement of. ...establishes techniques to be used for the measurement and determination of the electromagnetic interference characteristics (emission and susceptibility) of electrical, electronic, and electromechanical equipments, subsystems, and systems as required by MIL-STD-461A, Notice 4.

MIL-STD-463A, 1 June 1977

Definitions and Systems of Units, Electromagnetic Interference and Electromagnetic Compatibility Technology. ...is designed to assist in reaching a more common understanding of the meaning of terms used in the various military standards which provide a basis for assuring electromagnetic compatibility within the operational military environment. Definitions of terms and abbreviations are limited to statements of meaning related to this and applicable standards, rather than encyclopedia or textbook discussions.

MIL-STD-469, 1 December 1966

Radar Engineering Design Requirement, Electromagnetic Compatibility. Cancelled 28 February 1975.

MIL-STD-470, 21 March 1966

Maintainability Program Requirements (for Systems and Equipments). ...provides requirements for establishing a maintainability program and guidelines for the preparation of a maintainability program plan. The requirements of this standard are applicable to the development of other systems and equipment when specified.

MIL-STD-704C, 30 December 1977

Aircraft Electric Power Characteristics. ...establishes requirements for electric power characteristics on aircraft at the interface between the electric power system and the input to electric utilization equipment. The electric power characteristics covered...are of duration longer than 50 microseconds or less than 20 kilohertz. Electric power characteristics of duration less than 50 microseconds...are covered by MIL-E-6051.

MIL-HDBK-705B, 26 June 1972

Generator Sets, Electrical, Measurements and Instrumentations. ...covers a compilation of electrical term definitions and two series of methods of measurements for testing and determining the characteristics of electric generators, generator sets, and associated equipment. Illustrations and descriptions of the test instruments together with instructions for their use are included as applicable under each method.

MIL-STD-705B, 26 June 1972

Generator Sets, Engine Driven Methods of Tests and Instructions. ...explains, establishes and standardizes specific methods for measurements associated with the evaluation of electric generators, generator sets, and related components. This standard is closely allied with MIL-HDBK-705.

MIL-STD-706A, 25 November 1960

Power Supply Voltages, Regulated, D.C., Within Electronic Equipment. ...establishes nominal values of regulated direct current voltages within the range of 0 to 600 volts from power supplies that are contained within military electronic equipment. Voltages shall be selected from the following list: 1.5, 3, 6, 12, 25, 50, 100, 150, 250, 300, 450, and 600; or 6.3, 9.0, 12.6, 18.0, 26.5, 75.0, and 125 when required by electron tube filaments. Other values may be used as required or approved by the agency concerned.

MIL-STD-735A, 6 May 1965

Test Methods and Test Equipment for Thermometers Used in Machinery and Piping Systems. ...describes methods and equipment for testing of thermometers used in machinery and piping systems. ...Liquid-in-glass, Bimetallic, and filled systems.

MIL-STD-740B, 13 January 1965

Airborne and Structureborne Noise Measurements and Acceptance Criteria of Shipboard Equipment. ...covers acceptable instrumentation and procedures for the measurement of and acceptance criteria for, airborne and structureborne noise of Naval shipboard equipment. ...Basic method for airborne noise measurement is determination of sound power. (Second pressure may be specified for certain items.) Basic method for structureborne noise testing is measurement of vibrational acceleration of resiliently mounted equipment at its mounting points.

MIL-STD-750B, 27 February 1970

Test Methods for Semiconductor Devices. ...establishes uniform methods for testing semiconductor devices, including basic environmental tests to determine resistance to deleterious efforts of natural elements and conditions, and physical and electrical tests. Devices include: transistors, diodes, voltage regulators, rectifiers, and tunnel diodes. ...applies only to semiconductor devices.

MIL-STD-781C, 21 October 1977

Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution. ...covers the requirements for reliability qualification tests (preproduction) and reliability acceptance tests (production) for equipment that experiences a distribution of time-to-failure that is exponential. These requirements include: test conditions, procedures, and various fixed length and sequential test plans with respective accept/reject criteria.

Appendix E- ...sets forth minimum requirements for test equipment and facilities for the performance of reliability qualification and production acceptance tests.

MIL-STD-785A, 28 March 1969

Requirements for Reliability Program for Systems and Equipments Development and Production. ...establishes uniform criteria for reliability programs, and provides guidelines for the preparation and implementation of a reliability program plan.

MIL-STD-810C, 10 March 1975

Environmental Test Methods. ...establishes uniform environmental test methods for determining the resistance of equipment to the effects of natural and induced environments peculiar to military operations. It provides environmental test methods in order to obtain, as much as possible, reproducible test results. The test methods described are intended to be applied by the contractual documents.

MIL-STD-843, 1 April 1965

Altimeters, Pressure, General Test Requirements for. ...defines those tests which should be performed on pressure altimeters prior to acceptance, after extended periods of storage, or after servicing.

MIL-STD-883B, 31 August 1977

Test Methods and Procedures for Microelectronics. ...establishes uniform methods and procedures for testing microelectronic devices, including environmental, ...physical, and electrical tests. Includes monolithic, multichip, film, and hybrid microcircuits, microcircuit arrays, and the elements from which the arrays and circuits are formed.

MIL-S-901C, 15 January 1963

Shock Tests, H.I. (High-Impact); Shipboard Machinery and Systems, Requirements for. ...covers the shock testing requirements for shipboard machinery, equipment, and systems which are required to resist High Impact (HI) mechanical shock. The requirements are for the purpose of determining the suitability of machinery, equipment, and systems for use under the effects of the severe shock which may be incurred in war-time service.

MIL-E-917D, 28 January 1965

Electric Power Equipment, Basic Requirements. ...covers the general requirements applicable to the design, materials, and construction of Naval shipboard electric power equipment (exclusive of communications equipment and electronic equipment other than that used in electric power applications).

MIL-STD-976, 31 August 1977

Certification Requirements for JAN Microcircuits. ...establishes the minimum requirements for the certification of and maintenance of certification for manufacturing facilities/line(s) in fabricating, assembling, and testing high reliability JAN microcircuits per MIL-M-38510. This includes plant facilities, equipment, personnel training, process controls, testing, and documentation.

MIL-I-983E, 15 August 1966

Interior Communication Equipment, Naval Shipboard; Basic Design Requirements for. ...covers the basic design requirements, test and operating conditions for interior communications equipment to be used in Naval ships. The purpose is to secure uniformity of practice, quality of materials and workmanship necessary to meet the special requirements for equipments to be installed in ships of the U.S. Navy.

MIL-STD-1309B, 30 May 1975

Definitions of Terms for Test, Measurement, and Diagnostic Equipment. ...contains definitions of terms for test, measurement, and diagnostic equipment most commonly used. 438 definitions are given.

MIL-STD-1313A, 8 December 1967

Microelectronic Terms and Definitions. Cancelled - 22 May 1977.

MIL-STD-1326, 15 January 1968

Test Points, Test Point Selection and Interface Requirements for Equipments Monitored by Shipboard On-Line Automatic Test Equipment. ...establishes the requirements for providing test points in prime equipments for monitoring by on-line automatic test equipment (ATE). ...provides criteria for guidance in optimum test point selection. ...defines interface and data requirements, a system of test point data generation, and procedures for submission of data disclosing the selections of these test points.

MIL-E-415E, 11 January 1973

Electronic Equipment, Ground: General Requirements for. ...covers the general requirements of the design and manufacture of ground electronic equipment.

MIL-S-4456, 12 March 1953

Shock, Variable Duration, Method and Apparatus for. Obsolete.

MIL-E-5272C, 13 April 1959

Environmental Testing, Aeronautical and Associated Equipment.
Cancelled - Superseded by MIL-STD-810.
MIL-E-5400R, 31 October 1975

Electronic Equipment, Airborne, General Specification for.
...covers the general requirements for airborne electronic equipment for operation primarily in piloted aircraft. The detailed performance and test requirement for a particular equipment shall be specified in the detail specification for that equipment. The appendix lists the specifications, standards, and publications to be used in the design and construction of airborne electronic equipment.

MIL-T-5422F, 30 November 1971

Testing, Environmental, Airborne Electronic and Associated Equipment. ...contains procedures for testing airborne electronic and associated equipments under environmental conditions to demonstrate compliance with MIL-E-5400, MIL-T-21200, other general design specifications, and applicable detailed equipment specifications. The procedures contained herein specify, modify as necessary, and provide the required detail data for the applicable test method of MIL-STD-810 for Navy airborne electronic and associated equipment.

MIL-T-5494A, 28 November 1956

Thermocouples, Contact Aircraft Engine Spark Plug Gasket-Type.
...covers iron-constantan gasket-type thermocouples (14mm & 18mm gasket) Range: -55° to +300 °C; Intended use: on aircraft to actuate a thermocouple-type of indicator for the cylinder head temperature of air-cooled engine cylinders. Qualified Products List - 13 September 1974.

MIL-P-5640, 1 February 1950

Pickups; Strain Gage Types. ...covers equipment designed to provide a means of converting various flight test data of conventional and pilotless aircraft into electrical intelligence for injection into a telemetering transmitter. The various pickups shall utilize a strain-gage type of electrical pickoff to provide an electrical output. ...Types: pressure gage - 0 to 40 and 0 to 500 psia for non-corrosive liquids and gases; accelerometer - 2, 5, 10, and 20 g (dynamic and static).

MIL-E-6051D, 7 September 1967

Electromagnetic Compatibility Requirements, Systems. ...outlines the overall requirements for systems electromagnetic compatibility, including control of the system electromagnetic environment, lightning protection, static electricity, bonding, and grounding. It is applicable to complete systems, including all associated subsystems/equipments.

MIL-S-1503D, 3 August 1961

Salinity Indicating Equipment. ...covers salinity indicating equipment designed to indicate the amount of dissolved salts in boiler feed water, fresh water, distillate and submarine battery cooling water, and to warn operating personnel when predetermined values of salinity have been exceeded. [uses electrolytic cells]. Includes Qualified Products List - 8 March 1978.

MIL-T-15377F, 26 April 1979

Temperature Monitor Equipment. ...covers temperature monitoring equipment which continuously monitors and selectively indicates at a central location, a number of temperatures at remote equipment locations on board Naval ships. ...Temperature sensing techniques: resistance element - platinum; or thermocouple element - type K.

MIL-S-19500F, 15 December 1977

Semiconductor Devices General Specification for. ...establishes general requirements for semiconductor devices. Detail requirements and characteristics are specified in the detail specifications. Four levels of assurance requirements are provided for in this specification: JAN, JANTX, JANTXV, and JANS.

MIL-R-19610, 15 September 1956

Reliability of Production Electronic Equipment, General Specifications for. Cancelled 21 February 1966

MIL-I-19646, 5 December 1956

Thermometers, Remote Reading, Self-Indicating Dial, Gas Actuated. ...covers distant reading self-indicating dial thermometers of the gas-filled type for those applications and temperature ranges specified. Includes Qualified Products List - 23 December 1977.

MIL-A-22145B, 22 May 1967

Accelerometer Group, Counting Type, Designation MS25477 and MS25448. ...covers the design and performance requirements for a single-axis four load-factor counting accelerometer. ...consists of: (a) hermetically sealed force-balance accelerometer ...which furnishes a voltage proportional to applied acceleration, provides filter circuitry for required dynamic response and test circuits; (b) a display with electromagnetic counters to indicate number of times the aircraft is subjected to load factors of pre-set levels, power supply and regulator (18.5V), delay circuit, and a digital lock-out circuit.

MIL-T-231200L, 2 July 1973

Test Equipment of Use With Electronic and Electrical Equipment, General Specification for. Inactive for new equipment, 27 June 1977.

MIL-R-22256, 20 November 1959

Reliability Requirements for Design of Electronic Equipment or Systems. Superseded by MIL-STD-785.

MIL-R-22732C, 12 November 1973

Reliability Requirements for Shipboard Electronic Equipment. ...covers the procedures and requirements for achieving and verifying adequate levels of reliability during the design, feasibility study, development, test and evaluation, and production phases in the acquisition of shipboard electronic equipment.

MIL-A-23395, 15 August 1962

Altimeter, Pressure, Counter-Pointer Type MC-3 and MC-4. Cancelled, 9 May 1978.

MIL-T-23588C, 23 May 1974

Transducer, Pressure. ...establishes the requirements for the procurement of a pressure transducer, NAVORD Outline Drawing 1803636. ...Range to 500 psig; transduction Bourdon tube with wire strain gages in bridge circuit. ...must meet MIL-E-82590 ...specifies performance characteristic, environment.

MIL-T-23648A, 1 March 1966

Thermistor, (Thermally Sensitive Resistor), Insulated, General Specification for. ...covers the general requirements for general purpose insulated thermistors to be used for temperature compensation, control, and measurement over the temperature range specified. ...includes Qualified Products List, 9 February 1978.

MIL-L-23886A, 4 February 1965

Liquid Level Indicating Equipment (Electrical) (Naval Shipboard Use). ...covers the requirements for electrical liquid level indicating equipment for Naval shipboard use in fresh water, sea water, diesel fuel oil, lubricating oil, waste oil, refrigerants, and jet propulsion fuel in low pressure and high pressure tanks. ...Sensing technique; magnetic float, differential pressure, electro-magnetic, or heat transfer; ranges; Atm-100 psi or 100 psi and greater. Includes Qualified Products List, 26 September 1978.

MIL-P-24212B, 22 October 1976

Pressure Transducer Equipment. ...covers electrical output pressure transducer equipment for Naval ships - does not include readout or display. ...Types: gage, vacuum, compound (gage, vacuum), and water column. Sensing technique: Bourdon, diaphragm, bellows, or straight tube. Transduction: strain gage, variable reluctance, differential transformer. Fluids: steam, oil, flue gas and ammonia, oxygen, other gases, fresh water, and condensate.

MIL-F-24259, 17 October 1966

Fluid Flowmeter, Volume Velocity Type. ...covers fluid flowmeters for use in fresh water, sea water, and fuels and oils as specified herein and whose primary sensing element is driven by the impinging flow of the fluid. For example, turbine, vortex velocity, drag types are covered, while differential pressure, mass anemometer, batch weighing, and so forth would be excluded.

MIL-F-24291B, 10 August 1971

Flowmeter, Fluid Electromagnetic Type. ...applies to electromagnetic type fluid flowmeters for use in fresh or sea water, or any fluid having a conductivity as low as 10^{-4} mho/cm. ...sense and indicate rate of flow, total flow, and direction of flow in either direction through sensor. Flow sensor unit consists of metal tubing, with flanged ends and associated electrical wiring, containing an insulating liner along the complete length with insulated sensor electrodes penetrating through the metal tube and liner 100 degrees apart in the center of the flow sensor.

A water-tight housing around the outside of the sensor tube shall enclose the excitation coils, sensor electrodes, and wiring.

MIL-D-24304A, 21 July 1969

Differential Pressure Transducer (Electrical) (Naval Shipboard Use). ...covers the requirements for electrical output differential pressure transducer equipment for Naval ships but does not include readout or display. ...Sensing technique - diaphragm, bellows, straight tube; transduction - strain gage, variable reluctance, differential transformer; application - steam, oil, seawater, flue gas, condensate, other gases. Includes Qualified Products List, 23 April 1976.

MIL-T-24387, 1 June 1973

Temperature Measurement Equipment Signal Conditioner and Power Supply (Electrical) (Naval Shipboard Use). ...cover the requirements for signal conditioners and power supplies (electrical) used in conjunction with thermocouples and resistance temperature element assemblies for Naval ships. ...does not include the design of sensing elements and wells or the requirements for readout or display. Type: resistance - platinum; or thermocouple, type K. Qualified Products List, 29 September 1978.

MIL-T-24388B, 26 April 1979

Thermocouples and Resistance Temperature Elements. ...covers requirements for the design, manufacture, testing, and packaging of thermocouple and resistance temperature element assemblies for Naval ships and mounting hardware (but not thermowells). Temperature element: resistance - nickel, platinum; thermocouple - type K. Includes Qualified Products List, 16 December 1975.

MIL-L-24407, 22 December 1969
Liquid Level Transducer Equipment (Electrical) (Naval Shipboard Use). Cancelled 16 April 1979.

MIL-P-24423, 1 May 1970

Propulsion and Auxiliary Control Consoles and Associated Control and Instrumentation Equipment, Naval Shipboard Use, Basic Design Requirements. ...covers the basic general requirements applicable to the design, materials, construction, inspection, and operating conditions for automated or centralized propulsion and auxiliary control consoles together with their associated control and instrumentation equipment used for Naval shipboard service.

MIL-A-25719A, 8 July 1974

Accelerometer, Aircraft, Pilot's Warning, Type MA-1. ...covers one type of 1 7/8 inch dial, -2 to +4 g range accelerometer designated type MA-1. Includes Qualified Products List, 2 June 1978.

MIL-A-25915, 8 November 1957

Accelerometer, Aircraft, Pilot's Warning, Type MA-2. ...covers one type of 1 7/8 inch dial, -2 to +8 g range accelerometer, designated Type MA-2. Includes Qualified Products List, 2 June 1978.

MIL-A-25933, 20 August 1964

Altimeter, Pressurized Compartment, Integrally Lighted, 0-50,000 feet, 1 7/8 inch Dial. ...covers the requirements for a single pointer integrally lighted 0- to 50 000-foot range cabin altimeter, designated as AAU-3A/A. Includes Qualified Products List, 3 February 1976.

MIL-A-25949E, 25 April 1978

Accelerometer, Aircraft Range -5 to + 10 g, Integrally Lighted. ...covers integrally lighted -5 to +10 g range, aircraft accelerometer. ...(non-hermetically and hermetically sealed).

MIL-R-26474, 10 June 1959

Reliability Requirements for Production Ground Electronic Equipment. Cancelled - Superseded by MIL-STD-785.

MIL-R-26484A, 18 April 1960

Reliability Requirements for Development of Electronic Subsystems or Equipment. ...details the minimum requirements that must be followed by a contractor to assure the design of reliable equipment.

MIL-R-26667, 1 July 1963

Reliability and Longevity Requirements, Electronic Equipment, General Specifications. Superseded by MIL-STD-781.

MIL-R-27070, 25 March 1960

Reliability Requirements for Development of Ground Electronic Equipment. Superseded by MIL-STD-785.

MIL-A-27195, 27 May 1961

Accelerometer, Aircraft ABU-6/A. ...covers one type of integrally-lighted 1 7/8 inch dial, -2 to +8 g range accelerometer.

MIL-A-27261A, 8 November 1966

Accelerometer, Aircraft. ...covers integrally lighted 1 7/8 inch dial aircraft accelerometers having a range of -2 to +4 g. ...purpose: to indicate acceleration during maneuvers and in rough air ...Natural frequency 6 to 8 Hz and 0.5 to 0.7 critical damping ...operating temperature -62 to +71 °C.

MIL-R-27542A, 21 May 1963

Reliability Program for Systems, Subsystems, and Equipment. Superseded by MIL-STD-785.

MIL-T-28800B, 9 February 1976

Test Equipment for Use With Electrical and Electronic Equipment, General Specification for. ...describes the general requirements for test equipment used in testing electric and electronic equipment. The test equipment may be of military or commercial design and includes general purpose, special purpose, peculiar, console mounted, and automatic test equipment. This specification should also be used for built-in-test equipment (BITE) when the requirements for built-in-test are not included in the system specification. Detail requirements for a particular test equipment will be specified in a detail specification for that equipment.

MIL-P-38027A, 12 November 1973

Pressure Indicating System, Hydraulic A/A27J-1. ...covers one type of hydraulic pressure indicating system designated A/A27J-1. ...Range 0-4000 psi. ...Use indicating aircraft hydraulic system pressure.

MIL-A-38307, 31 July 1964

Accelerometer, Aircraft MX-6663/ATB-7. ...covers the requirements for one type of aircraft accelerometer design. ...is a component of the AN/AJB-1 computer set (MIL-C-38295) designed to sense aircraft acceleration normal to the longitudinal axis of the aircraft. ....consists of a spring supported mass and precision potentiometer pickoff enclosed in a sealed container. Range: linear acceleration 0 to 5 g; minimum natural frequency 8 Hz.

MIL-M-38510D, 31 August 1977

Microcircuits, General Specification for. ...establishes the general requirements for monolithic, multichip, and hybrid microcircuits and the quality and reliability assurance requirements which must be met in the procurement of microcircuits. Detail requirements, specific characteristics of microcircuits, and other provisions which are sensitive to the particular use intended shall be specified in the applicable device specification. Multiple levels of product assurance requirements and control for monolithic and multichip microcircuits and a single level for hybrid microcircuits are provided for in the specification.

MIL-T-38531, 15 March 1976

Transducer, Motional Pickup TR-299/G( ). ...establishes requirements for transducer motional pickup, TR-299/G( ), part of Alarm Set, Anti-Intrusion Restricted Area AN/GSS-26A. The transducer is a magnetic and seismic pressure sensitive cable suitable for burial under the surface of the earth where it detects magnetic and nonmagnetic disturbances caused by an intruder. Output = 1.00 ±0.05 mV pk-pk at specified frequency and magnetic fields. ...capable of withstanding 163 °C for 10 minutes during installation.

MIL-I-45208, 16 December 1963

Inspection System Requirements. ...establishes requirements for contractors' inspection systems. These requirements pertain to the inspections and tests necessary to substantiate product conformance to drawings, specifications, and contract requirements and to all inspections and tests required by the contract. These requirements are in addition to those inspections and tests set forth in applicable specifications and other contractual documents.

MIL-C-45662, 18 March 1960

Calibration of Standards. ...prescribes the minimum requirements for the calibration of standards which control the accuracy of inspection equipment used in contractor Inspection or Quality Control Systems established under the terms of specifications applicable to the contract.

MIL-G-45811B, 15 January 1974

Gage, Air, Low Presure, Pneumatic Floating Equipment. ...covers a direct reading gage calibrated to read air pressures up to 10 psi. (not electrical)

MIL-A-48515, 30 September 1974

Accelerometer, Integrating, Atomic Weapon, Training; M7. ...covers requirements, quality assurance provisions, and the preparation for delivery criteria for one type of integrating accelerometer assembly ...used with the Honest John warhead.

MIL-A-48734, 22 November 1974

Accelerometer, Integrating, Atomic Weapon: XM12. ...covers requirements, quality assurance provisions, and the preparation for delivery criteria for one type of accelerometer ...used with the Honest John warhead.

MIL-A-487333, 22 November 1974

Switch, Accelerometer, Atomic Weapon: XM49. ...covers requirements, quality assurance provisions, and the preparation for delivery criteria for one type of inertia-actuated, integrating electromechanical switch device ...used with the Honest John warhead.

MIL-A48799, 27 January 1975

Accelerometer, Integrating, M9. ...covers requirements, quality assurance provisions and the preparation for delivery criteria for one type of accelerometer ...which is used in the Sergeant warhead.

MIL-S-52868A, 11 January 1977

Sensor, Capacitance Proximity, DT-548/FSS-9(V). ...covers a capacitance proximity sensor designed to detect the presence of an intruder in close proximity to or in contact with protected metal objects. It is a component of the Joint-Services Interior Intrusion Detection System.

MIL-S-52871A, 10 March 1977

Sensor Group, Vibration: Detection DT-546/FSS-9(V) and Processor MX-9442/FS-9(V). ...covers a vibration signal detector and processor, which combine to form a vibration sensor designed to detect forcible entry through metal barriers placed over windows and ventilators. The sensor group is a component of the Joint-Services Interior Intrusion Detection System (J-S11DS). Appendix contains test methods to determine whether vibration sensors and major components procured under the specification conform to the requirements set forth.

MIL-A-81621, 25 February 1969

Accelerometer, Electrical, Linear ABU-13/A. ...The equipment covered by this specification shall operate as an acceleration sensor and electronic voltage multiplier. ...Service conditions: vibration - curves I & II of Mil-E-5400; temperature - -54° to +100 °C; shock - 25 g: acceleration (steady state) to 6 g.

MIL-P-82459, 28 July 1968

Pressure Transducer. ...covers requirements for the procurement of one type of pressure transducer. ...Range 0 to 500 psi; fluid - hydraulic oil, sea water, dry nitrogen. ...uses a potentiometer.

MIL-A-82516, 17 November 1967

Accelerometer. ...establishes requirements of one type of accelerometer. Range - 3 to 20 g; natural frequency 17 ±2 Hz.

MIL-E-82590, 9 September 1970

Environmental Requirements and Tests (for Torpedo Mk37 Components and Assemblies) establishes the environmental requirements and test procedures for all component parts and assemblies to be used in the torpedo Mk37. ...Non-operating temperature range +160 to -5 °F at 90-95 percent relative humidity; acceleration ±3 g at 30 to 100 kHz.

MIL-T-83460, 4 February 1975

Transducer, Motional Pick-up. ...covers a differential (airspeed) absolute (altitude) pressure transducer for aircraft application, designated TRU-164/A. Components: impact pressure transducer 0-42.938" Hg differential; static pressure transducer 31.019" - 0.810" Hg absolute. Output 0-5 V dc. Input from pitot tubes. Application: with airborne recording system measuring flight parameters relating to aircraft structural loads.

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9.1 References

Note: U. S. Government publications may be obtained from the National Technical Information Service (NTIS), U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151 (Tel. (703) 321-8507); or from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402.

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9.2 Bibliography of Sensor-Related Books

A number of books dealing with sensor-related subjects exist and it seemed worthwhile to attempt to review a number of them to provide information on their potential benefits and deficiencies to the user of the Sensor Handbook. There are some books, particularly those intended as college texts of an introductory nature, which are somewhat similar and it would be difficult to rank them qualitatively. The author feels that such an approach is not desirable, since, first of all, ease of information transfer between book and reader is quite subjective and, secondly, the incremental costs of additional reference books on any given aspect of measurement engineering and systems are probably negligible compared to the costs of the systems to be designed or selected.

The books are reviewed in the following section:

Hix, F. F., Jr., and Alley, R. P., Physical Laws and Effects, New York, John Wiley & Sons, Inc., 1958, 291 pages

This book is a compilation of some 300 physical effects and laws, where effects are "observed reactions in nature to certain stimuli," and laws are the more formalized and generalized descriptions of such effects. All transduction principles are based on such laws, and this listing may help stimulate possible new approaches to the solution of difficult measurement problems. The effects listed, while aimed at new applications, may also suggest positive pitfalls in measurement situations. Each law or effect is treated briefly and succinctly, usually with one or more references listed, from which additional details can be obtained.

Although of little direct assistance to the planners or users of practical ATE or measurement systems, it has good potential for the stimulation of research beyond the present state-of-the-art of sensing or control.

Lion, Kurt, Instrumentation in Scientific Research, New York, McGraw-Hill Book Company, Inc., 1959, 324 pages.

This book attempts to offer a reasonably complete collection of the existing basic methods and systems used as "input transducers" in electrical instrumentation. In this case input transducer is defined as a device which converts a non-electrical quantity into an electrical signal, e.g., a sensor. The book is intended to furnish a general coverage of the field with emphasis on simple descriptions of the physical mechanisms and principles of the sensing devices. Carefully selected references can give further detailed information.

The book is divided into chapters on: Mechanical Input Transducers (linear dimensions, force, velocity, level, pressure, flow and humidity), Temperature Transducers, Magnetic Transducers, Electrical Transducers, and Radiation Transducers.

The emphasis in this reference, which represents the state-of-the-art of instrumentation of about 1955 to 1957, is on the basic physics or mathematics of metrology. Hence there is little detailed information on applications, environment, calibration considerations, or ancillary equipment. The book is thus primarily a good basic reference for students and designers and of less help to the special application needs of systems procurement or testing.

Beckwith, T. G. and Buck, N. L., Mechanical Measurements, Reading, MA, Addison-Wesley, 1961, 316 pages

This book has two major parts: fundamentals of mechanical measurements and applied mechanical measurements. The first part approaches measurements from a general standpoint dividing measuring systems into function groups. It discusses possibilities and inherent limitations of each measuring system as well as standards and dynamic responses. The second part is devoted to a presentation of applications and techniques for special mechanical quantities. Only such electrical matters as apply to the problem being considered are discussed.

The chapters include: The Significance of Mechanical Measurements, The Generalized Measurement System, Basic Standards and Accuracy of Measurement, Characteristics of Dynamic Signals, Basic Detector-Transducer Elements, Intermediate Modifying Systems, Terminating Devices and Methods, Determination of Count, Events per Unit of Time and Time Interval, Displacement and Dimensional Measurement, Strain Measurement, Measurement of Force and Torque, Measurement of Pressure and Flow, Temperature Measurement, Vibration and Acceleration Measurement, Vibration and Shock Testing, and Application of Radioactive Isotopes to Mechanical Measurements.

The book is intended as an introduction to measurement problems for students and engineers and assumes a good general background in the elements of mechanical engineering and mathematics. It is well written and illustrated.

Cook, N. H. and Rabinowicz, E., Physical Measurement and Analysis, Reading, MA, Addison-Wesley Publishing Co., 1963, 311 pages.

The aim of this book is to make mechanical engineering students aware of the principles underlying physical measurements, stressing pitfalls and limitations of such measurements. The dynamic and statistical points of view are emphasized.

Chapters include: Experiments and Measurements, (Introduction), Experimental Statistics, Dynamics of Measurement, Displacement Measurement, Force and Torque Measurement, Temperature Measurement, Measurements on Fluids, and Radiotracing Techniques.

The philosophy of measurement error assessment and considerations of the dynamic nature of measurement are treated extensively and well. These two chapters make this a useful reference for designers and users of sensor-based measurement systems.

Neubert, H. K. P., Instrument Transducers, An Introduction to Their Performance and Design, Oxford, Oxford University Press, 1963, 390 pages.

This book is devoted to the basic principles of performance and design of instrument transducers with emphasis on the primary sensing element.

Chapters include: Classification of Instrument Transducers, Mechanical Input Characteristics, Electrical Output Characteristics, and Force-Balance Type Transducers. The author's introduction indicates that the coverage is restricted to those transducer types for which a sufficiently advanced technology had been developed by 1963, thus excluding piezo-resistive devices. Also excluded are thermocouples, microphones, and photocells, which are extensively covered in other publications.

The book specifically excludes chapters on calibration methods and environmental testing with the statement that a single chapter cannot do justice to those subjects.

Despite its stated limitations, this is also a fundamental and useful reference on sensors in general.

Norton, H. N., Handbook for Transducers for Electronic Measuring Systems, Englewood Cliffs, NJ, Prentice-Hall, 1969, 704 pages.

This book is intended not only for transducer designers and manufacturers but also for those who select, purchase, test and use transducers. It can also be used as a textbook. Chapters include: Electronic Measuring Systems, Transducers, Transducer Performance Determination, Acceleration, Attitude, Displacement, Flow, Force and Torque, Humidity and Moisture, Light, Liquid Level, Nuclear Radiation, Pressure, Sound, Speed and Velocity, Strain and Temperature.

The author in his preface makes a statement about this book which, in the opinion of this reviewer, is so generally applicable to the entire field of sensors that it is quoted below in its entirely:

> "Finally, a word of caution must be directed to the reader regarding the use of transducers and their associated measuring systems. The prime purpose of this book is to describe transducers, not measuring techniques. Although a number of relatively straightforward measurement problems can be solved solely on the basis of the material presented here, most successful transducer applications require considerable additional training and experience in measurement engineering, and a solid education foundation in the physical sciences relating to the measurands. Practical experience, often gained by discovering one's own mistakes, is probably the best road towards obtaining valid data from transducer installations."

The book addresses calibration methods, error analysis, and environmental considerations, although not with the detail which is required for a really thorough understanding of sensor performance characteristics in actual measurement systems. But then no such reference, as yet, has been found that meets these needs adequately.

Oliver, Frank J., Practical Instrumentation Transducers, New York, Hayden Book Company, Inc., 1971, 340 pages.

This is a guide to transducer selection and application with a comprehensive survey of physical-to-electrical transducers and their associated signal conditioning circuits for use in measurement and control systems. It describes and illustrates diagrammatically the basic operational principles, practical manifestations, and units of measurements of transducers for industrial and aerospace applications. Included are such topics as interference problems in hard wire telemetry systems, and transducers as feedback devices in solid-state systems. Chapter headings include: Transducer Fundamentals and Physical Effects, Evaluation and Calibration of Transducers, Measurement of Strain, Force, Load and Torque, Measurement of Linear Displacement and Thickness, Angular Position, Shaft-angle Encoders, Measurement of Rotary Speed, Measurement of Vibration and Shock, Measurement of Fluid Pressure, Temperature Measurement, Radiation Detectors, Measurement of Moisture, Humidity and Dewpoint, Measurement of Flow, Measurement of Liquid and Dry Bulk Level, Low Level Transducer Signal-Conditioning Circuits, and Interference in Transducer Signal Channels.

The treatment is quite thorough for physical quantities although electrical and magnetic quantities are not included among the sensor principles and types. Caution must be exercised as far as accepting statements of achievable accuracy in application examples. The state-of-the-art changes sufficiently rapidly that the most recent literature and manufacturers' data should always be consulted prior to any final system design, application, or procurement decision.

The treatment of environmental effects on sensor performance and the coverage of calibration considerations is not sufficiently adequate to be of much use. Nevertheless, this book is a generally good and important reference for those who design, specify, procure, test, or install sensor-based measuring systems.

Harvey, G. F., Editor, ISA Transducer Compendium, Parts 1, 2, 3, New York, IFI/Plenum Press, 1969, 212, 325, and 277 pages.

This publication was designed to be a centralized source of transducer information, based on an extensive survey of manufacturers of sensors. It is restricted to sensors with electrical output and presents extensive product information classified by the measurand. For each sensor class or type, information was sought on such characteristics as range, operating principle, output, error, natural frequency, operative life, etc. Photos of most of the sensors appear as well as a listing of sensor manufacturers.

The publication is in three parts, and the information in each part is arranged in tabular form by measurand and by range. Part 1 covers Pressure, Flow and Level; Part 2 covers Motion, Dimension, Force and Torque, and Sound; Part 3 covers Temperature, Chemical Composition, Physical Properties, Humidity and Moisture, and Radiation. Each measurand section is preceded by an introductory text dealing with such topics as: Units, Ranges, Sensing Techniques, Transducer Selection and Use, Evaluation and Consideration, Current Problems and Future Trends, and References.

Its outstanding feature is the easy-to-use tabular array that enables the user to find quickly a commercial sensor to meet particular requirements. A great deal of useful information is given for most sensors. The introductory chapters in each section are fairly brief, providing a good overview for the neophyte, but not giving enough application details for this compendium to serve as the sole sensor reference.

The principle limitation of the compendium is that most of the detailed information on sensors listed is obsolete. This is inevitable with any treatment of this type which attempts to survey the current state-of-the-art.

It nevertheless serves a very useful function by indicating the type of sensors available (at least in 1969) for most measurands, an indication of the performance characteristics obtainable, and the listing of transducer manufacturers. Consequently, consultation of the compendium should make it relatively easy to take a fast cut at picking a likely sensor for most applications, and then verifying its availability and characteristics from the manufacturer. By necessity, certain more recent developments would not be included, as might some manufacturers.

On balance, while it does not present today's state-of-the-art by giving a comprehensive coverage of the state-of-the-art of 1969, the ISA Compendium serves as a very useful reference foundation.

O'Higgins, P. S., Basic Instrumentation-Industrial Measurement, New York, McGraw-Hill Book Company, 1966, 495 pages.

This book is written primarily as a textbook for students of the fundamentals of the theory and practices of industrial process control instrumentation. It is divided into chapters on: Art and Science of Measurements, Dimensional Analysis and Engineering Units, Measurement of Weight, Density, and Specific Gravity, Basic Concepts of Pressure Measurements, Fluid Pressure and Vacuum Measurements, Level Measurements of Liquids and Solids, Viscosity Measurement, Fluid Flow Measurement, Temperature Measurement, Art and Science of Instrumentation, Applied Electricity and Measuring Circuits, Fundamental Electrical Measuring Instruments, Basic Electronics for Instrumentation, Electrical Transducers, Humidity, Dew-Point and Moisture Measurement, and Electrochemical Measurements.

There is almost nothing on calibration and operating environments in this treatment, and its main usefulness is in introducing the concepts of industrial process control measurements to technical people with a background knowledge of basic physics and mathematics.

Wightman, E. J., Instrumentation in Process Control, Cleveland, The Chemical Rubber Press, 1972, 367 pages.

This book deals specifically with the problems associated in the gathering of data from physical processes. Methods are outlined by which it is possible to relate transducers and their characteristics to digital data processing techniques which utilize the measurements obtained in control applications for industrial processes.

Chapters include: Transducer Performances, Temperature Measurement, Pressure Measurement, Liquid Density Measurement, Displacement Measurement, Application of A-D Conversion, Computing Corrections, Data Transmission, and Digital Control Techniques.

Although the book is aimed at process control applications, its extensive treatment of signal processing considerations makes it a useful reference for other instrumentation systems as well. Calibration considerations are treated separately; environmental effects not touched upon.

Soisson, H. E., Instrumentation in Industry, New York, John Wiley & Sons, 1975, 561 pages.

This book is intended to be a broad survey of industrial instrumentation, including general principles of operation and a brief coverage of operational characteristics. It provides a basic description of the theory and instrument function, a discussion of measurement and response limitation calibrations of the instruments, and an analysis of the success of the industrial process or operation in maintaining a quality product.

Chapters include: How Instruments are Used in Industry, Instrument Standards and Calibrations, Pressure and Vacuum, Thermometers, Pyrometry, Liquid and Dry Level Instrumentation, Flow Instrumentation and Measurement, Automatic Measurement and Control Concepts and Systems, Analytical Industrial Instrumentation, Radiation Measurement and Instrumentation, Nondestructive Testing Equipment, and Environmental and Pollution Measurements.

Heavily oriented toward process industries, this book touches calibration only lightly and operating environments not at all. It can serve as a moderately useful introduction to the field of instrumentation and sensors.

Doebelin, E. O., Measurement Systems: Application and Design, McGraw-Hill Book Company, Revised Edition, 1975, 772 pages.

Although this book is designed for use in connection with university courses in mechanical engineering, it can serve as a useful reference to the practicing engineer. The author, in his preface, describes the contents of the text as follows:

"Consideration of measurement as applied to research and development operations and also to monitoring and control of industrial and military systems and processes.

"A generalized treatment of error-compensating techniques.

"Treatment of dynamic response for all types of inputs: periodic, transient, and random, on a uniform basis, utilizing frequency response.

"Detailed consideration of problems involved in interconnecting components.

"Discussion, including numerical values, of standards for all important quantities. These give the reader a feeling for the ultimate performance currently achievable.

"Quotation of detailed numerical performance specification of actual instruments.

"Inclusion of significant material on important specific areas such as sound measurement, heat-flux sensors, gyroscopic instruments, hot-wire anemometers, digital methods, random signals, mass flow meters, amplifiers and the use of feedback principles."

Significantly, there is no consideration of operation in harsh environments or durability and reliability aspects of sensor applications. Despite this, the book is a fairly comprehensive reference on measurement.

Holman, J. P., Experimental Methods for Engineers, McGraw-Hill Company, Third Edition, 1978, 490 pages.

This book is designed as a first survey of experimental methods for undergraduate students. The author recognizes that this book may be lacking in depth in certain topics and includes references to more detailed coverages. It deals primarily with the theoretical basis of measurements and measurement systems. Its chapters include: Basic Concepts, Analysis of Experimental Data, Basic Electrical Measurements and Sensing Devices, Displacement and Area Measurements, Pressure Measurement, Flow Measurement, The Measurement of Temperature, Thermal- and Transport-Property Measurements, Force, Torque, and Strain Measurements, Motion and Vibration Measurements, Thermal and Nuclear-Radiation Measurements, Air-Pollution Sampling and Measurement, and Data Acquisition and Processing.

It represents an average textbook-style treatment of the subject.

Harris, C. M., and Crede, E. E., Shock and Vibration Handbook, McGraw-Hill Book Company, Second Edition, 1976, 1322 pages.

This is undoubtedly the most comprehensive and authoritative reference on classical vibration theory and its modern applications. This one-volume handbook covers fundamentals, instrumentation and measurements, data analysis and testing, practical methods of control solutions to engineering problems, equipment design and packaging, and the effects of vibration on people.

It contains 44 chapters written by 54 authorities from industry, government, and universities. The second edition contains three totally new chapters on vibration standards, environmental specifications and testing, and applications of digital computers.

It is the outstanding coverage of the subject of shock and vibration.

Considine, D. M., Editor, Handbook of Applied Instrumentation, New York, McGraw-Hill Book Company, 1964, 1167 pages.

This book, in conjunction with its companion, "Process Instruments and Controls Handbook," was intended as a "complete compendium on the subject." The book, as stated in the foreword, is directed to a variety of users: the manufacturing, process, and instrumentation engineer who analyzes the needs and benefits of instrumentation and selects or designs the equipment for the particular application, the instrument and control user who desires knowledge about these devices, the management person who desires to comprehend instrumentation to take full advantage of its potentialities in achieving management objectives, the student, the educator, and finally the instrument technician.

The book is arranged into seventeen major sections covering general principles of instrumentation, the measurement of a variety of measurands, controls and their applications, and instrumentation practices in a variety of industries. Sections include: Definition and Classification of Variables, Measurement Errors, Factors in Selection of Measuring Methods, Temperature Calorific Value, Radiation Fundamentals, Nuclear-Radiation Detectors, Radioisotopes in Instrumentation, Photometric Variables, Acoustic Measurements, Force Measurement, Pressure and Vacuum Measurement, Flow, Acceleration Measurement, Speed Measurement, Weight and Weight Rate of Flow, Liquid Level, Solids Level, Parts Dimension Measurement and Control, Thickness Measurement of Sheet and Web Materials, Position Measurement and Control, Fluid-Density and Specific-Gravity Measurement, Humidity and Dew Point, Moisture Control of Materials, Viscosity and Consistency, Analysis Instruments, Electrical Variables, Fundamentals of Automatic Control Engineering, Application of Photoelectric Controllers, Controller Types and Final Control Elements, Applications of Analog Computers, Application of Digital Computers, Instrumentation Data Processing, Counters and Digital Indicating Devices, Steel Production Instrumentation, Glass and Ceramics Industries Instrumentation, Instrumentation Practices in the Process Industries, Instrumentation of Heat Exchangers etc., Pulp and Paper Production Instrumentation, Food-Industry Instrumentation, Automatic Combustion Control Systems for Boilers, Steam Power Plant Instrumentation, Electric Power Generation and Distribution Control, Nuclear Reactor Instrumentation, Process Laboratory Instrumentation, Pilot-Plant Instrumentation, Environmental Test Instrumentation, Aircraft and Aerospace Vehicle Instrumentation, Aircraft-Flight Simulation Instrumentation, Basic Electricity and Electronics for Instrumentation Engineers, Preparation of Wiring Diagrams for Instrumentation Applications, Instrument Panel Board Design and Construction, and Instrument Air Supplies.

The individual sections of the book were written by experts in the particular subjects and represent an earnest attempt to cover the field briefly but with appropriate thoroughness.

Unfortunately, attempts to cover all of an enormous subject for a wide range of interested readers and users rarely succeed. This book is no exception. It is also inherent to this type of treatment that it is always out-of-date in an area of rapidly developing technology. This is not to totally condemn this kind of book; it does present a fairly complete, though dated, coverage of the field and thus provides a useful foundation and background reference.

Woolvet, G. A., Transducers in Digital Systems, Stevenage, England, Peter Peregrinus, Ltd., 1977.

This book presents a survey of transducers that give a digital output and which are used mainly in computer-based systems for which a digital output is required. The author points out that there appear to be no natural phenomena that provide digitally coded outputs in response to variations of a physical quantity. The possible exceptions are devices that produce a variable frequency. The book describes the latter, as well as systems which convert analog signals into digital ones.

There are chapters on: Digital Systems, Angular Digital Encoders, Frequency Dependent Transducers, Digital Linear Transducers, Analog Conversion Methods, Syncho-Resolver Conversion, and other Techniques.

The usefulness of this book is in its coverage of digitizing sensors for analog quantities. This information is most useful in supplementing earlier treatments of transducers with analog outputs.

Liptak, Bela G., Editor, Instrument Engineers Handbook, Volume 1, Process Measurement, Chilton Book Company, Philadelphia, PA, 1969.

This handbook is intended as a reference for the broad field of process instrumentation and aimed at process control loops specifically. The first volume is concerned with the measuring element (sensor), the second volume deals with other loop components (controllers, final control elements, and supervisory hardware) as well as control systems. The purposes of the book are to help the reader look for design features, make him aware of limitations, and help him decide on the type of instrument for a specific application.

The process variables covered by this handbook include: Level, Pressure, Density, Temperature, Flow, Viscosity and Weight. Analytical Sensors (such as for ph, Moisture Detection, Turbidity and Chromatography) are covered in a separate chapter. At the end of each chapter is a section titled "Conclusions." It is designed to guide the reader in the selection of sensors. The section on pressure states in the "Conclusions", "... care is to be taken in considering vibration, freezing, corrosion, temperature and hard-to-handle fluids." The introductory discussion on Measurement Accuracy and Sources of Error is of the same unsatisfactory brevity.

The general subject of calibrations is not discussed at all, nor is the measurement of motion (displacement, velocity, acceleration).

A large number of tables containing conversion factors, properties of gases, steam, flowmeter parameters, and others would be of use for process control system designers and users.

This is another of several references examined for the Sensor Handbook bibliography section, which while possessing some useful information, unfortunately lacks other equally needed information to serve as a comprehensive reference.

Moore, R. L., Basic Instrumentation Lecture Notes and Study Guide: Measurement Fundamentals, Instrument Society of America, 67 Alexander Drive, Research Triangle Park, NC 27709, Second Edition, 1976.

The guide contains descriptions of the working principles of measuring instrument for a variety of parameters. After a brief introduction to measurement fundamentals, there are chapters on Measurements of: Pressure, Level, Weight, Density, Flow, Temperature, Heat Flux, Humidity and Moisture, and Physical and Chemical Measurements. Some application information is included as guidelines for application. The manufacturer's information on a given device is typical for that device; no attempt has been made to include material from all manufacturers. The ISA Transducer Compendium is intended to serve as an adjunct to the guide.

The guide is intended for teaching purposes, to be supplemented by additional texts suggested by the instructor. A large number of references is given. The treatment, while intended to be general, appears aimed at process industry applications. Significantly, vibration and force measurements are not covered.

There is no discussion of calibration and evaluation methods, environmental conditions, signal conditioning, or data reduction considerations. The treatment is not complete enough to serve as sole source, but does provide some information which may be useful.

Anon., Training Manual: Physical Measurements, Navy Metrology Calibration Program, Pomona, CA 91766, Navair 17-35QAL-2, Revision 3, June 1979.

This is an illustrated, elementary treatment of physical measurement principles. It includes a large number of sample numerical problems in all chapters, as well as practice problems at the end of each chapter. Chapters include: Introduction to Measurements, Physical Concepts, Electrical Indicating Devices, Errors, Temperature, Humidity, Force, Torque, Rotational Measurement, Mass, Weight and Balances, Pressure, Vacuum, Viscosity and Specific Gravity, Fluid Flow, and a chapter on Pressure and Flow Fittings and Tubing. Vibration has been omitted.

While principles of measurement are covered, sensors with electrical outputs are only sometimes discussed specifically. There is a table of contents, but no index or list of references. The manual is presumably intended for training purposes, but there is no foreword to indicate this.

Anon., Suggestions for Designers of Navy Electronic Equipment, NOSC TD 250, 1979 Edition, Naval Ocean Systems Center, San Diego, CA 92151, 147 pages.

This booklet is designed to serve as a checklist for engineers during the development of naval electronic equipment. The objectives are to save engineering, development, and testing time and effort, and to increase operational availability of better electronic equipment. The intent is to alert the designer to possible trouble spots in his design, or to areas of conflict outside his realm of expertise or specialization.

The booklet has chapters on: Physical Characteristics, Maintainability, Environmental Conditions, Thermal Design, Materials, Processes and Parts, Electromagnetic Compatibility, Safety, and Human Engineering.

While the material is intended for equipment developed for the Naval Material Command, most of it applies to all types of military equipment. Although sensors are not specifically monitored, many of the considerations listed are applicable to sensors. Pertinent military standards and specifications are referenced.

A very comprehensive and useful treatment, this booklet should be consulted by all engineers concerned with ATE equipment design and procurement.

Benedict, R. P., Fundamentals of Temperature, Pressure and Flow Measurements, Second Edition, New York, John Wiley & Sons, 1977, 517 pages.

This book is intended as a working reference for practicing engineers and associated workers involved in the measurement of temperature, pressure, and flow rate and as a text for engineering students. It provides a review of measurement techniques and includes practical data. Applications are illustrated by practical, worked-out, numerical examples.

Chapters include: Early Attempts to Measure Degrees of Heat, The Air Thermometer, Thermodynamic View Points of Temperature, The International Practical Temperature Scale, Liquid-in-Glass Thermometers, Resistance Thermometer, Thermoelectric Thermometry, Optical Pyrometry, Calibration of Temperature Sensors, Uncertainties and Statistics, Temperature Measurement in Moving Fluids, Installation Effects on Temperature Sensors, Transient Temperature Measurements, The Concepts of Pressure, Pressure Standards, Principles of Conventional Pressure Transducers, Pressure Measurement in Moving Fluids, Transient Pressure Measurement, The Concept of Flow Rate, Open-Channel Flow, Theoretical Rates in Closed-Channel Flow, the Discharge Coefficient, The Expansion Factor, and Installations and Uncertainties.

This book covers the theoretical measurement considerations for temperature, pressure, and flow extremely well. Other measurands are not covered at all.

There is also a good deal of practical application information. There is little coverage of calibration and evaluation of sensors or environmental effects. Despite this lack, it is one of the best treatments of the measurements of the three parameters.

Ferson, L. M., Standards and Practices for Instrumentation, Sixth Edition, Instrument Society of America (ISA), Research Triangle Park, NC, 1980, 600 pp.

This book provides complete texts of all current ISA Standards and recommended practices; titles and abstracts for over 900 instrumentation-related standards published by other U.S. and international organizations; and a subject index, cross-references to the over 900 titles and abstracts.

This is an extremely useful comprehensive listing of existing civilian standards documents in the general field of instrumentation. Existing sensor standards are included. ISA intends to up-date this volume at three or four-year intervals.

One of its good features is the listing of all (as far as known) organizations and their addresses, enabling users of the handbook to easily obtain up-to-date information on new standards or those under development. A very valuable reference.

10. GLOSSARY

To facilitate understanding and the interchange of information, a glossary of selected terms is included in this handbook. Most of the terms listed apply to sensors, although other areas such as ATE systems and reliability are also represented. The sensor terms are largely taken from ANSI and ISA Standards, particularly ANSI MC6.1-1975 (ISA S 37.1) "Electrical Transducer Nomenclature and Terminology." Additional terms were taken from MIL-STD-1309C (15 April 1980) "Definitions of Terms for Test, Measurement, and Diagnostic Equipment."

A Note of Caution: The terminology of any specialized field should be used with caution. Often terms may have a somewhat different meaning in a related field. In critical documents, it may be desirable to cite the entire definition following the term itself, to preclude possible misunderstandings.

-A-

Absolute Pressure -- Pressure referenced to a vacuum.

Acceleration Error -- The maximum difference, at any measurand value within the specified range, between output readings taken with and without the application of a specified constant acceleration along a specified axis.

Acceleration Function -- The relation between measured amplitude and frequency normally encountered by a sensor and the corresponding values specified in an accelerated life-test for the sensor.

Acceleration Limit -- The maximum vibration and shock acceleration which an acceleration sensor can accept in either direction along its sensitive axis without permanent damage, usually stated as $\pm$ ___ g's. The acceleration limits are usually much wider than the acceleration range and represent the overload capability of the sensor.

Acceptable Quality Level -- The quality standard associated with a given producer's risk prescribed by the customer or quality engineer for the products on order. It is usually expressed in terms of percent defective per hundred units.

Accuracy -- The ratio of the error to full-scale output or the ratio of the error to measurand output, as specified, expressed in percent. Accuracy may also be expressed in units of the measurand. The term accuracy should not be used in specifications; the term error is preferred.

Acoustic Sensitivity -- The output of a sensor in response to a specified acoustical environment. This is sometimes expressed as that measurand value sufficient to produce the same output as that induced by a specified sound pressure level spectrum having an overall value of 140 dB referenced to 0.0002 dyne per square centimeter rms.

ADC -- Abbreviation for analog-to-digital converter.

Algorithm -- A method of algebraic or numerical computation; in computer terminology, a detailed, logical procedure for the solution of a particular problem.

Aliasing Error -- Errors caused in fast fourier transform analysis by an insufficiently high rate of sampling of frequencies of interest.

Ambient Conditions -- The conditions (pressure, temperature, etc.) of the medium surrounding the case of a sensor.

Ambient Pressure Error -- The maximum change in output, at any measurand value within the specified range, when the ambient pressure is changed between specified values.

Amplification Factor at Resonant Frequency -- The ratio of the sensitivity of a sensor at its resonant frequency to its reference sensitivity. Amplification factor at resonant frequency is sometimes referred to as "Q."

Analog Output -- Sensor output which is a continuous function of the measurand, except as modified by the resolution of the sensor.

AQL -- Abbreviation for "acceptable quality level."

Arrhenius Law -- The table which relates the rate of a chemical reaction to an exponential function of temperature.

ATE -- Abbreviation for "automatic test equipment."

Attitude Error -- The error due to the orientation of a sensor relative to the direction in which gravity acts upon the sensor. (See acceleration error)

Automatic System -- A system in which the operations are performed by electrically controlled devices without the intervention of operators.

Automatic Test Equipment -- An equipment that is designed to automatically conduct analyses of functional or static parameters, evaluate the degree of performance degradation, and isolate faults in malfunctioning units. The decision making, control, and evaluative functions are conducted without reliance on human intervention.

Automation -- The investigation, design, development, and application of methods of rendering processes automatic, self-acting, or self-controlling.

-B-

Back Pressure -- The absolute pressure level measured four pipe-diameters downstream from a turbine flowmeter under operating conditions expressed in Pa (or psi).

Bellows -- A series of capsules used in pressure measurement.

Berkson's Premise -- The assumption that the independent variable in a planned experiment is without error when it is carefully set to a preassigned value.

Bernoulli's Theorem -- Within an incompressible fluid under conditions of steady flow, the sum of the energy of velocity, energy of pressure, and potential energy of elevation remain constant; therefore, if the velocity of a fluid in a horizontal tube increases, the pressure must decrease, and vice versa.

Best Straight Line -- A line midway between the two parallel straight lines closest together and enclosing an output vs measurand values on a calibration curve.

BITE -- Abbreviation for "built-in test equipment."

Bourdon Tube -- A curved or twisted tube whose end rotates when pressure is applied to the inside of the tube.

Boxcar Filter -- Ideal electrical filter with flat amplitude and linear phase response and with infinite attenuation at frequencies beyond design filter limits.

Built-in Test Equipment -- Any device which is functionally separate from, but permanently connected to, the prime equipment and used for the express purpose of testing the prime equipment. (See "BITE")

Burn In -- The operation of components or units prior to their ultimate application intended to stabilize their characteristics and to identify early failures.

-C-

Calibration -- A test during which known values of measurand are applied to a sensor under specified conditions and the corresponding output readings recorded.

Calibration Curve -- A graphical representation of the calibration cycle.

Calibration Cycle -- The application of known values of measurand and the recording of corresponding output readings over the full (or specified portion) range of a sensor in an ascending and descending direction.

Calibration Interval -- The specified time interval between calibrations needed to assure knowledge of effects of time and use on the performance characteristics of the sensor.

Calibration Traceability -- The ability to compare a sensor calibration, through a specified step-by-step process, with an instrument or group of instruments calibrated by the National Bureau of Standards. The estimated error incurred in each step must be known.

Calibration Uncertainty -- The maximum calculated error in sensor output due to causes not attributable to the sensor.

Capsule -- An enclosure made up of two corrugated diaphragms used in pressure measurement.

Center of Seismic Mass -- The point within an acceleration sensor where acceleration forces are considered to be summed.

Checkout Equipment -- See test equipment.

Compensation -- Provision of a supplemental device, circuit, or special materials to counteract known sources of error.

Completion Network -- Passive components, external to a sensor, which complete the electrical network to form a complete bridge or similar array to enhance signal conditioning.

Condition Monitoring -- Monitoring performed to assess the functional state of equipment(s) by measurement of selected static and dynamic physical characteristics.

Corrective Maintenance -- Maintenance performed to restore a failed or degraded equipment. Corrective maintenance includes fault isolation, repair or replacement of defective units, alignment, and checkout.

Creep -- Change in output occuring over a specified time period while the measurand and all environmental conditions are held constant. (See also "drift")

Critically Damped -- See damping.

-D-

Damping -- The energy-dissipating characteristic of a sensor which, together with its natural frequency, determines the limit of frequency response and the response time characteristics. In response to a step function of measurand, an underdamped (periodic) system oscillates about its final steady-state value before coming to rest at the value, an overdamped (aperiodic) system comes to rest without overshoot, and a critically damped system is at the point of change between the underdamped and overdamped conditions.

Damping Ratio -- The ratio of the actual damping to that required for critical damping. (See "Damping")

DAS -- Abbreviation for "data acquisition system."

Data Reduction -- The process of transforming masses of raw or experimentally obtained data, usually gathered by instrumentation, into useful, ordered, or simplified intelligence.

Dead Volume -- The total volume of the pressure port cavity of a pressure sensor with room barometric pressure applied.

Defect -- A characteristic which does not conform to applicable specification requirements and which adversely affects or potentially affects the quality of a device.

Degradation -- Gradual deterioration in performance as a function of time.

Derating -- The intentional reduction of stress/strength ratio in the application of an item, usually for the purpose of reducing the occurrence of stress-related failures.

Diagnostic Phenomenon -- A physical event or condition reflecting or relatable to the functional condition of an equipment component.

Dielectric Withstand Voltage -- The limiting voltage used to specify the ability of insulated portions of a sensor to withstand a specified overvoltage for a specified time without arcing or conduction above a specified current value across the insulation.

Diffuse-Field Response -- Frequency response of a piezoelectric sound-pressure sensor with the sound incident from random directions.

Digital Output -- Sensor output that represents the magnitude of the measurand in the form of a series of discrete quantities or steps. (See analog output)

Dither -- The application of intermittent or oscillatory forces just sufficient to minimize static friction within a sensor.

Doppler Effect -- The apparent change in frequency caused by relative motion between the frequency source and the observer.

Downtime -- The period of time during which an item is not in a condition to perform its intended function.

D/P -- Abbreviation for "differential pressure."

Drift -- An undesired change in output over a period of time, which change is not a function of the measurand. (See also "creep")

Durability -- The ability of a sensor to continue to perform its measurement function in adverse environments and over an extended period of time. (See "stability" for quantitative description of durability.)

Dynamic Calibration -- A calibration performed under room conditions and in the absence of any vibration or shock, unless the latter is the measurand. The applied measurand varies with time in a prescribed manner during the calibration.

Dynamic Characteristics -- Those characteristics of a sensor which relate to its response to variations of the measurand with time.

-E-

Electromagnetic Field Sensitivity -- The maximum output of a sensor in response to a magnetic field of specified amplitude and frequency; usually expressed in gauss equivalent to a stated fraction of the measurand.

End Points -- Sensor outputs at the upper and lower limits of the specified range.

End-Point Line -- The straight line between the end points.

End-to-End Calibration -- A calibration during which a known actual or simulated measurand input is applied to a sensor and the corresponding system output recorded.

Environmental Conditions -- Specified external conditions (shock, vibration, temperature, etc.) to which a sensor may be exposed during shipping, storage, handling, and operation.

Environmental Conditions, Operating -- Environmental conditions during operation during which the sensor must perform in some specified manner.

Error -- The algebraic difference between the indicated value and the true value of a measurand, usually expressed in percent of full-scale output, but some times expressed in percent of the output reading of the sensor.

Error Band -- The band of maximum deviations of output values from a specified reference line or curve due to causes attributable to the sensor. The error band should be specified, and verified, over at least two calibration cycles so as to include repeatability. The band of allowable deviations is usually expressed as ± ___ percent of full-scale output (%FSO), whereas in test and calibration reports the band of maximum actual deviations is expressed as + ___ percent, - ___ percent of full-scale output.

Excitation -- An external electrical voltage or current required for the proper operation of a sensor, as distinguished from the measurand which is the physical quantity to be measured.

Failure -- Termination of the ability of an item to perform its required function.

Failure Analysis -- The logical, systematic examination of an item or its diagrams(s) to identify and analyze the probability, causes, and consequences of potential or real failures.

Failure, Catastrophic -- Failures that are both sudden and complete.

Failure Mode -- The way in which a unit, equipment, or system deteriorates, malfunctions, or fails.

Failure, Random -- Any failure whose cause and/or mechanism make its time of occurrence unpredictable, but which is predictable in a probabilistic or statistical sense.

Failure Rate -- The number of failures of an item per unit measure of life (time, cycles, etc.). During the useful life period, the failure rate is considered constant.

Failure, Wearout -- A failure that occurs as a result of deterioration processes or mechanical wear and whose probability of occurrence increases with time.

Fault -- An attribute which adversely affects the reliability of a device.

FDM -- Abbreviation for "frequency division multiplex."

Floating Point -- A method used by computers to preserve the significant figures in a number by writing the numbers as a decimal fraction multiplied by a power of ten.

FM -- Abbreviation for "frequency modulation."

Free-Field Frequency Response -- The ratio, as a function of frequency of the output of a sound-pressure sensor in a sound field to the sound pressure existing at the sensor location in the absence of the sensor.

Frequency Division Multiplex -- A method of transmitting data from multiple sources over the same link by assigning a different frequency to each source.

Frequency, Natural -- The frequency of free (not forced) oscillations of the sensing element of a fully assembled sensor; also defined as the frequency of a sinusoidally applied measurand at which the sensor output lags the measurand by 90 degrees.

Frequency Output -- Sensor output in the form of a frequency which varies as a function of the applied measurand (e.g. angular speed, flow rate).

Frequency Resonant -- The measurand frequency at which a sensor responds with maximum output amplitude; when major amplitude peaks occur at more than one frequency, the lowest of these frequencies is the resonant frequency. A peak is considered major when it has an amplitude at least 1.3 times the amplitude at the frequency to which the specified frequency response is referred.

Frequency Response -- The change with frequency of the ratio of sensor output amplitude to measurand amplitude (and of the phase difference between sensor output and measurand) for a sinusoidally varying measurand applied to a sensor within a stated range of measurand frequencies. Frequency response should be referred to a frequency within the stated range and to a specific measurand value.

Frequency Response, Calculated -- The frequency response of a sensor calculated from its transient response, its mechanical properties, or its geometry, and so identified.

Frequency, Ringing -- The frequency of the oscillatory transient occurring in a sensor output as a result of a step change in measurand.

Friction Error -- The maximum change in output at any measurand value within a specified range before and after minimizing friction within the sensor by dithering.

Friction-Free Error Band -- The error band applicable at room conditions with friction within the sensor minimized by dithering.

FSO -- Abbreviation for "full-scale output."

Full-Scale -- See "Range."

Full-Scale Output -- The algebraic difference between end points.

-G-

Gage Factor -- The ratio of the relative change of resistance to the relative change in length of a resistive strain sensor (strain gage).

Gage, Nude -- A bulbless thermionic ionizing vacuum sensor for direct installation in vacuum vessels.

Gage Pressure -- Pressure referenced to atmospheric pressure.

Grounded, Ungrounded -- Refers to the presence or absence of an electrical connection between the "low" side of a sensor element and the sensor case or the portion of the sensor intended to be in contact with the test structure. An ungrounded sensor should be further characterized by stating "internally ungrounded" or "grounded by means of a separate stud."

-H-

Hall Effect -- The potential gradient across a conductor which experiences a magnetic field at right angles to the current in the conductor. The potential gradient is perpendicular to both the current in the conductor and the magnetic field.

Harmonic Content -- Distortion in the form of harmonics in the sinusoidal output of a sensor.

Hooke's Law -- The deformation of a rigid body is proportional to the stress applied to the body provided the elastic limit of the material is not exceeded.

Hysteresis -- The maximum difference in output, at any measurand value within the specified range, when the value is approached first with increasing and then with decreasing measurand. Friction error is included unless dithering is specified. Hysteresis is expressed as percent of full-scale output during any one calibration cycle.

-I-

IAT -- Abbreviation for "individual acceptance test."

Incipient Failure -- A condition wherein the first signs of failure become apparent by an acceptable means of detection.

Infant Mortality -- High failure rate during the early life of a new equipment caused by faulty components or built-in flaws. This failure rate decreased rapidly and stabilizes when the weak units have died out.

Input Impedance -- The impedance presented to the excitation source, measured across the excitation terminals of a sensor. Unless otherwise specified, input impedance is measured at room conditions, with no measurand applied, and with the output terminals open-circuited.

Instrumentation -- Those devices (electrical, mechanical, magnetic, chemical, optical) used to test, observe, measure, monitor, alter, generate, record, calibrate, manage, or control physical or chemical properties, actions, or other characteristics.

Insulation Resistance -- The resistance measured between specified insulated portions of a sensor when a specified dc voltage is applied at room conditions unless otherwise stated.

Isolating Element -- A movable membrane, usually of metal, that physically separates the measurand fluid from the sensing element. Its purpose is to provide material compatibility with the measured fluid while maintaining the performance integrity of the sensing element. Usually this membrane is considerably more flexible than the sensing element and is coupled to the sensing element by a transfer fluid.

Interchangeability Error -- The error band defined by the maximum deviation obtained when a sensor is replaced by another sensor of the same type with equivalent measurand inputs and environmental conditions, usually expressed in units of measurand.

-J-

Jerk -- Time rate of change of acceleration; expressed in g per second, m per second^3, or feet per second^3.

-K-

-L-

Least-Squares Line -- The straight line for which the sum of the squares of the residuals (deviations) is minimized.

LED -- Abbreviation for "light emitting diode."

Life, Cycling -- The specified minimum number of full-range excursions or specified partial-range excursions over which a sensor will operate as specified without changing its performance beyond specified tolerances.

Life, Operating -- The specified minimum length of time over which the specified continuous and intermittent rating of a sensor applies without change in sensor performance beyond specified tolerances.

Life, Storage -- The specified minimum length of time over which a sensor can be exposed to specified storage conditions without changing its performance beyond specified tolerances.

Linearity -- The closeness of a calibration curve to a specified straight line, expressed as a percentage of full-scale output. It is the maximum deviation of any calibration point from the specified line during any one calibration cycle.

Linearity, End Point -- Linearity referred to the end-point line.

Linearity, Least Squares -- Linearity referred to the least-squares line.

Load Impedance -- The impedance presented to the output terminals of a sensor by the associated external circuitry.

Loading Error -- Error due to the effect of the load impedance on sensor output.

LSB -- Abbreviation for "least significant bit."

-M-

Magnetic Damping -- Damping accomplished by using the current induced in electrical conductors by changes in a magnetic flux.

Maintainability -- The characteristic of design and installation which expresses the probability that an item will be retained in, or restored to, a specified condition within a given period of time when maintenance is performed in accordance with prescribed procedures and resources.

Maintenance -- All actions required to keep equipment (hardware) or programs (software) in satisfactory working condition, including tests, measurements, replacements, adjustments, repairs, program copying, and program improvement.

Maintenance, Corrective -- Maintenance performed to restore a system to operate after a failure.

Maintenance Monitoring -- Monitoring performed to determine when corrective maintenance actions are required.

Maintenance, Preventive -- Systematic maintenance performed in an attempt to detect incipient failures.

Manual Test Equipment -- Test equipment that requires separate manipulations for each task (for example, connection to signal to be measured, selection of suitable range, and insertion of stimuli).

Maximum (Minimum) Ambient Temperature -- The highest (lowest) ambient temperature that a sensor can withstand, with or without excitation applied, without being damaged, or subsequently showing a performance degradation beyond specified tolerances.

Maximum Excitation -- The maximum value of excitation voltage or current that can be applied to a sensor at room conditions without causing damage or performance degradation beyond specified tolerances.

Mean Time Between Failures -- For a particular interval, the total functioning life of a population of an item divided by the total number of failures within the population during the measurement interval involved.

Mean Time Between Maintenance -- The mean of the distribution of the time intervals between maintenance actions, either preventive, corrective, or both.

Mean Time to Repair -- The mean of the distribution of time intervals between failure of an item and its repair or replacement.

Measurand -- A physical quantity, property, or condition which is measured. The term "measurand" is preferred to "input," "parameter to be measured," "physical phenomenon," "stimulus," and "variable."

Measured Fluid -- The fluid which comes in contact with the sensing element. The chemical and/or physical properties of this fluid must be considered in selecting a sensor.

Mechanical Isolation of Transduction Element -- The internal construction of a sensor which allows forces (particularly bending forces and external pressures) to be applied to the sensor case whith negligible resulting forces on the sensor element.

Median Time to Failure -- Time interval during which half of all identical units will have failed.

Mission Time -- That element of uptime during which the item is performing its designated mission.

Modem -- Acronym for "modulator/demodulator."

Monitoring -- The continuous observation of diagnostic phenomena for an indication of a change reflecting a change in the performance of an equipment component.

Mounting Error -- Error resulting from mechanical deformation of a sensor caused by mounting the sensor and making all electrical and measurand connections.

MTBF -- Abbreviation for "mean time between failures."

MTBM -- Abbreviation for "mean time between maintenance."

MTTF -- Abbreviation for "median time to failure."

MTTR -- Abbreviation for "mean time to repair."

-N-

Natural Frequency -- See frequency, natural.

Noise -- Any spurious variation in electrical output not present in the input. In a potentiometric sensor, noise is defined quantitatively in terms of an equivalent parasitic transient resistance appearing between the wiper and the resistance element while the shaft is being moved.

Non-Volatile Memory -- A computer memory which retains stored information when power to the system is turned off.

Nude Gage -- See gage, nude.

Null -- A condition, such as of balance, which results in a minimum absolute value of output.

-O-

On-Line Testing -- Any method of testing which allows the unit under test to be tested in its operational environment.

Operating Temperature Range -- The range of ambient temperature within which a sensor must perform to the requirements of the "temperature error" or "temperature error band."

Output -- The electrical quantity, produced by a sensor, which is a function of the applied measurand.

Output Impedance -- The impedance across the output terminals of a sensor. Unless otherwise specified, output impedance is measured at room conditions, with no measurand applied, and with the input terminals either open-circuited or short-circuited (to be specified).

Output Noise -- The rms, peak, or peak-to-peak (as specified) a-c component of a sensor's d-c output in the absence of measurand variations.

Overdamped -- See "Damping."

Overload -- The maximum magnitude of measurand that can be applied to a sensor without causing a change in performance beyond specified tolerance.

Overshoot -- The amount by which the amplitude of the output of a sensor exceeds the final steady output value in response to a step change in the measurand.

-P-

Passive Sensor -- A sensor requiring no source of power other than the signal being measured.

PCM -- Abbreviation for "pulse code modulation."

Performance Monitor -- A device which continuously or periodically scans a selected number of test points to determine if the unit-under-test is operating within specified limits. This device may include provisions for the insertion of stimuli.

Performance Monitoring -- Monitoring performed to (1) detect performance degradation, (2) predict failures, (3) isolate faults, and (4) predict maintenance requirements by processing measurements of selected static and dynamic characteristics of a prime equipment.

Periodic Check -- A test or series of tests performed at designated intervals to determine if all elements of the unit-under-test are operating within their designated limits.

Phase Shift -- The amount of time by which the output of a sensor lags a sinusoidally varying measurand, usually expressed in degrees or as a fraction of a cycle of the measurand frequency.

Pickup -- See "Sensor."

Pirani Gage -- A compensated, thermoconductive vacuum sensor which measures low gas pressures by measuring the resistance of a heated filament whose temperature and, hence, resistance is a function of gas pressure.

Poisson's Ratio -- If a rod of elastic material is stretched, the ratio of the contraction of the lateral dimension to the elongation of the length is a constant.

Polarity -- The relationship between sensor output and the direction of the applied measurand. Polarity is taken as "standard" when acceleration directed from the mounting surface into the body of the accelerometer produces a positive charge or voltage on the "high" side of the sensor. Also, a positive (increasing) pressure applied to the diaphragm of a pressure sensor produces as "standard" a positive-going output signal. Similar considerations can be applied to other types of sensors.

Potentiometric Element -- The resistance part of a transduction element upon which the wiper (movable contact) slides and across which excitation is applied. It may be constructed of a continuous resistance or of small-diameter wire wound on a form (mandrel).

Pressure Connection (Pressure Port) -- The opening and surrounding surface of a sensor used to permit access by the measured fluid to the sensing or isolating element. This can be a standard industrial or military fitting, a tube hose fitting, or a hole (orifice) in a base plate. For differential pressure sensors, there are two pressure connections: the measurand and reference ports.

Prime Equipment -- An equipment or system that is to be monitored. (See also "Unit-under-test.")

Prognosis -- The art or act of predicting a future condition on the basis of present signs and symptons.

PSF -- Abbreviation for "presampling filter."

Pulse Code Modulation -- A modulation method in which each element of information is represented by the presence or absence of a pulse.

Pyrometer -- A device which measures temperatures, usually by means of radiation or optical phenomena, without contacting the body or substance to be measured.

-Q-

Q -- Amplification factor at the resonant frequency; a measure of the sharpness of resonance.

-R-

Randomness -- The occurrence of an event in accordance with the laws of chance.

Ramp Function -- A sensor input whose amplitude is a linear function of time.

Range -- The measurand values, specified by their upper and lower limits, over which a sensor is intended to measure.

Rangeability -- The ratio between the maximum upper and minimum lower range values for a single sensor.

Recovery Time -- The time interval after a specified event (e.g., overload, excitation transient, output short circuiting, etc.) before a sensor will again perform within its specified tolerances.

Redundancy -- Provision of more than one means of performing a function.

Redundancy, Standby -- Redundancy wherein the alternative means of performing a function is inoperative until needed, and is switched on by failure of the primary means of performing the function.

Reference Port -- See "Pressure Connection."

Reference Pressure -- The pressure relative to which a differential pressure sensor measures pressure.

Reference Pressure Error -- In a differential pressure sensor, the error resulting from variations of the reference pressure within the applicable reference pressure range.

Reliability -- The characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time.

Reliability Engineering -- The science of designing systems by including those factors which will assure the required degree of reliability.

Reliability, Inherent -- The potential reliability present in the design of an item.

Reliability, Intrinsic -- The probability that a device will perform its specified function based on a statistical analysis of the failure rates and other characteristics of the parts and components which comprise the device.

Repeatability -- The ability of a sensor to reproduce output readings when the same measurand value is applied to it consecutively under the same conditions between output readings expressed as a percentage of full-scale output. Two calibration cycles are used to determine repeatability unless otherwise specified.

Resolution -- The magnitude of output step changes as the measurand is continuously varied over the range. This term relates primarily to potentiometric transducers.

Resonances -- Amplified vibrations within narrow frequency bands of sensor components observable in the output as vibration is applied along specified sensor axes.

Resonant Frequency -- See "Frequency, Resonant."

Response Time -- The length of time required for the output of a sensor to rise between specified percentages of its final value as a result of a step change of measurand. Unless otherwise stated, the specified percentages are 10 and 90 percent of the final value.

RF -- Abbreviation for "radio frequency."

Ringing Frequency -- See "Frequency, Ringing."

Ringing Period -- The period of time during which the amplitude of output oscillations excited by a step change in measurand exceeds the steady-state output value by more than a specified amount.

Room Conditions -- Ambient environmental conditions under which sensors most commonly operate:

a) Temperature: 25 ±10 °C (77 ±18 °F)
b) Relative humidity: 90 percent or less
c) Barometric pressure: 26 to 32 inches Hg

Tolerances closer than those shown are frequently specified for sensor calibration and test environments.

RTD -- Abbreviation for "resistance temperature detector," the temperature-responsive element of a resistance thermometer.

-S-

Screening Test -- A test or combination of tests intended to remove unsatisfactory items or those likely to exhibit early failures.

Sealed Reference Differential Pressure Sensor -- Sensor which measures the difference in pressure between an unknown pressure and the pressure of a fluid in an integral, sealed reference chamber.

Self Test -- A test or series of tests performed by a device upon itself to determine whether or not it is operating within designed limits. This includes test programs which check out the performance status and readiness of computers and automatic test equipment.

Semiautomatic Test Equipment -- Any automatic testing device which requires human participation in the decision-making, control, or evaluative functions.

Sensing Element -- That part of a sensor which responds directly to the measurand. This term is preferred to "primary element," "primary detector," and "primary detecting element."

Sensitivity -- The ratio of the change in sensor output to the corresponding change in the value of the measurand. The slope of the straight line representing the calibration curve.

Sensitivity Shift -- A change in the slope of the calibration curve.

Settling Time -- The time required after the application of a step change in measurand for a sensor output to settle within a small percentage (usually 5 percent) of its final value.

Shock -- A substantial disturbance characterized by an abrupt rise and decay of acceleration from a constant value.

Shunt Calibration Resistor -- A shunt resistor which, when placed across a specified element of the electrical circuit of a sensor, will electrically simulate a specified percentage of the sensor's full-scale output at room temperature.

Shunting Resistance -- The electrical resistance observed between the two terminals of a piezoelectric sensor or its integral cable.

Signal -- A manifestation of an event containing information of interest.

Signature -- A characteristic of a waveform which is related to a known condition of interest; a combination of signals characteristic of some known conditions of a device.

Software -- Programs and documentation required for the operation or maintenance of a system.

Source Impedance -- The impedance which the excitation supply presents to the excitation terminals of a sensor.

Span -- The algebraic difference between the limits of the range.

SPG -- Abbreviation for "sinusoidal pressure generator."

SPS -- Abbreviation for "samples per second."

Stability -- The ability of a sensor to retain its performance characteristics for a relatively long period of time, expressed as a percentage of full-scale output for a stated period of time. Unless otherwise stated specifically, stability is the ability of a sensor to reproduce the output readings obtained during its original calibration at room conditions for a specified period of time. (See "durability")

Static Calibration -- A calibration performed under room conditions and in the absence of any vibration, shock, or acceleration unless the latter is the measurand. The applied measurand is invariant with time during each step of the calibration.

Step Function -- An infinitely fast (rise time approaching zero) change in the value of a measurand.

Step Stress Test -- A test consisting of several stress levels applied sequentially to a sample for periods of equal duration; during each period a stated stress level is applied, and the stress level is increased from one step to the next.

Stimulus -- See "Measurand."

Storage Life -- See "Shelf life."

Strain Error -- The error resulting from a strain imposed on a surface to which a sensor, other than a strain sensor (strain gage), is mounted.

Strain Sensitivity -- Sensitivity to strains applied to the base of a sensor by bending, in the absence of any rigid-body motion of the sensor. It is expressed as the equivalent measured level for a unit strain in the plane of the base.

Stress, Component -- The stresses on component parts during testing or usage which affect the failure rate and hence the reliability of the parts. Voltage, power, temperature, and thermal environments stress are included.

Survivability -- A measure of the degree to which an item will withstand hostile environments and not suffer abortive impairment of its ability to accomplish its designated mission.

System Effectiveness -- A measure, which may be expressed as a function of availability, dependability, and capability, of the degree to which an item can be expected to achieve a set of specific mission requirements.

-T-

TDM -- Abbreviation for "time division multiplex."

TDME -- Abbreviation for "test, measurement, and diagnostic equipment."

Temperature Error -- The maximum change in sensor output, at any measurand value within the specified range, when the sensor temperature is changed from room temperature to specified temperature extremes.

Temperature Error Band -- The error band applicable over stated environmental temperature limits.

Temperature Gradient Error -- The transient deviation in the output of a sensor at a given measurand value when the ambient temperature or the measured fluid temperature changes at a specified rate between specified magnitudes.

Temperature Range, Operating -- See "Operating Temperature Range."

Terminal Line -- A theoretical line for which the end points are 0 and 100 percent of both measurand and output.

Test -- A procedure or action to determine under real or simulated conditions the capabilities, limitations, characteristics, effectiveness, reliability, or suitability of a material, device, system, or method.

Test Analysis -- The examination of test results to determine whether the device is in an operationally ready state, or to determine the reasons for, or location of, a malfunction.

Test Equipment (Checkout Equipment) -- Electric, electronic, chemical, optical, mechanical, hydraulic, or pneumatic equipment, either automatic, semi-automatic, manual, or any combination thereof, which is required to perform the test or checkout function.

Test Point -- A convenient safe access to an equipment, system, or circuit so that a significant quantity can be measured or introduced.

Test-to-Failure -- The practice of inducing increased electrical and mechanical stresses in a device in order to determine its maximum capability so that the derating required to extend the life of the device in subsequent applications can be determined.

Theoretical Slope Line -- A line representing the calibration points with theoretical end points at 0 percent and 100 percent of both measurand and output.

Thermal Sensitivity Shift -- Sensitivity shift due to changes of the ambient temperature from room temperature to the specified limits of the operating temperature range.

Thermal Zero Shift -- Zero shift due to changes of the ambient temperature from room temperature to the specified limits of the operating temperature range.

Thermometer -- A temperature-measuring device which is inserted into or attached to the body or substance that is to be measured.

Threshold -- The smallest change in a measurand that will result in a measurable change in sensor output. When the threshold is influenced by the measurand values, these values must be specified.

Throughput Rate -- The total number of data points or measurands that a data acquisition system or automatic test equipment can process in a given period of time; a measure of the speed of the system.

Time Division Multiplex -- A method of transmitting data from multiple sources over the same link by assigning a distinct time period to each source and transmitting the data in time sequence.

Tolerance -- The total permissible variation of a quantity from a designed value.

Transducer -- See "Sensor."

Transduction Element -- The electrical portion of a sensor in which the output originates.

Transfer Fluid -- A degassed liquid used to provide hydraulic coupling of the pressure between the isolating and sensing elements of a pressure sensor.

Transfer Function -- The ratio of the output of a sensor to its input, expressed in the frequency or time domain.

Transient Response -- The response of a sensor to a step change in measurand.

Transient Temperature Error -- The output of a sensor resulting from a specified transient temperature change within a specified operating temperature range. The associated capacitance and load resistance, as well as the time after the applied transient at which the amplitude peak occurs, must be specified.

Transmitter -- A term used synonymously with sensor in process-control applications.

Transverse Sensitivity -- The sensitivity of a sensor to transverse acceleration or other transverse measurand, usually expressed in percent of the sensitivity of the sensor along its sensitive axis.

Two Phase -- A fluid state consisting of a mixture of liquid with gas or vapors.

-U-

Underdamped -- See "Damping."

Ungrounded -- See "Grounded."

Unit-Under-Test -- The prime equipment or portion thereof whose proper functions are to be monitored by automatic test equipment.

Uptime -- The period of time during which an item is in condition to perform its intended function. (See Mission Time)

UUT -- Abbreviation for "unit-under-test."

-V-

Vapor Pressure -- At a given temperature, the pressure of a vapor at which the liquid and vapor are in equilibrium. Vapor pressure increases with temperature.

Variable -- See "Measurand."

Venturi Meter -- An instrument which measures the pressure difference created by a constriction in a pipe to determine the rate of flow of a fluid.

Vibration Error -- The maximum change in output, at any measurand value within the specified range, when vibration levels of specified amplitude and range of frequencies are applied to the sensor along specified axes.

Viscosity -- The property of a liquid that presents a resistance to flow.

Viscosity, Kinematic -- The ratio of absolute viscosity to density: the SI unit is the meter^2/s.

Viscous Damping -- Damping affected by the viscosity of fluids.

Volatile Memory -- A computer memory in which stored information is retained only while power is applied to the system.

Voltage Ratio -- In a potentiometric sensor, the ratio of output voltage to excitation voltage, usually expressed in percent.

-W-

Warm-Up Period -- The period of time, starting with the application of excitation to the sensor, required to assure that a sensor will perform within all specified tolerances.

Wearout -- The process of attrition which results in an increase of failure rate with increasing age (cycles, time, miles, events, etc., as applicable for the item).

Wet-Dry -- Configuration of differential pressure sensor in which a liquid measurand is applied to one port, and a gaseous (dry) referenced to the other port.

Wet-Wet -- Configuration of differential pressure sensor in which liquid measurands can be applied to both ports.

Wheatstone Bridge -- An electrical network in which the outputs of two resistive dividers are compared by a sensitive galvanometer to obtain accurate resistance measurements.

White Noise -- Signal with a mean square spectral density value constant at all frequencies.

-Y-

Yield Margin -- The amount of an item of a particular quality level obtained by selecting from the total production those items which fall within the desired tolerance range, usually expressed as a percentage of total productions.

-Z-

Zero-Measurand Output -- The output of a sensor, under room conditions unless otherwise specified, with normal excitation and zero measurand applied.

Zero Shift -- A change in the zero-measurand output at room conditions over a specified period of time, usually characterized by a parallel displacement of the entire calibration curve.

11. RESOURCES

11.1 Manufacturers of Sensors and Related Items

In order to enhance the usefulness of the handbook, it was thought desirable to append a listing of manufacturers of sensors and related items. It should be clearly understood that this listing is, of necessity, incomplete. Changes in the field are rapid and even with unlimited resources it would not be possible for such a listing to be totally complete or up-to-date or correct. The listing of, or exclusion of, any particular manufacturer does not constitute an endorsement or condemnation of that manufacturer in any way, shape, or form by the writer or publishers of this handbook. The information was obtained from a variety of sources. Much of it was obtained, with permission, from tables in "Measurement and Control" (the Journal of the Measurement and Control Society) Pittsburgh, PA 15216, various volumes 1977 to 1979. Subsequent editions of the handbook will attempt to keep this section updated.

Manufacturers are listed alphabetically within each class of device. The devices are arranged by measurands and further by transduction principles (class of device).

Strain Gage Pressure Sensors

Action Instruments Co., Inc.
8601 Aero Drive
San Diego, CA 92123
(714) 279-5726

Alltech, A Cutler Hammer Co.
19535 E. Walnut Drive
City of Industry, CA 91748
(213) 965-4911

B & F Instruments Division
FX Systems
CPO 1818
Kingston, NY 12401
(914) 338-0515

BLH Electronics
42 Fourth Avenue
Waltham, MA 02254
(617) 890-6700

Barber-Colman Industrial
Instruments Div.
1700 Rock Street
Rockford, IL 61101
(815) 877-0241

Bell & Howell
CEC Division
360 Sierra Madre Villa
Pasadena, CA 91109
(213) 796-9381

Brewer Engineering Labs, Inc.
P.O. Box 288
Marion, MA 02738
(617) 748-0103

C. J. Enterprises
P.O. Box 834
Tarzana, CA 91356
(213) 966-4131

Celesco Transducer Products Inc.
P.O. Box 1457
7800 Deering Avenue
Canoga Park, CA 91304
(213) 884-6860

Cognition, Inc.
765 Ravendale Drive
Mountain View, CA 94043
(415) 969-8300

Conrac Corporation
Three Landmark Square
Stamford, CT 06901
(203) 348-2100

Consolidated Controls Corp.
15 Durant Avenue
Bethel, CT 06801
(203) 743-6721

Control Process, Inc.
201 Atwater Street
Plantsville, CT 06479
(203) 628-4721

D.J. Instruments Inc.
11 E. Esquoirm Road
N. Billerica, MA 01862
(617) 667-5301

Data Instruments
4 Hartwell Place
Lexington, MA 02173
(617) 861-7450

Degamo, Inc.
500 Ashland Avenue
Chicago Heights, IL 60411
(312) 754-3131

Digilin Inc./Dynamic Sciences
(See: Dynamic Sciences)

Dynamic Sciences International Inc
16150 Stagg Street
Van Nuys, CA 91406
(213) 893-6341

Dynisdo, Inc.
20 Southwest Park
Westwood, MA 02090
(617) 326-8210

Eldec Corporation
16700 13th Ave., West
P.O. Box 100
Lynwood, WA 98036
(206) 743-1313

Electronic Flo-Meters, Inc.
P.O. Box 38269
Dallas, TX 75238
(214) 349-1982

Electrosyn Corporation
480 Neponset Street
Canton, MA 02021
(617) 828-2840

Encore Electronics, Inc.
RD 2, Route 50
Saratoga Springs, NY 12866
(518) 584-5354

Endevco
30700 Rancho Viejo Road
San Juan Capistrano, CA 92675
(714) 493-8181

Entran Devices, Inc.
145 Paterson Avenue
Little Falls, NJ 07424
(201) 785-4060

FX Systems
CPO 1818
Kingston, NY 12401
(914) 338-0515

Fatigue Dynamics Inc.
P.O. Box 2533
Dearborn, MI 48123
(313) 273-8270

Foxboro/I.C.T. Inc.
1750 Junction Avenue
San Jose, CA 95112
(408) 998-8720

GSE Inc.
23640 Research Drive
Farmington Hills, MI 48024
(313) 476-7875

Genisco Technical Corporation
18435 Susana Road
Compton, CA 90221
(213) 537-4570

Gentran, Inc.
1290 Hammerwood Avenue
Sunnyvale, CA 94086
(408) 734-5060

Gould, Inc.
Measurement Systems Division
2230 Statham Blvd.
Oxnard, CA 93030
(805) 487-8511

Harwood Engineering Co., Inc.
South Street
Walpole, MA 02081
(617) 668-3600

S. Himmelstein & Company
2500 Estes Avenue
Elk Grove Village, IL 60007
(312) 439-8181

Hottinger Baldwin Measurements, Inc.
10 Strathmore Road
Natick, MA 01760
(617) 655-0950

ICT Instruments, Inc.
5335 McDonnel Avenue
Los Angeles, CA 90066
(213) 390-4043

I.C. Transducers, Inc.
(See: Foxboro/I.C.T., Inc.)

ITT Barton
Box 1882
City of Industry, CA 91749
(213) 961-2547

Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, CO 80933
(303) 599-1500

Kistler-Morse
13227 Northrup Way
Bellevue, WA 98005
(206) 641-4200

Konigsberg Instruments, Inc.
2000 E. Foothill Blvd.
Pasadena, CA 91107
(213) 449-0016

Kistler Instrument Corp.
75 John Glenn Drive
Amherst, NY 14120
(716) 691-5100

Kulite Semiconductor Products Co.
1039 G Hoyt Avenue
Ridgefield, NJ 07657
(201) 945-3000

LFE Corporation
Process Control Division
1601 Trapelo Road
Waltham, MA 02154
(617) 890-2000

Lake Shore Cryotronics, Inc.
64 E. Walnut Street
Westerville, OH 43081
(614) 891-2243

Lebow Associates
1728 Maplelawn Road
Troy, MI 48099
(313) 643-0220

MBIS, Inc.
MB Products
25865 Richmond Road
Bedford Heights, OH 44146
(216) 292-5850

MKS Instruments, Inc.
22 Third Avenue
Burlington, MA 01803
(617) 272-9255

Measurements Group
P.O. Box 27777
Raleigh, NC 27611
(919) 365-3800

Micro-Strain, Inc.
Spring City, PA 19475
(215) 948-4550

Millar Instruments
P.O. Box 18227
Houston, TX 77023
(713) 923-9171

Moore Industries, Inc.
166650 Schoenborn Street
Sepulveda, CA 91343
(213) 897-7111

Narco Bio-Systems, Inc.
7651 Airport Blvd.
P.O. Box 12511
Houston, TX 77017
(713) 644-7521

Paine Instruments
2401 S. Bayview Street
Seattle, WA 98144
(800) 426-0366
(206) 723-1705

Precise Sensors Inc.
235 W. Chestnut Street
Monroevia, CA 91016
(213) 358-4578

Pressure Products Inc.
Duriron Company, Inc.
900 Louis Drive
Warminister, Pa 18974
(215) 675-1600

Pressure Systems Inc.
17 Research Drive
Hampton, VA 23666
(804) 838-1234

Schaevitz Engineering
P.O. Box 505
Camden, NJ 08101
(609) 662-8000

Senso-Metrics, Inc.
7775 Kester Avenue
Van Nuys, CA 91405
(213) 988-6070

Sensotec
1200 Chesapeak Avenue
Columbus, OH 43212
(614) 486-7723

Sigma Instruments, Ltd.
55 Six Point Road
Ontario, Canada M82 2X3
(416) 239-8161

Standard Controls, Inc.
(See: Paine Instrs.)

Strainsert Company
Union Hill Industrial Park
West Conshohocken, PA 19428
(215) 825-3310

Teledyne/Taber
455 Bryand Street
N. Tonawanda, NY 14120
(716) 694-4000

Trans Metrics Inc.
701 Beta Drive
Cleveland, OH 44143
(216) 461-0463

Tyco Instr. Division
(See: Data Instruments)

Unimeasure Division
Konigsberg Instruments
(See: Konigsberg Instr. Inc.)

Viatran Corporation
300 Industrial Drive
Grand Island, NY 14072
(716) 773-1700

Vishay Instruments, Inc.
Photoelastic Division
63 Lincoln Highway
Malvern, PA 19355
(215) 647-5115

West Coast Research Corporation
P.O. Box 25061
2100 S. Sepulveda
Los Angeles, CA 90025
(213) 478-8833

Potentiometric Pressure Sensors

AST Servo Systems, Inc.
930 Broadway
Newark, NJ 07104
(201) 484-4233

Ametek Controls Division
860 Pennsylvania Blvd.
Feasterville, PA 19047
(215) 355-6900

Bourns, Inc.
Adv. Department
1200 Columbia Avenue
Riverside, CA 92507
(714) 781-5070

Bunker Ramo Instrs. Division
902 Wisconsin Street
Delavan, WI 53115
(414) 728-5531

Conrac Corporation
Three Landmark Square
Stamford, CT 06901
(203) 348-2100

Gulton Industries, Inc.
Piezo Products Division
212 Durham Avenue
Metuchen, NJ 08840
(201) 548-2800

Gulton Industries
S-C Division
1644 Whittier Avenue
P.O. Box 2176
Costa Mesa, CA 92627
(714) 642-2400

Konigsberg Instruments
(See: Unimeasure)

Litton Industries
Potentiometer Division
226 3rd Street
Mt. Vernon, NY 10550
(914) 664-7733

Robinson-Halpern
1 Apollo Road
Plymouth Meeting, PA 19462
(215) 825-9200

Sparton Southwest, Inc.
P.O. Box 1784
9621 Coors Road, NW
Albuquerque, NM 87103
(505) 898-1150

Systems Science and Software
P.O. Box 1620
LaJolla, CA 92038
(714) 453-0060

Unimeasure Division
Konigsberg Instruments
2000 E. Foothill Blvd.
Pasadena, CA 91107
(213) 449-0016

Vernitech Corporation
Division of Vernitron
300 Marcus Blvd.
Deer Park, LI, NY 11729
(516) 586-5100

Reluctive and Linear Variable Differential Transducer Sensors

AST Servo Systems, Inc.
930 Broadway
Newark, NJ 07104
(201) 484-4233

Ametek
Controls Division
P.O. Box 152
Feasterville, PA 18960
(215) 355-6900

Automation Associates, Inc.
1339 Lawrence Drive
Newbury Park, CA 91320
(805) 498-6787

Biotronex Lab., Inc.
4225 Howard Avenue
Kensington, MD 20795
(301) 942-1800

C. J. Enterprises
P.O. Box 834
Tarzana, CA 91356
(213) 996-4131

Celesco Transducer Products Inc.
7800 Deering Avenue
P.O. Box 1457
Canoga Park, CA 91304
(213) 884-6860

Columbia Research Labs, Inc.
MacDade Blvd. & Bullens Lane
Woodlyn, PA 19094
(215) 532-9464

Computer Instruments Corp.
100 Madison Avenue
Hempstead, LI, NY 11550
(516) 483-8200

Consolidated Controls Corp.
15 Durant Avenue
Bethel, CT 06801
(203) 743-6721

Electrosyn Corporation
480 Neponset Street
Canton, MA 02021
(617) 828-2840

Gulton Industries
S-C-D
1644 Whittier Avenue
Costa Mesa, CA 92627
(714) 642-2400

Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, CO 80933
(303) 599-1500

Kavlico Corporation, Inc.
20869 Plummer Street
Chatsworth, CA 91311
(213) 882-2400

The Lewis Engineering Company
Transducer Division
19-29 Sheldon Street
Norwich, NY 13815
(607) 334-3939

Robinson-Halpem Company
One Apollo Road
Plymouth Meeting, PA 19462
(215) 825-9200

Schaevitz Engineering
P.O. Box 505
Camden, NJ 08101
(609) 662-8000

Validyne Engineering Corporation
19414 Londelius Street
Northridge, CA 91324
(213) 886-8488

Piezoelectric Pressure Sensors

BBN Instruments Company
Div. of Bolt, Beranek & Newman
50 Moulton Street
Cambridge, MA 02138
(617) 491-0091

Celesco Transducer Products, Inc.
P.O. Box 1457
Canoga Park, CA 91304
(213) 884-6860

Channel Industries
Box 3680
839 Ward Drive
Santa Barbara, CA 93111
(805) 967-07171

Columbia Research Labs, Inc.
McDade Blvd. & Bullens Lane
Woodlyn, PA 19094
(215) 532-9464

Degamo, Inc.
500 Ashland Avenue
P.O. BOx 653
Chicago Heights, IL 60411
(312) 754-3131

Dunegan/Endevco
30700 Rancho Viejo Road
San Juan Capistrano, CA 92675
(714) 831-9131

Gulton Industries, Inc.
Piezo Products Division
212 Durham Avenue
Metuchen, NJ 08840
(201) 548-2800

Gulton Industries, Inc.
S-C Division
1644 Whitter Avenue
Costa Mesa, CA 92627
(714) 642-2400

Kistler Instrument Corporation
75 John Glenn Drive
Amherst, NY 14120
(716) 691-5100

Massa Division
Dynamics Corp. America
280 Lincoln Street
Hingham, MA 02043
(617) 749-4800

Metrix Instrument Company
1711 Townhurst Drive
Houston, TX 77043
(713) 461-2131

National Controls, Inc.
1160 Hopper Lane
Santa Rose, CA 95401
(707) 527-5555

PCB Piezotronics
P.O. Box 33
Buffalo, NY 14225
(716) 684-0001

Quantum Dynamics
19458 Ventura Blvd.
P.O. Box 865
Tarzana, CA 91356
(213) 345-6828

Scientific-Atlanta Inc.
3845 Pleasantdale Road
Atlanta, GA 30340
(404) 449-2000

Sundstrand Data Control Inc.
Overlake Industrial Park
Redmond, WA 98052
(206) 885-3711

Transmed Scientific (formerly Biocom)
860-C Capitolio Way
San Luis Obispo, CA 934401
(805) 541-1103

Vibro-Meter Corporation
22109 South Vermont Avenue
Torrence, CA 90502
(213) 320-8410

Capacitive Pressure Sensors

Bell & Howell
360 Sierra Villa
Pasadena, CA 91109
(213) 796-9381

Computer Instruments Corp.
92 Madison Avenue
Hempstead, LI, NY 11550
(516) 483-8200

Datametrics
(See Gould Inc. Control &
Systems Div.)

Disa Electronics
779 Susquehanna Avenue
Franklin Lakes, NJ 07417
(201) 891-9460

Engineering Dynamics Inc.
6651 S. Wellington
Littleton, CO 81020
(303) 798-3941

Gould Inc.
Control & Systems Div.
(formerly Data-metrics)
340 Fordham Road
Wilmington, MA 01887
(617) 658-5410

Hamilton Standard
Div. of United Aircraft Corp.
P.O. Box 300
Windsor Locks, CT 06096
(203) 623-1621

Hitec Corporation
65 Power Road
Westford, MA 01886
(617) 692-4793

Kratos
403 South Raymond Ave, BIN 45
Pasadena, CA 91109
(213) 449-3090

Lion Precision Inc.
60 Bridge Street
Newton, MA 02195
(617) 969-4710

MKS Instruments Inc.
22 Third Avenue
Burlington, MA 01803
(617) 272-9255

Mechanical Technology, Inc.
MTI Instruments Division
968 Albany Shaker Road
Latham, NY 12110
(518) 785-2323 / (518) 456-4131

Parascientific Inc.
14827 N. E. 40th Street
Redmond, WA 98052
(206) 883-8700

Rosemount Inc.
12001 W. 78th Street
Minneapolis, MN 55435
(612) 941-5560

Ruska Instrument Corporation
6121 Hillcroft
P.O. Box 36010
Houston, TX 77036
(713) 774-2533

Setra Systems
1 Strathmore Road
Natick, MA 01760
(617) 655-4645

Siltran Digital
P.O. Box 437
Silverado, CA 92676
(714) 649-2704

Sundstrand Data Control Inc.
Overlake Industrial Park
Redmond, WA 98052
(206) 885-3711

Digital Pressure Sensors

Bell & Howell
CEC Division
360 Sierra Madre Villa
Pasadena, CA 91109
(213) 796-9381

Foxboro/I.C.T., Inc.
1750 Junction Avenue
San Jose, CA 95112
(408) 998-8720

Hamilton Standard Div. of
United Aircraft Corp.
P.O. Box 300
(203) 623-1621

I. C. Transducers
(See: Foxboro/I.C.T., Inc.)

Kollsman Instrument Company
Daniel Webster Highway South
Merrimack, NH 03054
(603) 889-2500

Mensor Corporation
1055 Conrad Sauer Road
P.O. Box 55642
Houston, TX 77055
(714) 464-6228

Paroscientific Inc.
14827 N.E. 40th Street
Redmond, WA 98052
(206) 883-8700

Pneumatron
10459A Roselle Street
San Diego, CA 92121
(714) 453-4365

Ruska Instrument Corp.
Box 36010
6121 Hillcroft Avenue
Houston, TX 77036
(713) 774-2533

Scanivalve Inc.
P.O. Box 20005
San Diego, CA 92120
(714) 283-5851

Siltran Digital
P.O. Box 437
Silverado, CA 92676
(714) 649-2704

Volumetrics
1025 W. Arbor Vitae Street
Inglewood, CA 90301
(213) 641-3747

Wallace & Tiernan Division
Pennwalt Corporation
25 Main Street
Belleville, NJ 07109
(201) 759-8000

Western Systems Inc.
P.O. Box 2133
Evergreen, CO 80439

TEMPERATURE

Thermocouples

ARI Industries Inc.
9000 King Street
Franklin Park, IL 60131
(312) 671-0511

Acromag, Inc.
30765 Wixom Road
Wixom, MI 48096
(313) 624-1541

Action Instruments Co., Inc.
8601 Aero Drive
San Diego, CA 92123
(714) 279-5726

Acurex Corporation
485 Clyde Avenue
Mt. View, CA 94040
(415) 964-3200

Alltech
A Cutler Hammer Company
19535 E. Walnut Drive
City of Industry, CA 91748
(213) 965-4911

Alberox Corporation
Industrial Park
New Bedford, MA 02745
(617) 995-1725

Alnor Instruments Company
7301 N. Caldwell Avenue
Niles, IL 60648
(312) 647-7866

Amperex Electronic Corporation
230 Duffy Avenue
Hicksville, NY 11802
(516) 931-6200

Amprobe Instrument
Div. of SOS Consolidated Inc.
630 Merrick Road
Lynbrook, NY 11563
(516) 593-5600

Atlas Wire & Cable Co., Inc.
72 N. Broadway
Yonkers, NY 10701
(914) 969-5158

B & F Instruments
Div. of FX Systems
P.O. Box 238
Cornwells Heights, PA 19020
(215) 639-7100

BLH Electronics
42 Fourth Avenue
Waltham, MA 02254
(617) 894-6700

Bailey Instruments, Inc.
P.O. Box 800
515 Victor Street
Saddle Brook, NJ 07662
(201) 845-7252

Bailey Meter Company
29801 Euclid Avenue
Wickliffe, OH 44092
(216) 943-5500

Barber-Colman Company
Industrial Instruments Div.
1706 Rock Street
Rockford, IL 61101
(815) 877-0241

Bristol Division, ACCO
929 Connecticut Ave.
Bridgeport, CT 06607
(203) 335-2511

Burns Engineering Inc.
10201 Bren Road East
Minnetonka, MN 55343
(612) 935-4400

CGS/Thermodynamics
Industrial Blvd.
Southhampton, PA 18966
(215) 355-9550

Calimatic Instruments Inc.
965 Richard Avenue
Santa Clara, CA 95050
(408) 247-1231

Cambridge Instrument Co., Inc.
73 Spring Street
Ossining, NY 10562
(914) 941-8100

Camille Bauer, Kimberly-James Inc.
P.O. Box D
Newton Square, PA 190/3
(215) 353-2828

Canadian Research Institute
85 Curlew Drive
Don Mills, Ontario M3R 7R2,
Canada
(416) 445-6363

Celesco Transducer Products Inc
7800 Deering Avenue
Canoga Park, CA 91304
(213) 884-6860

Ceramaseal, Inc.
P.O. Box 25
New Lebanon Center
New York, NY 12116
(518) 794-6101

Cerro Wire & Cable Company
285 Nicoll Street
New Haven, CN 06504
(203) 772-2550

Conax Corporation
Esterline Corporation
2300 Walden Avenue
Buffalo, NY 14225
(716) 684-4500

Consolidated Controls Corp.
15 Durant Avenue
Bethel, CN 06801
(203) 743-6721

Control Process Inc.
201 Atwater Street
Plantsville, CN 06479
(203) 628-4721

Control Products Corporation
4431 W. Division
Chicago, IL 60651
(312) 235-1131

Cor-Tem Products, Inc.
(See ARI Industries)

Daburn Electronics & Cable Corp.
2359-B Hoffman Street
Bronx, NY 10458
(212) 295-0050

Degussa Inc.
Metals Division
Rt. 46 at Hollister Road
Teterboro, NJ 07608
(201) 288-6500

Devar Inc.
Control Products Division
706 Bostwick Avenue
Bridgeport, CT 06605
(203) 368-6751

Delta-T Company
P.O. Box 473
Santa Clara, CA 95052
(408) 243-0241

Dietert, H. W. Company
9330 Roselawn Avenue
Detroit, MI 48204
(313) 933-9790

Digetec
(See United Systems)

Digilin, Inc.
3521 W. Pacific Avenue
Burbank, CA 846-1800
(213) 846-1800

Doric Scientific Company
3883 Ruffin Road
San Diego, CA 92123
(714) 565-4415

Driver Harris Company
201 Middlesex Street
Harrison, NJ 07029
(201) 483-4800

Driver Wilbur B. Company
1875 McCarter Highway
Newark, NJ 07104
(201) 481-3100

Du-Co Ceramics
P.O. Box 278
Saxonburg, PA 16056
(412) 352-1511

Dynatech Medical Products
Dynatech R&D Company
99 Erie Street
Cambridge, MA 02139
(617) 868-8050

ECD Corporation
196 Broadway
Cambridge, MA 02139
(617) 661-4400

EDN Instrumentation, Inc.
15547 Cabrito Road
Van Nuys, CA 92111
(213) 781-2185

Ectron Corporation
8159 Engineer Road
San Diego, CA 92111
(714) 278-0600

Electro-Nite Company
10501 Decatur Road
Philadelphia, PA 19154
(215) 737-0600

Electro Optical Inc.
Transducer & Controls Division
255 N. Halstead
Pasadena, CA 91107
(213) 449-1230

Electronic Dev. Labs, Inc.
19 Newton Road
Plainview, NY 11803
(516) 293-8997

Engelhard Industries Division
2655 U. S. 22
Union, NJ 07083
(201) 589-5000

Eppley Labs
Sheffield Avenue
Newport, RI 02840
(401) 847-1020

Extech International Corp.
177 State Street
Boston, MA 02109
(617) 227-7090

Fenwal Electronics Inc.
63 Fountain Street
P.O. Box 585
Framingham, MA 01701
(617) 822-8841

Fisher Controls Company
205 S. Center Street
Marshalltown, IA 50158
(515) 754-3011

John Fluke Manufacturing Co., Inc.
P.O. Box 43210
Mountlake Terrace, WA 98043
(206) 774-2211

Foster Cambridge Limited
Howard Road, Eaton, Socon
Huntingdon, Cambridgeshire, England
PE 19 3EU

Foxboro Company
38 Neponset
Foxboro, MA 02035
(617) 543-8750

GIC Thermodynamics Division
George Instrument Company
4949 Delemere
Royal Oak, MI 48073
(313) 576-4700

Gay Engrg. & Sales Co., Inc.
P.O. Box 13232
5425 Blossom Street
Houston, TX 77019
(713) 869-3306

Gencom Division
Emitronics Inc.
80 Express Street
Plainview, NY 11803
(516) 433-5900

General Resistance, Inc.
75 Haven Avenue
Mt. Vernon, NY 10553
(212) 292-1500

Gordon, Claud S. Company
5710 Kenosha Street
Richmond, IL 60071
(815) 678-2211

Gulton Industries
Measurement & Control Systems Div.
Middle Road & Route 2
E. Greenwich, RI 02818
(401) 884-6800

Hades Manufacturing Corporation
151 A Verdi Street
Farmingdale, LI, NY 11735
(516) 249-4244

Harco Laboratories
186 Cedar Street
Brandord, CT 06405
(203) 488-8371

Harrop Laboratories
3470 E. Fifth Avenue
Columbus, OH 43219
(614) 231-3621

Hitec Corporation
65 Power Road
Westford, MA 01886
(617) 692-4793

Honeywell, Inc.
Process Control Division
1100 Virginia Drive
Ft. Washington, PA 19034
(215) 643-1300

Hoskins Manufacturing Company
4445 Lawton Avenue
Detroit, MI 48208

Honeywell Instruments Inc.
3479 W. Vickery Blvd.
Ft. Worth, TX 76107
(817) ED6-7411

Hy-Cal Engineering
12105 Los Nietos Road
Santa Fe Springs, CA 90670
(213) 698-7785

Industrial Pyrometer
2107 Holland Street
Alton, IL 62002
(618) 465-7623

Industrial Temperature Control Co.
23419 Ford Road
Dearborn, MI 48128
(313) 278-2210

Instrulab
1205 Lamar Street
Dayton, OH 45404
(513) 223-2241

Instrumatics, Inc.
916 Boundary Street
P.O. Box 8762
Houston, TX 77009
(713) 225-6626

K West
9371 Kramer Avenue
Westminister, CA 92683
(714) 893-6593

Karn Chemical Equipment Co.
815 Camp Horne Road
Pittsburgh, PA 15237
(412) 931-2983

Kaye Instruments, Inc.
737 Concord Avenue
Cambridge, MA 02138
(617) 868-7080

Kontes Glass Company
Spruce Street
Vineland, NJ 08360
(609) 692-8500

LFE Corporation
API Instruments
1601 Trapelo Road
Waltham, MA 02154
(617) 890-2000

Land Instruments Inc.
P.O. Box 1623
Tullytown, PA 19007
(215) 943-7882

Leeds & Northrup Company
Sumneytown Pike
N. Wales, PA 19454
(215) 643-2000

Leico Industries, Inc.
250 W. 57th Street
New York, NY 10019
(212) 765-5290

Lewis Engineering Company
238 Water Street
Naugatuck, CT 06770
(203) 729-5253

Love Controls Corporation
1714 S. Wolf Road
Wheeling, IL 60090
(312) 541-3232

Marlin Mfg. Corporation
12404 Triskett Road
Cleveland, OH 44111
(216) 941-6200

Matthew Bishop, Inc.
Platinum Works
Malvern, PA 19355
(215) 644-3100

McDaniel Refractory Porcelain Co.
510 Ninth Avenue
Beaver Falls, PA 15010
(412) 843-8300

Medtherm Corporation
P.O. Box 412
Huntsville, AL 35804
(205) 534-7331

Minco Products, Inc.
7300 Commerce Lane
Minneapolis, MN 55432
(612) 786-3121

Modutec Incorporated
18 Marshall Street
Norwalk, CT 06854
(203) 853-3636

Molecu Wire Corporation
P.O. Box 495
Farmingdale, NJ 07727
(201) 922-9400

Moore Industries, Inc.
16650 Schoeborn Street
Sepulveda, CA 91343
(213) 894-7111

Moore, Samuel & Company
Dekoron Division
Aurora, OH 44202
(216) 562-5151

Mykroy Ceramics Company
P.O. Box 496
Ledgewood, NJ 07852
(201) 398-7000

Nanmac Corporation
9-11 Mayhew Street
Framingham Centre, MA 01701
(617) 872-4811

Natel Engineering Co., Inc.
8954 Mason Avenue
Canoga Park, CA 91306
(213) 882-9620

Nationwide Electronic Systems
1536 Brandy Parkway
Streamwood, IL 60103
(312) 289-8820

Newport Labs, Inc.
630 E. Young Street
Santa Ana, CA 92705
(714) 540-4914

Noral, Inc.
23600 Mercantile Road
Cleveland, OH 44122
(216) 831-2345

Noronix Ltd.
8 Thomas Street
London SE18 6HR
England

Omega Engineering Inc.
P.O. Box 4047
27 Knapp Street
Stamford, CT 06907
(203) 359-1660

Pace Wiancko Division
Whittaker Corporation
12838 Saticoy Street
N. Hollywood, CA 91605

Pacific Transducer Corp.
2301 Federal Avenue
Los Angeles, CA 90064
(213) 478-1134

Pak-Tronics Inc.
Dept. ET
4044 N. Rockwell Avenue
Chicago, IL 60618
(312) 478-8282

Precision Digital
1329 Highland Avenue
P.O. Box 18
Needham, MA 02192
(617) 449-2265

Projects Inc.
38 Addison Road
Glastonbury, CT 06033
(203) 633-4615

Pyco, Inc.
600 E. Lincoln Highway
Penndel, PA 19047
(215) 757-3704

Pyro-Serve Instrument Inc.
348 River Road
N. Arlington, NJ 07032
(201) 991-8000

Pyrometer Instr. Co., Inc.
234 Industrial Parkway
Northvale, NJ 07647
(201) 768-2000

RDF Corporation
23 Elm Avenue
Hudson, NH 03051
(603) 882-5195

RFL Industries, Inc.
Powerville Road
Boonton, NJ 07005
(201) 334-3100

Raeco, Inc.
550 Armory Drive
South Holland, IL 60473
(312) 331-6001

Reacor, Inc.
740 S. Sherman Street
Richardson, TX 75080
(214) 235-1952

Revere Corp. of America
845 N. Colony Road
Wallingtford, CT 06492
(203) 269-7201

Richards, Arklay S. Company Inc.
72M Winchester Street
Newton Highlands, MA 02161
(617) 527-4385

The Riley Company
7401 N. Hamlin Avenue
Skokie, IL 60076
(312) 675-2500

Rochester Inst. Systems, Inc.
275 N. Union Street
Rochester, NY 14605
(716) 325-5120

Rosemount-Nashville, Inc.
100 Heil-Quaker Blvd.
Lavergne, TN 37086
(615) 793-7561

Scanivalve, Inc.
10222 San Diego Mission Road
San Diego, CA 92120
(714) 283-0010

Science Products Corporation
U.S. Route 46
Dover, NJ 07801
(201) 366-0827

Scientific Eng. & Mfg. Co., Inc.
11505 Vanowen Street
N. Hollywood, CA 91605
(213) 982-1400

Sensor Corporation
303 Scottdale Avenue
P.O. Box 140
Scottdale, PA 15683
(412) 887-4080

Sentel Associates, Inc.
1125 C Stewart Drive
Sunnyvale, CA 94086
(408) 737-1400

Service Associated, Inc.
339 W. 112th Place
Chicago, IL 60628
(312) 568-4545

Sierracin Corporation
Harrison Division
3020 Empire Avenue
Burbank, CA 91504
(213) 849-6581

Sigma Insts. (Canada) Ltd.
P.O. Box 43
55 Sixpoint Road
Toronto 18, Ontario, Canada
(416) 239-8161

Simpson Electric Company
853 Dundee Avenue
Elgin, IL 60120
(312) 697-2260

Spectran Inst.
P.O. Box 891
La Habra, CA 90631
(213) 333-0666

Standard Wire & Cable Company
3440 Overland Avenue
Los Angeles, CA 90034
(213) 870-9231

Syscon International Inc.
1239 South Bend Avenue
South Bend, IN 46617
(219) 287-5916

Tem Tex Temp. Sys. & Components
5619 Dyer Street
Dallas, TX 75206
(214) 361-7100

Templine
23555 Telco Avenue
Torrance, CA 90505
(213) 539-2333

Temp-Pro Inc.
P.O. Box 265
Haydenville, MA 01039
(413) 268-7715

Tensolite Company
Div. Carlisle Corp.
198 W. Main Street
Tarrytown, NY 10591
(914) 631-2300

Theall Engineering Company
Box 362
Oxford, PA 19363
(215) 932-2488

Thermalogic
Div. of Dytron Inc.
241 Crescent Street
Waltham, MA 02154
(617) 891-9496

Thermo-Couple Product Co., Inc.
27 W. Beecher
Winfield, IL 60190
(312) 653-1400

Thermo Electric Co., Inc.
109 Fifth Street
Saddle Brook, NJ 07662
(201) 843-5800

Thermometrics Corporation
8645 Yolanda Avenue
Northridge, CA 91324
(213) 886-3755

Thermonetics Corporation
1028 Garnet Avenue, #160
San Diego, CA 92109
(714) 453-2164

Thermotronic Devices Inc.
P.O. Box 184
Forrest & Hector Sts.
Conshohocken, PA 19428
(215) 828-4790

Thornthwaite, C.W. Assoc.
Route 1 Centerton
Elmer, NJ 08318
(609) 358-2350

Tracor Westronics Inc.
5050 Mark IV Parkway
P.O. Box 4619
Fort Worth, TX 76106
(817) 625-2311

Transmation Inc.
977 Mt. Read Blvd.
Rochester, NY 14606
(716) 254-9000

Trans-Met Eng. Inc.
601 S. Palm Street
La Hara, CA 90631
(213) 691-2266

Triplett Corporation
Dept. P-R
Bluffton, OH 45817
(419) 358-5015

Tudor Technology, Inc.
424 Caredean Drive
Horsham, PA 19094
(215) 674-4150

Tylok International
25700 Lakeland Blvd.
Euclid, OH 44132
(216) 361-0400

United Electric Controls Co.
85 School Street
Watertown, MA 02172
(617) 926-1000

United Systems Corporation
Digitec
918 Woodley Road
Dayton, OH 45403
(513) 254-5251

Unitronix Corporation
1081 U.S. Hwy 22
P.O. Box 6515
Bridgewater, NJ 08807
(201) 725-2560

Validyne Engrg. Corporation
19414 Londelius Street
Northridge, CA 91324
(213) 886-8488

Virtis Company, Inc.
Route 208
Gardiner, NY 12525
(914) 255-5000

William Wahl Corporation
12908 Panama Street
Los Angeles, CA 90066
(213) 391-7234

Ward Leonard-Hagerstown Division
Angstrohm Precision Inc.
P.O. Box 1827
Hagerstown, MD 21740
(301) 739-9722

Watlow Electric Mfg. Company
12001 Lackland Road
St. Louis, MO 63141
(314) 878-4600

Weed Instruments Company Inc.
P.O. Box 549
109 W. 11th Street
Elgin, TX 78621
(512) 285-3411

West Coast Research Corporation
P.O. Box 25061
Los Angeles, CA 90025
(213) 478-8833

Wilcon Industries
9557 E. Rush Street
S. El Monte, CA 91733
(213) 579-0268

Yokogawa Corp. of America
5 Westchester Plaza
Elmsford, NY 10523
(914) 592-6767

Resistance Thermometers

ARI Industries, Inc.
9000 King Street
Franklin Park, IL 60131
(312) 671-0511

ARRGH Manufacturing Co., Inc.
P.O. Box S
San Rafael, CA 94903
(415) 479-0220

Abrams, A. J. Company
P.O. Box 571
Westport, CT 06880
(203) 226-3010

Action Instruments Co., Inc.
8601 Aero Drive
San Diego, CA 92123
(714) 279-5726

Airpax/North American Philips
Controls Corporation
Frederick Division
Husky Park, Frederick, MD 21701
(301) 663-5141

Amprobe Instrument Division
630 Merrick Road
Lynbrook, NY 11563
(516) 593-5600

Analog Devices
Rt. 1, Industrial Park
P.O. Box 280
Norwood, MA 02062
(617) 329-4700

Analogic Corporation
Audubon Road
Wakefield, MA 01880
(617) 246-0300

Ancom Ltd.
Denmark House
Devonshire Street
Cheltenham, Glos, GL50 3PR England

Andonian Cryogenics, Inc.
26 Farwell Street
Newtonville, MA 02160
(617) 484-0500

Artronix Inc.
18081 Chesterfield Airport Rd.
Chesterfield, MO 63017
(314) 532-8200

Athena Controls Inc.
20 Clipper Road
W. Conchohocken, PA 19428
(215) 828-2490

Atkins Technical
3401 S.W. 40th Blvd.
Gainesville, FL 32608
(904) 378-5555

B & F Instruments Division
FX Systems
(See: FX Systems)

BLH Electronics
42 Fourth Street
Waltham, MA 02154
(617) 890-6700

Barber-Colman Company
Industrial Instruments Division
1700 Rock Street
Rockford, IL 61101
(815) 877-0241

Bayley Instrument Company
Box 357
Kenwood, CA 95452
(707) 833-6014

Beacon Electronics Inc.
1800 Tilton Road
Pleasantville, NJ 08232
(609) 646-3770

Bristol Division
ACCO
929 Connecticut Avenue
Bridgeport, CT 06607
(203) 335-2511

Burns Engineering, Inc.
10201 Bren Road East
Minnetonka, NM 55343
(612) 935-4400

CGS Thermodynamics
LaCrue Street
Concord Industrial Park
Concordville, PA 19331
(215) 358-1510

Cal-R Inc.
Thermonetics Division
1601 Olympic Blvd.
Santa Monica, CA 90404
(213) 450-1761

Canadian Research Institute
85 Curlew Drive
Don Mills, Ontario M3R 7R2 Canada
(416) 445-6363

Canadian Thermostat & Control Devices
2255 Dandurand Street
Montreal, Quebec, Canada H2G 1Z6
(514) 270-7135

Carborundum Company
Graphite Products Division
P.O. Box 339
Niagara Falls, NY 14302
(716) 278-2521

Chemtrix, Inc.
135 North West Adams Street
Hillsboro, OR 91723
(503) 648-0762

Climatronics
1324-A Motor Pkwy.
Hauppauge, NY 11787
(516) 234-2772

Cole-Parmer Instrument Company
7425 N. Oak Avenue
Chicago, IL 60648
(312) 647-0272

Columbia Research
MacDade Blvd. & Bullens Lane
Woodlyn, PA 19094
(215) 532-9464

Conax Corporation
2300 Walden Avenue
Buffalo, NY 14225
(716) 684-4500

Daniel Industries Inc.
Flow Products Division
9720 Katy Road
P.O. Box 19097
Houston, TX 77024
(713) 467-6000

Datametrics
340 Fordham Road
Wilmington, MA 01887
(617) 729-9480

Degussa Corporation
Metals Division
Rte. 46 at Hollister Road
Teterboro, NJ 07608
(201) 288-6500

Dentronics, Inc.
60 Oak Street
Hackensack, NJ 07601
(201) 343-9405

Doric Scientific Company
3883 Ruffin Road
San Diego, CA 92123

ECD Corporation
196 Broadway
Cambridge, MA 02139
(617) 661-4400

ESE
142 Sierra Street
El Segundo, CA 90245
(213) 322-2136

Edison Electronics Division
McGraw-Edison Company
Grenier Field
Municipal Airport
Manchester, NH 03103
(603) 669-0940

Electronic Control Systems, Inc.
P.O. Box 1232
Fairmont, WV 26554
(304) 363-8632

Electronic Development Labs, Inc.
19 Newtown Road
Plainview, NY 11803
(516) 293-8997

Electronic Research Company
(see: Industrial Timer Corp.)

Elnik Instruments, Inc.
410 Garibaldi Avenue
Lodi, NJ 07644
(201) 779-7388

Eltex Inc.
25165 Southport Street
Laguna Hills, CA 92653
(714) 770-9236

Engelhard Industries
2655 U.S. Rte. 22
Union, NJ 07083
(201) 589-5000

Extech International Corp.
114 State St.
Boston, MA 02109
(617) 227-7090

FX Systems
CPO 1818
77 Cornell Street
Kingston, NY 12401
(914) 338-0515

Fenwal Inc.
400 Main Street
Ashland, MA 01721
(617) 881-2000

Foster Cambridge Limited
Howard Road
Eaton, Socon, Huntingdon
Cambridgeshire, England PE19 3EU

Foxboro Company
38 Neponset Avenue
Foxboro, MA 02035
(617) 543-8750

Gencom Division
Emitronics, Inc.
80 Express Street
Plainview, NY 11803
(516) 433-5900

General Scientific Equipment Co.
Limekiln Pike & Williams
Avenue
Philadelphia, PA 19150
(215) 354-9677

Genisco Technology
Corporation
18435 Susana Road
Compton, CA 90221
(213) 537-4750

Gentran, Inc.
1290 Hammerwood Avenue
Sunnyvale, CA 94086
(408) 734-5060

Gordon, Claud S. Company
5710 Kenosha Street
Richmond, IL 60071
(817) 678-2211

Gould Control & Systems Division
(see: Datametrics)

Gulton Industries, Inc.
Measurement & Control Systems Div.
Middle Rd & Rt. 2
East Greenwich, RI 02818
(401) 884-6800

Gulton Industries, Inc.
Piezo Products Division
212 Durham Avenue
Metuchen, NJ 08840
(201) 548-2800

Harrel, Inc.
16 Fitch Street
E. Norwalk, CT 06855
(203) 866-2573

Helitrope General
3733 Kenora Drive
Spring Valley, CA 92077

Hewlett-Packard
Delcon Division
1501 Pase Mill Road
(415) 969-0880

Honeywell, Inc.
Process Control Division
1100 Virginia Drive
Fort Washington, PA 19034
(215) 643-1300

Hy-Cal Engineering
12105 Los Nietos Road
Santa Fe Springs, CA 90670
(213) 698-7785

ITT Components Group Europe
Edinburgh Wah
Hawlow, Essex, England

Industrial Timer Corporation
An Esterline Company
U.S. Highway 287
Parsippany, NJ 07054
(201) 887-2200

Instrulab, Inc.
1205 Lamar Street
Dayton, OH 45404
(513) 223-2241

Julie Research Labs, Inc.
211 W. 61st Street
New York, NY 10023
(212) 245-2727

Keystone Carbon Company
Thermistor Division
1935 State Street
St. Marys, PA 15857
(814) 781-1591

Kulite Semiconductor Products, Inc.
1039 Hoyt Avenue
Ridgefield, NJ 07657
(201) 945-3000

Kurz Instruments
P.O. Box 849
20 Village Square
Carmel Valley, CA 93924
(408) 659-3421

LFE Corporation
Process Control Division
1601 Trapelo Road
Waltham, MA 02154
(617) 890-2000

Lake Shore Cryotronics, Inc.
64 E. Walnut Street
Westerville, OH 43081
(614) 891-2243

Leeds & Northrup Company
Sumneytown Pike
N. Wales, PA 19454
(215) 643-2000

Leico Industries Inc.
250 W. 57th Street
New York, NY 10019
(212) 765-5290

The Lewis Engineering Company
Transducer Division
19-29 Sheldon Street
Norwich, NY 13815
(607) 334-3939

Logical Technical Services Corp.
71 West 23rd Street
New York, NY 10010
(212) 741-8340

Love Controls Corporation
1475 S. Wheeling Road
Wheeling, IL 60090
(312) 541-3232

Mag-Con, Inc.
1626 Terrace Drive
St. Paul, MN 55113
(612) 633-8820

Matthey Bishop Inc.
4 Main Road
Malvern, PA 19355
(215) 648-8000

Measurement Science Corporation
P.O. Box 338
Brigham City, UT 84302
(801) 723-8541

Mensor Corporation
2230 IH-35 South
San Marcos, TX 78666
(512) 392-6091

Measurement Group
P.O. Box 27777
Raleigh, NC 27611
(919) 365-3800

Midwest Components, Inc.
P.O. Box 726
Muskegon, MI 49443
(616) 777-2602

Minco Products Inc.
7300 Commerce Lane
Minneapolis, MN 55432
(612) 786-3121

Molecu-Wire Corporation
P.O. Box 495
Farmingdale, NJ 07727
(201) 922-9400

Multi-State Devices Ltd.
(see Canadian Thermostat & Control Devices)

National Basic Sensor Corporation
Box 205
Feasterville, PA 19047
(215) 322-4700

Newport Laboratories, Inc.
630 E. Young Street
Santa Ana, CA 92705
(714) 540-4914

Noral, Inc.
23600 Mercantile Road
Commerce Park
Cleveland, OH 44122
(216) 841-2345

Noronix, Ltd.
8 Thomas Street
London, SE18 6HR, England

Oven Industries, Inc.
Hempt Road
P.O. Box 229
Silver Spring Industrial Park
Mechanicsburg, PA 17055
(717) 766-0721

Palmer Electronics, Inc.
156 Belmont Avenue
Garfield, NJ 07026

Pennsylvania Electronics Technology Inc.
1397 Frey Road
Pittsburgh, PA 15235
(412) 243-3816

Phoenix Precision Instrument Company
Division Virtis
Rte. 208
Gardiner, NY 12525
(914) 255-5000

Photofabrication Technology, Inc. (PTI)
Century Building
Derry, NH 03038
(603) 434-4113

Prime Manufacturing Corporation
7730 South 6th Street
Oak Creek, WI 53154
(414) 764-1400

Protective Controls Inc.
(see Airpax/North American
Philips Controls Corp.)

Pyco, Inc.
600 E. Lincoln Highway
Penndel, PA 19047
(215) 757-3704

Quality Thermistor, Inc.
2096 South Cole Road
Suite 7
Boise, ID 83705
(208) 377-3373

RCD Corporation
8 Blueberry Lane
Bedford, NH 03102
(603) 669-0054

RDF Corporation
23 Elm Avenue
Hudson, NH 03051
(603) 882-5195

RFL Industries
Powerville Road
Boonton, NJ 07005
(201) 334-3100

R.T.D. Company
Box 7604
Colorado Springs, CO 80933
(303) 599-3700

Relco Products, Inc.
5594 E. Jefferson
Denver, CO 80237
(303) 756-1143

Reotemp Instrument Corporation
11568 Sorrento Valley Rd.
Suite 10
San Diego,, CA 92121
(714) 481-7737

The Riley Company
Panalarm Division
7401 N. Hamlin Avenue
Skokie, IL 60076
(312) 675-2500

Rochester Instrument Systems, Inc.
255 North Union Street
Rochester, NY 14605
(716) 325-5120

Rosemount Inc.
12001 W. 78th Street
Minneapolis, MN 55435
(612) 941-5560

Seci-Societa
Electtrotecnica Chimica Italiana
Via G. B. Grassi
97, 20157 Milano, Italy

Sensing Devices Limited
97 Tithebar Road
Southport PR8 6AG
Lancashire, England

Senso-Metrics Inc.
7775 Kester Avenue
Van Nuys, CA 91405
(213) 988-6070

Sentel Associates, Inc.
1125 C Stewart Drive
Sunnyvale, CA 94086
(408) 737-1400

Service Tectonics Instr. Div. of
Maskote Corporation
17168 E. Warren Avenue
Detroit, MI 48224
(313) 882-9100

Sierracin Corporation
Harrison Division
3020 Empire Avenue
Burbank, CA 91504
(213) 849-6581

Sigma Instruments Ltd.
P.O. Box 43
Toronto 18, Ontario, Canada
(416) 239-8161

Sigmund Cohn Corporation
121 S. Columbus Avenue
Mt. Vernon, NY 10553
(914) 664-5300

Simpson Electric Company
853 Dundee Avenue
Elgin, IL 60120
(312) 697-2260

Stow Laboratories, Inc.
Kane Industrial Drive
Hudson, MA 01749
(617) 562-9347

Syscon International Inc.
1239 South Bend Avenue
South Bend, IN 44617
(219) 287-5916

Sys-Tec, Inc.
877 Third Street, SW
New Brighton, NM 55112
(612) 636-6373

Technical Hardware, Inc.
P.O. Box 3609
Fullerton, CA 92634
(714) 870-1882

Temp, Inc.
407 Diamond Street
P.O. Box 929
Fairmont, WV 26554

Tempkey, Inc.
2155 Park Blvd.
Palo Alto, CA 94306
(415) 324-8798

Templine
23555 Telo Avenue
Torrance, CA 90505
(213) 539-2333

Temp-Pro Inc.
P.O. Box 265
35 Main Street
Haydenville, MA 01039
(413) 268-7263

Temtex
5619 Dyer Street
Dallas, TX 75206
(214) 361-7108

Texas Instruments
13500 N. Central Expressway
Dallas, TX 75231
(214) 238-03741

Thermalogic
Division of DYTRON Inc.
241 Crescent Street
Waltham, MA 02154
(617) 891-9496

ThermoElectric Co., Inc.
109 Fifth Street
Saddle Brook, NJ 07662
(201) 843-5800

Thermometrics Inc.
808 U.S. Highway #1
Edison, NJ 08817
(201) 287-2870

Transmation Inc.
977 Mt. Read Blvd.
Rochester, NY 14605
(716) 254-9000

Tudor Technology, Inc.
424 Caredean Drive
Horsham, PA 19044
(215) 674-4150

Tylan Corporation
19220 S. Normandie
Torrance, CA 90502
(213) 532-3420

United Electric Controls
85 School Street
Watertown, MA 02172
(617) 926-1000

United Systems Corporation
Digitec
918 Woodley Road
Dayton, OH 45403
(513) 254-6251

Vaisala Oy (Industrial Sales)
PL 26, SF-00421
Helsinki 42, Finland

Validyne Engineering Corporation
19414 Londelius Street
Northridge, CA 91324
(213) 886-8488

Vertronix, Inc.
P.O. Box 907
Evergreen, CO 80439

Victory Engineering
Victory Road
Springfield, NJ 07081
(201) 379-5900

Virtis Company
(see: Phoenix Precision)

Vitec Incorporated
23645 Mercantile Road
Cleveland, OH 44122
(216) 464-4670

Wahl, William Corporation
12908 Panama Street
Los Angeles, CA 90066
(213) 391-7234

WeatherMeasure Corporation
P.O. Box 41257
Sacramento, CA 95841

Weed Instrument Company, Inc.
P.O. Box 549
109 W. Eleventh Street
Elgin, TX 78621
(512) 285-3411

West Coast Research Corporation
P.O. Box 25061
Los Angeles, CA 90025
(213) 478-8833

Western Thermistor Corporation
354 Via Del Monte
Oceanside, CA 92054
(714) 433-4484

Westinghouse Electric Corporation
95 Oragne Street
Newark, NJ 07102
(201) 465-0222

West Instruments
Gulton Measurement & Control
Systems
Gulton Industrial Park
East Greenwich, RI 02818
(401) 884-6800

Yellow Springs Instrument Company
P.O. Box 279
Yellow Springs, OH 45387
(513) 767-7242

Yokogawa Corp. of America
5 Westchester Plaza
Elmsford, NY 10523
(914) 592-6767

Thermal Radiation Sensors, Pyrometers, Heat Flow Sensors

Bailey Instruments, Inc.
515 Victor Street
P.O. Box 800
Saddle Brook, NJ 07662
(201) 845-7252

Barber-Colman Industrial Instruments Div.
1700 Rock Street
Rockford, IL 61101
(815) 877-0241

Barnes Engineering Company
30 Commerce Road
Stamford, CT 06904
(203) 348-5381

Bristol Division
ACCO
929 Connecticut Avenue
Bridgeport, CT 06607
(203) 335-2511

CGS/Thermodynamics
LaCrue Street
Concord Industrial Park
Concordville, PA 19331
(215) 358-1510

Capintec Instruments Inc.
136 Summit Avenue
Montvale, NJ 07645
(201) 391-3930

Chino Works Ltd.
1-22-8 Nishi-Ikebukuro
Toshima-Ku
Tokyo, Japan

Dynalco Corporation
5200 N.W. 37th Avenue
P.O. Box 8187
Ft. Lauderdale, FL 33310
(305) 739-4300

E T
P.O. Box 404
6315 Carpinteria Avenue
Carpinteria, CA 93013
(805) 684-5461

Electro Optical Industries Inc.
P.O. Box 3770
Santa Barbara, CA 93105
(805) 964-6701

Epic, Inc.
150 Nassau Street
New York, NY 10038
(212) 349-2470

Eppley Laboratory, Inc.
12 Sheffield Avenue
Newport, RI 02840
(401) 847-1020

Hamamatsu Corporation
120 Wood Avenue
Middlesex, NJ 08846
(201) 469-6640

Honeywell, Inc.
Process Control Division
1100 Virginia Drive
Ft. Washington, PA 19034
(215) 643-1300

International Thermal Instrs. Co.
P.O. Box 309
Del Mar, CA 92014
(714) 755-4436

Ircon, Inc.
7555 N. Linder Avenue
Skokie, IL 60076
(312) 967-5151

Irtronics
Division of Mechtronics Corp.
57 Commerce Road
Stamford, CT 06902
(302) 348-2671

Kane-May Ltd.
for U.S. Freeman Associates
Burrowfield, Welwyn Garden City
Hertfordshire, England

Land Instruments, Inc.
P.O. Box 1623
Tullytown, PA 19007
(215) 943-7882

Laser Precision Corporation
1231 Hart Street
Utica, NY 13502
(315) 797-4449

Leeds & Northrup Company
Sumneytown Pike
North Wales, PA 19454
(215) 643-2000

Mikron Instrument Company
P.O. Box 211
Ridgewood, NJ 07451
(201) 891-7330

Molectron Corporation
177 N. Wolfe Road
Sunnyvale, CA 94086
(408) 738-2661

Newport Laboratories, Inc.
630 E. Young
Santa Ana, CA 92705
(714) 540-4914

Niagara Scientific Inc.
118 Boss Road
E. Syracuse, NY 13211
(315) 437-0821

Optronic Labs, Inc.
7676 Fenton Street
Silver Spring, MD 20910
(301) 587-2255

Pyrometer Instrument Co., Inc.
234 Industrial Parkway
Northvale, NJ 07647
(201) 768-2000

Raeco, Inc.
550 Armory Drive
S. Holland, IL 60473
(312) 33106001

Ratio Controls Corporation
260 Laura Drive
Addison, IL 60101
(312) 543-9330

Raytek, Inc.
325 E. Middlefield Road
Mountain View, CA 94043
(415) 961-1650

Sensors, Inc.
3908 Varsity Drive
Ann Arbor, MI 48104
(313) 973-1400

Sensor Technology
21012 Lassen Street
Chatsworth, CA 91311
(213) 882-4100

Sick Optik-Elektronik, Inc.
113 S. Main Street
Stillwater, NM 55082
(612) 439-6516

Syscon International, Inc.
1239 South Bend Avenue
South Bend, IN 46617
(219) 287-5916

Telatemp Corporation
P.O. Box 5160
Fullerton, CA 92635
(714) 879-2901

Thermogage, Inc.
330 Allegany Street
Frostburg, MD 21532
(301) 689-6630)

Thermometrics Inc.
808 U.S. Highway #1
Edison, NJ 08817
(201) 287-2870

UTI
325 N. Mathilda Avenue
Sunnyvale, CA 94086
(408) 738-3301

Victory Engr. Corporation
Victory Road
Springdfield, NJ 07081
(201) 379-5900

Wahl, William Corporation
12908 Panama Street
Los Angeles, CA 90066
(213) 391-7234

Wilco Inc.
(see: Sick Optik-Elektronik, Inc.)

Williamson Corporation
1152 Main Street
West Concord, MA 01742
(617) 369-9607

FLOW

Differential Pressure Flow Meters

Action Instruments Co., Inc.
8601 Aero Drive
San Diego, CA 92123
(714) 279-5726

Ametek, Inc.
Schutte & Koerting Div.
State Road
Cornwells Heights, PA 19020
(215) 639-0900

Asahi Instruments Co., Ltd.
Head Office
19-17 Tamachi, Kokurakita-Ku
Kitakyushu-City 803, Japan

BIF
General Signal
1600 Division Road
West Warwick, RI 02893
(401) 885-1000

Badger Meter Inc.
Instruments Division
4545 W. Brown Deer Road
Milwaukee, WI 53223
(414) 355-0400

Badger Meter Inc.
Precision Products Division
6116 E. 15th Street
Tulsa, OK 74112
(918) 836-4631

Bailey Controls Company
29801 Euclid Avenue
Wickliffe, OH 44092
(216) 943-5000

Bristol Division
ACCO
929 Connecticut Avenue
Bridgeport, CT 06607
(203) 335-2511

Beckman Instruments, Inc.
Technical Information Services
Cedar Grove Operation
89 Commerce Road
Cedar Grove, NJ 07009
(201) 239-6200

Bubble-O-Meter
Box 338
Temple City, CA 91780

Capital Controls Company
P.O. Box 211
Colmar, PA 18915
(215) 822-2901

Computer Instruments Corp.
100 Madison Avenue
Hempstead, NY 11550
(516) 483-8200

Conometer Corporation
Box 383
Haddonfield, NJ 08033
(609) 428-7776

Consolidated Controls Corp.
15 Durant Avenue
Bethel, CT 06801
(203) 743-6721

Datametrics
340 Fordham Road
Wilmington, MA 01887

Davis Instrument
513 E. 36th Street
Baltimore, MD 21218
(301) 243-4301

Dieterich Standard Corporation
Subsidiary of Dover Corp.
Box 9000
Boulder, CO 80306
(303) 449-9000

Henry G. Dietz Company, Inc.
14-26 28th Avenue
Long Island City, NY 11102
(212) 726-3347

Dwyer Instruments, Inc.
Box 373
Jct. Ind. 212 & US12
Michigan City, IN 46360
(219) 872-9141

Estech, Inc.
308 Talmadge Road
P.O. Box 594
Edison, NJ 00817
(201) 287-1111

Erdco Engineering Corporation
136 Official Road
Addison, IL 60101
(312) 543-6733

Fischer & Porter Company
775 Warminster Road
Warminster, PA 18974
(215) 674-6000

Flo-Tron, Inc.
495 E. 30th Street
Paterson, NJ 07504
(201) 279-6500

Flow-Dyne Engineering Inc.
P.O. Box 9034
Fort Worth, TX 76107
(817) 732-2858

Fluid Components Inc. (FCI)
870 Remmet Avenue
Canoga Park, CA 91304
(213) 883-0806

Fluidynamic Devices Ltd.
3216 Lenworth Drive
Mississauga, Ontario, Canada L4X, 2G1
(416) 625-9501

Fluidyne Instrumentation
2930 Lakeshore Avenue
Oakland, CA 94610
(415) 444-2376

The Foxboro Company
Dept. 120
38 Neponset Avenue
Foxboro, MA 02035
(617) 543-8750

Fox Valve Development Co., Inc.
222 Great Meadow Lane
E. Hanover, NJ 07936
(201) 887-7474

Gould Inc.
Measurement Systems Div.
2230 Statham Blvd.
Oxnard, CA 93030
(805) 487-8511

Honeywell Inc.
Process Control Division
1100 Virginia Drive
Fort Washington, PA 19034
(215) 643-1300

ITT Barton
580 Monterey Pass Road
Box 2013
Monterey Park, CA 91754
(213) 289-3581

The W.A. Kates Company
P.O. Box 627
Deerfield, IL 60015
(312) 945-0950

Konigsberg Instruments
2000 E. Foothill Blvd.
Pasadena, CA 91107
(213) 795-9719

Kontes Manufacturing Company
Spruce Street
P.O. Box 729
Vineland, NJ 08360
(609) 692-8500

Leeds & Northrup Company
Sumneytown Pike
North Wales, PA 19454
(215) 643-2000

Leslie Company
399 Jefferson Road
Parsippany, NJ 07054
(201) 887-9000

Meriam Instrument
Div. of Scott & Fetzer Co.
10920 Madison
Cleveland, OH 44102
(216) 281-1100

Mid-West Instrument
P.O. Box 939
Troy, MI 48099
(313) 585-0900

Orange Research Inc.
404 Boston Post Road
Orange, CT 06477
(203) 795-6225

RCM Industries
P.O. Box 351
Orinda, CA 94563
(415) 687-8363

Ramapo Instr. Co., Inc.
2 Mars Court
P.O. Box 428
Montville, NJ 07045
(201) 263-8800

Robertshaw Controls Company
Industrial Instrumentation Div.
1809 Staples Mill Road
Richmond, VA 23230
(804) 358-2301

Ruska Instrument Corporation
6121 Hillcroft
P.O. Box 36010
Houston, TX 77036
(713) 774-2533

Scanivalve, Inc.
P.O. Box 20005
San Diego, CA 92120
(714) 283-5851

Setra Systems, Inc.
1 Strathmore Road
Natick, MA 01760
(617) 655-4645

The Singer Company
American Meter Division
13500 Philmont Avenue
Philadelphia, PA 19116
(215) 673-2100

J.W. Sweet Company
P.O. Box 6395
Columbia, SC 29260
(803) 754-7492

Taylor Instrument Company
Div. of Sybron Corporation
95 Ames Street
Rochester, NY 14601
(716) 235-5000

Teledyne Hastings-Raydist Co.
P.O. Box 1275
Newcomb Avenue
Hampton, VA 23361
(703) 723-6531

Trimount Instrument Company
932 W. Wrightwood
Chicago, IL 60614
(312) 327-2288

UGC Industries, Inc.
P.O. Box 3736
Shreveport, LA 71103
(318) 631-0373

Unimeasure
(see: Konigsberg Instrs.)

United Sensor & Control Corp.
85 School Street
Watertown, MA 02172
(617) 926-1000

Validyne Engineering Corporation
19414 Londelius Street
Northridge, CA 91324
(213) 886-8488

Waugh Controls Corporation
9001 Fullbright Avenue
Chatsworth, CA 91311
(213) 998-8281

West Coast Research Corporation
S. Sepulveda Boulevard
P.O. Box 25061
Los Angeles, CA 90025
(213) 8833

Westinghouse Electric Corporation
Computer & Instrumentation Div.
Box 402
Orrville, OH 44667

Turbine Flow Meters

American Meter Company
(see: Singer)

Autotronic Controls Corporation
6908 Commerce
El Paso, TX 79915
(915) 772-7431

Badger Metals Inc.
Instruments Division
4545 W. Brown Deer Road
Milwaukee, WI 53223
(414) 355-0400

Badger Meter Inc.
Precision Products Div.
6116 E. 15th Street
Tulsa, OK 74112
(918) 836-8411

Ball Manufacturing Inc.
903 W. Center Street, North
Salt Lake City, UT 84054
(801) 364-6451

Barton Instruments
900 S. Turnbull Canyon Road
Box 1882
City of Industry, CA 91749

Bearingless Flow Meter Co., Inc.
294 Beacon Street
Boston, MA 02116
(617) 262-4509

Brooks Instrument Division
Emerson Electric Company
P.O. Box 450
Statesboro, GA 30458
(912) 764-5471

C-E Invalco
P.O. Box 556
Tulsa, OK 94101
(918) 932-5671

Camco Inc.
Energy Measurement & Control Group
7010 Ardmore
P.O. Box 14484
Houston, TX 77021
(713) 747-4000

Cox Instrument Division
Lynch Corporation
15300 Fullerton
Detroit, MI 48227
(313) 838-5780

Daniel Industries, Inc.
P.O. Box 19097
Houston, TX 77024
(713) 467-6000

Eastech Inc.
308 Talmadge Road
P.O. Box 594
Edison, NJ 08800
(201) 287-1111

Electrac, Inc.
1614 Orangethrope Way
Anaheim, CA 92801
(714) 879-6021

Electronic Flo-Meters Inc.
P.O. Box 38269
Dallas, TX 75238
(214) 359-1982

Engineering Measurements Co., Inc.
600 Diagonal Hwy.
Longmont, CO 80501
(303) 651-0550

Fischer & Porter
755 Warminster Road
Warminster, PA 18974
(215) 675-6000

Floscan Instrument Company
3016 N.E. Blakely Street
Seattle, WA 98105
(206) 524-6625

Flo-Tech, Inc.
403 S. Washington Street
Mundelein, IL 60060
(312) 566-9120

Flowcon System
Div. of Bower Industries
P.O. Box 1631
1601 West Orangewood Ave.
Orange, CA 92668
(714) 633-8334

Flow Technology Inc.
4250 E. Broadway Road
Phoenix, AZ 85040
(602) 268-8776

Foxboro Company
38 Neponset Avenue
Foxboro, MA 02035
(617) 543-8650

Geosource, Inc.
Flow Measurement & Control Div.
1602 Wagner Avenue
P.O. Box 559
Erie, PA 16512
(814) 899-0661

Halliburton
Special Products Division
P.O. Drawer 1431
1015 Bois D'Arc
Duncan, OK 73533
(405) 255-3760

Hersey Products Inc.
Hersey Division
250 Elm Street
Dedham, MA 02026
(617) 326-9400

Hersey Products Inc.
Industrial Measurement Div.
Old Valley Falls Road
Spartanburg, SC 29303
(803) 578-3800

Hoffer Flow Controls Inc.
P.O. Box 745
149 Highway 36
Port Monmouth, NJ 07758
(201) 787-1998

ITT Barton
Box 1882
City of Industry, CA 91749
(213) 961-2547

Kent Meter Sales, Inc.
7 East Silver Springs Blvd.
Suite 400, Concord Square
Ocala, FL 32670
(904) 732-4670

Mead Instruments Corporation
One Dey Lane
Riverdale, NJ 07457
(201) 835-5988

Mergas Meters Inc.
Mercury Instruments Inc.
3940 Virginia Avenue
Cincinnati, OH 45227
(513) 272-1111

Moore Industries, Inc.
16650 Schoenborn Street
Sepulveda, CA 91343
(213) 894-7111

Olymic Controls Inc.
11246 South Post Oak
Houston, TX t77035
(713) 721-3431

Precision Flow Measurements
(see: Sponsler Co.)

Quantum Dynamics Inc.
19458 Ventura Blvd.
P.O. Box 865
Tarzana, CA 91365
(213) 345-6828

Richard Lee Company
12 Park Street
Canford, NJ 07016
(201) 276-0710

Simmonds Precision Products Inc.
Rockingham Road
Bellows Balls, VT 05101
(802) 463-4576

The Singer Company
American Meter Division
13500 Philmont Avenue
Philadelphia, PA 19116
(215) 673-2100

Smith Meter Systems Div.
Geosource Inc.
(see: Geosource, Inc.)

Sponsler Company, Inc.
1 Hendry Lane
Brick Town, NJ 08723
(201) 477-2095

Waugh Controls Corporation
9001 Fullbright Avenue
Chatsworth, CA 91311
(213) 998-8281

Mass Flow Sensors

Agar Instrumentation
2203 Blalock Road
Houston, TX 77080
(713) 461-2427

American Meter Division
Singer Company
(see: The Singer Co.,
American Meter Div.)

Bendix Corporation
Instrument & Life Support Div.
P.O. Box 4508
Davenport, IA 52808

Bristol Division (ACCO)
929 Connecticut Avenue
Bridgeport, CT 06607
(203) 335-2511

Brooks Instrument Div.
Emerson Electric Co.
407 W. Vine Street
Hatfield, PA 19440
(215) 368-2000

Datametrics
340 Fordham Road
Wilmington, MA 01887
(617) 658-5410

Eldec Corporation
16700 13th Avenue, West
P.O. Box 100
Lynwood, WA 98036
(206) 743-1313

Electrac, Inc.
1614 Orangethorpe Way
Anaheim, CA 92801
(714) 879-6021

Electronic Flo-Meters, Inc.
P.O. Box 38269
Dallas, TX 75238
(214) 349-1982

Flo-Tron, Inc.
495 E. 30th Street
Paterson, NJ 07504
(201) 279-6500

The Foxboro Company
Dept 120, 38 Neponset Ave.
Foxboro, MA 02035
(617) 543-8750

ITT Barton
Box 2013
Monterey Park, CA 91754
(213) 289-3581

Jiskoot Autocontrol Ltd.
c/o A.W. Risser Company
64 Edgewood Drive
Grafton, OH 44044
(216) 458-5091

Kay-Ray, Inc.
516 W. Campus Drive
Arlington Heights, IL 60004
(312) 259-5600

Kurz Instruments
P.O. Box 849, 20 Village Square
Carmel Valley, CA 93924
(408) 659-3421

Leeds & Northrup Company
Sumneytown Pike
North Wales, PA 19454
(215) 643-2000

Matheson Gas Products
P.O. Box E
1275 Valley Brooke Ave.
Lyndhurst, NJ 07071
(201) 935-6660

Micromotion Inc.
2700 29th Street
Boulder, CO 80301
(303) 442-5911

Milltronics, Inc.
2409 Avenue J
Arlington, TX 76011
(817) 649-8540

Moore Industries Inc.
16650 Schoenborn Street
Sepulveda, CA 91343
(213) 894-7111

Precision Flow Devices Inc.
P.O. Box 2364
Santa Clara, CA 95051

Quantum Dynamics, Inc.
19458 Ventura Blvd.
Tarzana, CA 91356
(213) 345-6828

Ramapo Instruments Co., Inc.
P.O. Box 428
2 Mars Court
Montville, NJ 07045
(201) 263-8800

The Singer Company
American Meter Div.
13500 Philmont Avenue
Philadelphia, PA 19116
(215) 673-2100

TSI Inc.
500 Cardigan Road
P.O. Box 43394
St. Paul, MN 55164
(612) 483-0900

Technology Inc.
Instruments & Controls Div.
P.O. BOX 3036
Overlook Branch
Dayton, OH 45431
(513) 426-2405

Teledyne Hastings-Raydist
P.O. Box 1275
Hampton, VA 23361
(703) 723-6531

Thermal Instruments Co.
217 Stemer Mill Road
Trevose, PA 19047
(215) 355-8400

Tylan Corporation
19220 S. Normandie
Torrance, CA 90502
(213) 532-3420

UGC Industries Inc.
P.O. Box 3736
Shreveport, LA 71103
(318) 631-0373

Wallace & Tiernan Division
Penwalt Corporation
25 Main Street
Belleville, NJ 07109
(201) 759-8000

Westinghouse Electric Corp.
Computer & Instrumentation Div.
200 Beta Drive
Pittsburgh, PA 15238
(412) 782-1730

Westinghouse Electric Corp.
Computer & Instrumentation Div.
Box 402
Orrville, OH 44667

Ultrasonic Flow Sensors

Accusonic Division
O.R.E., Inc.
P.O. Box 709
Falmouth, MA 02541
(617) 548-5800

Badger Meter, Inc.
Instruments Div.
4545 W. Brown Deer Road
Milwaukee, WI 53223
(414) 355-0400

Badger Meter, Inc.
Precision Products Div.
6116 E. 15th Street
Tulsa, OK 74112
(918) 836-4631

Bailey Scientific
P.O. Box 1245
West Sacramento, CA 95691
(916) 371-1472

Baird Controls, Inc.
522 West 5th Avenue
Napierville, IL 60540

Brooks Instrument
Emerson Electric Canada
Box 150
Markham, Ontario, Canada L3P 3J6
(416) 297-2330

Columbia Controls
4545 Pine Timbers
Bldg. 300
Houston, TX 77041
(713) 462-7800

Controlotron Corporation
155 Plant Avenue
Hauppauge, NY 11787
(516) 231-3600

DuPont Company
Instrument Products Div.
1007 Market Street
Wilmington, DE 19898
(302) 772-5500

Endress & Hauser Inc.
2350 Endress Place
Greenwood, IN 46142
(317) 535-7138

Hersey Products, Inc.
Industrial Measurement Div.
Old Valley Falls Road
Spartanburg, SC 29303
(803) 578-3800

Inventron Industries Inc.
4005 W. Jefferson Blvd.
Los Angeles, CA 90016
(213) 731-2507

Leeds & Northrup Company
Sumneytown Pike
North Wales, PA 19454
(215) 643-2000

Linden Laboratories, Inc.
P.O. Box 920
State College, PA 16801
(814) 355-5491

Manning Environment Corp.
120 Dubois Street
P.O. Box 1356
Santa Cruz, PA 95061
(408) 427-0230

Mapco Inc.
(Nusonics) Process & Pollution
Cont.
1800 S. Baltimore Avenue
Tulsa, OK 74119
(918) 488-1010

Milltronics Inc.
2409 Avenue J
Arlington, TX 76011
(817) 649-8540

O.R.E.
(Ocean Research Equipment, Inc.)
(see: Accusonic)

Polysonics
3230 Mercer Street
P.O. Box 22488
Houston, TX 77027
(713) 623-2134

Siemans Corporation
Medical Systems Group
186 Wood Avenue, South
Iselin, NJ 08830
(201) 494-1000

Sirco Controls
2795 152nd Avenue, NE
Redmond, WA 98052
(206) 885-5303

Sparling
Div. Envirotech Corp.
4097 N. Temple City Blvd.
El Monte, CA 91731
(213) 444-0571

Stevens International Inc.
P.O. Box 619
Kennett Square, PA 19348
(215) 444-0616

Tech/Sonics
(see: Polysonics)

Texas Nuclear Division
Ramsey Engineering Company
Box 9267
Austin, TX 78766

Tri-Aid Sciences, Inc.
830 Linden Avenue
Rochester, NY 14625
(716) 381-1642

Wesmar
905 Dexter Avenue, N.
Seattle, WA 98109
(206) 285-2420

Westinghouse Electric Corp.
Computer & Instrumentation Div.
Box 402
Orrville, OH 44667

Westinghouse Electric Corp.
Computer & Instrumentation Div.
200 Beta Drive
Pittsburgh, PA 15238
(412) 782-1730

Open Channel Flow Meters

American Meter Division
(see: The Singer Co.)

BIF, A Unit of General Signal
1600 Division Road
West Warwick, RI 02893
(401) 885-1000

BIF, Sanitrol, A Unit of General Signal
1800 12th Street, SE
P.O. Box 4
Largo, FL 33540
(813) 584-2157

Badger Meter, Inc.
Instruments Div.
4545 W. Brown Deer Road
Milwaukee, WI 53223
(414) 355-0400

Badger Meter, Inc.
Precision Products Div.
6116 E. 15th Street
Tulsa, OK 74112
(918) 836-8411

Bailey Scientific
P.O. Box 1245
Sacramento, CA 95691
(916) 371-1472

C-E Invalco
Div. of Combustion Engineering Inc.
P.O. Box 556
Tulsa, OK 74101
(918) 932-5671

Computer Instruments Corp.
100 Madison Avenue
Hempstead, LI, NY 11550
(516) 483-8200

Controlotron Corporation
155 Plant Avenue
Hauppauge, NY 11787
(516) 231-3600

Cushing Engineering Inc.
(see: Monitek, Inc.)

Cues, Inc.
P.O. Box 5516
3501 S. Fineland Road
Orlando, FL 32805
(305) 241-1671

Drexelbrook Engineering Co.
205 Keith Valley Road
Horsham, PA 19044
(215) 674-1234

Endress & Hauser Inc.
2350 Endress Place
Greenwood, IN 46142
(317) 535-7138

Fischer & Porter Company
775 Warminster Road
Warminster, PA 18974
(215) 674-6000

Flow Technology, Inc.
4250 E. Broadway Road
Phoenix, AZ 85040
(602) 268-8776

The Foxboro Company
Dept. 120, 38 Neponset Ave.
Foxboro, MA 02035
(617) 543-8750

Hersey Products Inc.
Industrial Measurement Div.
Old Valley Falls Road
Spartanburg, SC 29303
(803) 578-3800

Honeywell Inc.
Process Control Div.
1100 Virginia Drive
Fort Washington, PA 19034
(215) 643-1300

ISCO
4700 Superior Avenue
Lincoln, NE 68504
(402) 464-0231

Inventron Industries, Inc.
4005 W. Jefferson Blvd.
Los Angeles, CA 90016
(213) 731-2507

Kahl Scientific Instrument Corp.
P.O. Box 1166
El Cajon, CA 92022
(714) 444-2158

Leupold & Stevens, Inc.
P.O. Box 688
600 N.W. Meadow Drive
Beaverton, OR 97005
(503) 646-9171

Macrodyne Inc.
153 Princeton Road
Schenectady, NY 12306
(518) 356-3500

Manning Environmental Corporation
120 DuBois Street
P.O. Box 1356
Santa Cruz, CA 95061
(408) 427-0230

Marsh-McBirney Inc.
8595 Grovemont Circle
Gaithersburg, MD 20760
(301) 869-4700

Mead Instrument Corporation
One Day Lane
Riverdale, NJ 07457
(201) 835-5988

Milltronics Inc.
2409 Avenue J
Arlington, TX 76011
(817) 649-8540

Monitek, Inc.
Monitor Technology Inc.
630 Price Avenue
Redwood City, CA 94063
(415) 365-6550

NB Instruments Inc.
935 Horsham Road
Horsham, PA 19044
(215) 674-8660

NP Industries, Inc.
P.O. Box 746
Niagara Falls, NY 14302
(716) 282-0022

Pro-Tech, Environmental Instr. Div.
Crane Company
1510 Russell Road
Paoli, PA 19301
(215) 644-4420

Raeco Inc.
550 Armory Drive
South Holland, IL 60473
(312) 331-6001

Ramapo Instrument Co., Inc.
P.O. Box 428
2 Mars Court
Montville, NJ 07045
(201) 263-8800

Robertshaw Controls Co.
Industrial Instrumentation Div.
333 N. Euclid Way
Anaheim, CA 92803
(714) 535-8151

Sierra Instruments Inc.
P.O. Box 909
Village Square Building
Carmel Valley, CA 93924
(408) 659-3177

Sigmamotor Incorporated
14 Elizabeth Street
Middleport, NY 14105
(7116) 735-3616

The Singer Company
American Meter Division
13500 Philmont Avenue
Philadelphia, PA 19116
(215) 673-2100

Sirco Controls Company
2795 - 152nd Avenue, NE
Redmond, WA 98052
(206) 885-5303

Sparling Division
Envirotech Corporation
4097 N. Temple City Blvd.
El Monte, CA 91731
(213) 444-0571

Stevens International, Inc.
P.O. Box 619
Kennett Square, PA 19348
(215) 444-0616

Tri-Aid Sciences, Inc.
830 Linden Avenue
Rochester, NY 14625
(716) 381-1642

Turner Designs
2247A Old Middlefield Way
Mountain View, CA 94043
(415) 965-9800

Universal Engineered Systems, Inc.
7071 Commerce Circle
Pleasanton, CA 94566
(415) 462-1543

Wesmar, Environmental Meas. Systems
905 Dexter Avenue, N
Seattle, WA 98109
(206) 285-2420

Linear Displacement Sensors

ADE Corporation
127 Coolidge Hill Road
Watertown, MA 02172
(617) 923-2180

ASI
840 Del Rey Avenue
Sunnyvale, CA 94086
(408) 739-6700

Acme Cleveland Corporation
Box 91276
Cleveland, OH 44101

Alco Electronic Products Inc.
1551 Osgood Street
Andover, MA 01845
(617) 685-4371

Alina Corporation
175 Sunnyside Blvd.
Plainview, NY 11803
(615) 433-1000

Allen-Bradley Company
1201 S. Second Street
Milwaukee, WI 53204
(414) 671-2000

American Electronic Controls
Scientronics Division
25 Clark Drive
Barrington, NJ 08007
(609) 546-5792

B. C. Ames Company
131 Lexington Street
Waltham, MA 02154
(617) 893-0095

Ametek Controls Division
860 Pennsylvania Blvd.
Feasterville, PA 18960
(215) 355-6900

Anorad Corporation
116 Plant Avenue
Smithtown, NY 11787
(516) 234-1824

Astrosystems Inc.
6 Nevada Drive
Lake Success, NY 11040
(516) 328-1600

Atmospheric Sciences Inc.
(see: ASI)

Autech Corporation
7020 Huntley Road
Columbus, OH 43229
(614) 888-9924

Automatic Switch Company
50-56 Hanover Road
Florham Pk, NJ 07932
(201) 966-2000

Automatic Timing & Controls Inc.
King of Prussia, PA 19406
(215) 265-0200

Automation Systems, Inc.
Del Mar Drive
Brookfield, CT 06804
(203) 775-2581

BIE Instruments Inc.
2100 West Loop South
Houston, TX 77027
(713) 961-1921

Banner Engineering
(see: Truck Multiprox Inc.)

Bentley Nevada Corporation
P.O. Box 157
Minden, NV 89423
(702) 782-3611

Burrell Corporation
2223 Fifth Avenue
Pittsburgh, PA 15219
(412) 471-2527

Columbia Research Laboratories
MacDade Blvd. and Bullens Lane
Woodlyn, PA 19094
(215) 532-9464

Dearborn Gage Company
32330 Ford Road
Garden City, MI 48135
(313) 422-8300

Delavan Electronics Inc.
1441 North 73rd Street
Scottsdale, AZ 85260
(602) 948-6530

R.B. Denison Inc.
(see: Gould Inc Controls Div)

Disa Electronics
779 Susquehanna Avenue
Franklin Lakes, NJ 07417
(201) 891-9460

Dynapar Corporation
1675 Delany Road
Gurnee, IL 60031
(312) 662-2666

Edwards High Vacuum, Inc.
3279 Grand Island Blvd.
Grand Island, NY 14072
(716) 773-7552

Eldec, formerly Electro Devel. Corp.
Box 100
16700 13th Avenue
W. Lynnwood, WA 98036
(206) 743-1313

Electro Corporation
1845 57th Street
Sarasota, FL 33580
(813) 355-8411

Electromatic Equipment Co., Inc.
600 Oakland Avenue
Cedarhurst, NY 11516
(516) 295-4300

Electronic Counters & Controls Inc.
1500 McCormick Blvd.
Mundelein, IL 60060
(312) 362-8910

Electro Sonic Control
(see: Key Electro Sonic)

Engery Inc.
Idaho Falls, ID 83401
(208) 524-1000

Gagne Associates Inc.
1080 Chenango & Hillcrest
Binghamton, NY 13901
(607) 723-9556

Gould Inc. Controls Div.
R.B. Dennison
103 Broadway
Bedford, OH 44146
(216) 232-8200

Gould Inc. Instruments Div.
3631 Perkins Avenue
Cleveland, OH 44114
(216) 361-3315

Hamlin Incorporated
Lake and Grove Streets
Lake Mills, WI 53551
(414) 648-2361

Hammond Industries, Inc.
155 Michael Drive
Syosset, NY 11791
(516) 364-1900

Helm Instrument Co., Inc.
4511 South Avenue
Toledo, OH 43615
(419) 531-0146

Hitec Corporation
65 Power Road
Westford, MA 01886
(617) 692-4793

Hottinger Baldwin Measurements Inc.
17 Mercer Road
Natick, MA 01760
(617) 655-0950

IRD Mechanalysis, Inc.
6150 Huntley Road
Columbus, OH 43229
(614) 885-5376

Ideal Aerosmith Inc.
1505 E. Fox Farm Road
Cheyenne, WY 82001
(307) 634-7714

Indikon Company, Inc.
71 Coolidge Hill Road
Watertown, MA 02172
(617) 926-2710

Industrial Solid State Controls
Inc.
435 West Philadelphia St.
P.O. Box 934
York, PA 17405
(717) 848-1151

Integrated Photomatrix Inc.
The Grove Trading Estate
Dorchester, Dorset, England

JMR Electronics Corporation
1525 Blondell Avenue
Bronx, NY 10461
(212) 792-9620

Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, CO 80933
(303) 599-1500

Kavlico Corporation
20869 Plummer Street
Chatsworth, CA 91311
(213) 882-2400

Key ElectroSonic
P.O. Box 6
Milton-Freewater, OR 97862
(503) 938-5556

Konigsberg Instruments
(see: Unimeasure Div.)

Krautkramer-Branson, Inc.
250 Long Beach Blvd.
Stratford, CT 06497
(203) 377-3900

LEL Company
5 Burns Place
Cresskill, NJ 07626
(201) 569-8641

Lion Precision Inc.
60 Bridge Street
Newton, MA 02195
(617) 969-4710

MTS Systems Corporation
Motion Products Div.
P.O. Box 24012
Minneapolis, MN 55424
(612) 944-4095

McFadden Electronics Co.
8953 Atlantic Blvd.
South Gate, CA 90280
(213) 564-5958

Mechanical Technology Inc.
MTI Instruments Division
968 Albany Shaker Road
Lathan, NY 12110
(518) 785-2211

Metrix Instrument Co.
1711 Townhurst Drive
Houston, TX 77043
(713) 461-2131

Micro Switch Div. of Honeywell Inc.
11 W. Spring Street
Freeport, IL 61032
(815) 235-5500

Namco Controls
(see: Acme Cleveland Corp.)

New England Instrument Co.
14 Kendall Lane
Natick, MA 01760
(617) 873-9711

North American Philips Control Corp.
Cheshire Industrial Park
Cheshire, CT 06410
(203) 272-0301

The Ohmart Corporation
4241 Allendorf Drive
Cincinnati, OH 45209
(513) 272-0131

Omron Corp. of America
233 South Wacker Drive
Chicago, IL 60606
(312) 876-0800

Ono Sokki Co., Ltd.
22-16 Shimomaruko 2-Chome
Ohta-Ku, Tokyo, Japan

Optron Division, Universal Tech.
(see: Universal Tech. Inc.,
Optron Div.)

Ortec Inc.
100 Midland Road
Oak Ridge, TN 37830
(615) 482-4411

PPR Electronics Co.
209 W. Church Street
P.O. Box 396
Centre Hall, PA 16828
(814) 364-9162

Panametrics Inc.
221 Crescent Street
Waltham, MA 02154
(617) 899-2719

Photomation Inc.
270 Polaris Avenue
P.O. Box 460
Mountain View, CA 94042
(415) 967-8992

Pickering and Co., Inc.
Measurement & Controls Div.
101 Sunnyside Blvd.
Plainview, NY 11803
(516) 681-0200

Post Electronic Products Inc.
P.O. Box 494
Beverly, MA 01905
(617) 922-5005

Powell Magnetic Industries
Div. of Powell Electrical Mfg. Co.
8550 Mosley Drive
Houston, TX 77034

Power/Mation Division
1441 Iglehart Ave.
St. Paul, MN 55104
(612) 645-0781

Research Inc.
Box 24064
Minneapolis, MN 55424

Rechner Electronics
8651 Buffalo Avenue
Niagara Falls, NY 14304
(716) 283-8744

Robinson-Halpern Company
One Apollo Road
Plymouth Meeting, PA 19462
(215) 825-9200

SIC Division
(see: Automatic Timing & Controls)

Schaevitz Engineering
U.S. Rte. 130 & Union Ave.
Pennsauken, NJ 08110
(609) 662-8000

Scientific Technology Inc.
1201 San Antonio Road
Mountain View, CA 94043
(415) 965-0910

Sensor Corporation
303 Scottsdale Avenue
P.O. Box 140
Scottsdale, PA 15683
(412) 887-4080

Sick Optik-Elektronik, Inc.
113 South Main Street
Stillwater, MN 55082
(612) 439-6516

Sigma Laboratories Inc.
88-11 31st Avenue
East Elmhurst, NY 11369
(212) 898-2427

Siltran Digital
P.O. Box 437
Silverado, CA 92676
(714) 649-2704

Sonic Instruments Inc.
1018 Whitehead Road Ext.
Trenton, NJ 08638
(609) 883-5030

Techmet Company
6060 Executive Blvd.
Dayton, OH 45424
(513) 233-9935

Temposonics Inc.
131 East Ames Ct.
Plainview, NY 11803
(516) 935-4100

Terra Technology Corporation
3018 Western Avenue
Seattle, WA 98121
(206) 682-9946

Testing Machines, Inc.
400 Bayview Avenue
Amityville, NY 11701
(516) 842-5400

Textron Inc.
Waterbury Farrel Division
Cheshire, CT 06410

Theta Instrument Corporation
24 Dwight Place
Fairfield, NJ 07006
(201) 227-1700

Turck Multiprox Inc.
9710 Tenth Avenue, N.
Minneapolis, MN 55441
(612) 544-7977

UPA Technology Inc.
60 Oak Drive
Syosset, NY 11791
(516) 364-1080

Unimeasure Division
Konigsberg Instruments
2000 E. Foothill Blvd.
Pasadena, CA 91107
(213) 795-9719

United Detector Technology, Inc.
2644 30th Street
Santa Monica, CA 90405
(213) 396-3175

Unit Process Assemblies, Inc.
(see: UPA Technology Inc.)

Universal Technology Inc.
Optron Division
30 Hazel Terrace
Woodbridge, CT 06525
(203) 389-5384

Valmet Inc.
100 Production Court
New Britain, CT 06051
(203) 223-6784

Vexilar, Inc.
9345 Penn Avenue, South
Minneapolis, MN 55431

Warmer Electric Brake & Clutch Co.
449 Gardner Street
Beloit, WI 53511
(815) 389-3771

Wilco Inc.
(see: Sick Optik-Elektronik, Inc.)

Wilson Instrument Company
587 South Hill Avenue
Pasadena, CA 91106
(213) 449-4858

Zygo Corporation
Laurel Brook Road
Middlefield, CT 06455
(203) 347-8506

Linear and Angular Position Encoders

Airflyte Electronics Company
Box 231, New Hook Road
Bayonne, NJ 07002
(201) 436-2230

Altek Corporation
2150 Industrial Parkway
Silver Spring, MD 20904
(301) 622-3907

Anadex Instruments, Inc.
9825 DeSota Avenue
Chatsworth, CA 91311
(213) 988-8010

Astrosystems Inc.
6 Nevada Drive
Lake Success, NY 11040
(516) 328-1600

Auto-Trol Corporation
5650 N. Pecos Street
Denver, CO 80221
(303) 458-5900

BEI Electronics, Inc.
1101 McAlmont Street
Little Rock, AR 72203
(501) 372-7351

Bendix Corporation
Environmental Science Div.
1400 Taylor Avenue
Baltimore, MD 21204
(301) 825-5200

Bendix Corporation
Industrial Tools Div.
1901 S. Rockwell Street
Chicago, IL 60608
(312) 247-5900

Clifton Precison
(see: Litton Encoder Div.)

Computer Conversions Corporation
6 Dunton Ct.
East Northport, NY 11731
(516) 261-3300

Datacap Inc.
732 S. Federal Street
Chicago, IL 60605
(312) 922-5366

Datametrics
340 Fordham Road
Wilmington, MA 01887
(617) 658-5410

Data Technology, Inc.
4 Gill Street
Woburn, MA 01801
(617) 935-8820

Disc Instruments Inc.
102 E. Baker Street
Costa Mesa, CA 92626
(714) 979-5300

Dunlap Instrument Corp.
2254 Kingsway Drive
P.O. Box 521
Cape Girardeau, MO 63701
(314) 335-0522

Dynamics Research Corp.
Components Division
60 Concord Street
Wilmington, MA 01887
(617) 658-6100

Electronic Counters & Controls
1500 McCormick Blvd.
Mundelein, IL 60060
(312) 362-8910

Elographics, Inc.
1976 Oak Ridge Turnpike
Oak Ridge, TN 37830
(615) 482-4038

Flight Research
Div. of Geotel, Inc.
Charles City & Lewis Roads
P.O. Box 1-F
Richmond, VA 23201
(804) 222-0163

Hutchinson Industrial Corp.
40 W. Highland Park
Hutchinson, MN 55350
(612) 879-2371

Hybrid Systems Corporation
Crosby Drive
Bedford, MA 01730
(617) 275-1570

ILC Data Device Corporation
105 Wilbur Place
Bohemia, NY 11716
(516) 567-5600

Integrated Photomatrix Ltd.
The Grove Trading Estate
Dorchester, Dorset, England

Itek Measurement Systems Div.
Itek Corporation
27 Christina Street
Newton, MA 02161
(617) 969-7300

JMR Electronics Inc.
1525 Blondell Avenue
Bronx, NY 10461
(212) 792-9620

Key Electro Sonic
Box 6
Milton-Freewater, OR 97862
(503) 938-5556

LaBarge Inc.
Electronics Division
6540 E. Apache
P.O. Box 36
Tulsa, OK 74101
(918) 836-7611

Leupold & Stevens Inc.
P.O. Box 688
600 N.W. Meadow Drive
Beaverton, OR 97005
(503) 646-9171

Librascope Division
(see: Singer)

Litton Encoder Division
Marple at Broadway
Clifton Heights, PA 19018
(215) 622-1000

Litton Systems, Encoder Div.
20745 Nordhoff Street
Chatsworth, CA 91311
(213) 341-6161

Los Angeles Scientific Instrument Co., Inc.
2451 Riverside Drive
Los Angeles, CA 90039
(213) 662-2128

North Atlantic Ind. Inc.
200 Terminal Drive
Plainview, NY 11803
(516) 681-8600

Northern Precision Laboratories
202 Fairfield Road
Fairfield, NJ 07006
(201) 227-4800

Perrine Inc.
Paraiso Hot Springs
Soledad, CA 93960
(408) 678-3502

Randall, Douglas
6 Pawcatuck Avenue
Pawcatuck, CT 02891
(203) 599-1750

Renco Corporation
26 Coromar Drive
Goleta, CA 95017
(805) 968-1525

Sangamo Weston, Inc., EMR Teletry Div.
Sarasota, FL 33578
(813) 371-0811

Science Accessories Corporation
970 Kings Highway West
Southport, CT 06490
(203) 255-1526

Sequential Information Sys. Inc.
249 N. Sawmill River Road
Elmsford, NY 10523
(914) 592-5930

Siltran Digital
P.O. Box 437
Silverado, CA 92676
(714) 649-2704

Singer Company, Librascope Div.
833 Sonora Avenue
Glendale, CA 91201
(213) 245-8711

Standard Microsystems Corp.
35 Marcus Blvd.
Hauppauge, NY 11787
(516) 273-8898

Teledyne Gurley
514 Fulton Street
Troy, NY 12181
(518) 272-6300

Transmagnetics Inc.
210 Adams Blvd.
Farmingdale, NY 11735
(516) 293-3100

Unidyne Inc.
Subsidiary of Tri-Tronics Co., Inc.
619 Enterprise Drive
Oak Brook, IL 60511

Zeiss, Inc.
444 Fifth Avenue
New York, NY 10018
(212) 730-4400

Accelerometers and Vibration Equipment

Acurex Autodata Corporation
485 Clyde Avenue
Mountain View, CA 94043
(415) 964-3200

Airpot Corporation
Norwalk, CT 06852
(203) 846-2021

BBN Instruments Company
50 Moulton Street
Cambridge, MA 02138
(617) 491-0091

B&K Instruments Inc.
5111 W. 164th Street
Cleveland, OH 44142
(216) 267-4800

Bailey Scientific
P.O. Box 1245
West Sacramento, CA 95691
(916) 371-1472

Bell & Howell, CED Div.
360 Sierra Madre Villa
Pasadena, CA 91109
(213) 796-9381

Bently Nevada
P.O. Box 157
Minden, NV 89423
(702) 782-3611

Bouche Laboratories
11042 Olinda Street
Sun Valley, CA 91352
(213) 767-7273

Bourns Inc.
1200 Columbia Avenue
Riverside, CA 92507
(714) 781-5070

California Controls Company
2212 6th Street
Berkeley, CA 94710
(415) 549-1080

Columbia Research Lab, Inc.
McDade Blvd. & Bullens Lane
Woodlyn, PA 19094
(215) 532-9464

Conrac Corporation, Instruments/
Control Div.
1600 S. Mountain Avenue
Duarte, CA 91010
(213) 359-9141

Dallas Instruments, Inc.
P.O. Box 38189
Dallas, TX 75238
(214) 341-2990

Degamo Inc.
500 Ashland Avenue
P.O. Box 653
Chicago Heights, IL 60411
(312) 754-3131

Disa Electronics
779 Susquehanna Avenue
Franklin Lakes, NJ 07417
(201) 891-9460

Ehrenreich Photo-Optical Ind., Inc.
Instrument Group
623 Stewart Avenue
Garden City, NY 11530
(516) 222-0200

Electrodyne Inc., Advanced Dynamics
Instrs. Div.
2316 Jefferson Davis Hwy.
P.O. Box 358
Alexandria, VA 22313
(703) 836-4641

Electro-Physics Company
9303 N. Major Avenue
Morton Grove, IL 60053
(312) 966-4752

Endevco Dynamic Instruments Division
30700 Rancho Viejo Road
San Juan Capistrano, CA 92675
(714) 493-8181

Entran Devices Inc.
10 Washington Avenue
Fairfield, NJ 07006
(201) 785-4060

Epic Inc.
150 Nassau Street, Suite 1430
New York, NY 10038
(212) 349-2470

General Axial Engine Company
38 Franklin Avenue
Lockport, NY 14094

GenRad Inc.
300 Baker Avenue
Concord, MA 01742
(617) 369-8770

GenRad Inc., Time/Data Div.
2855 Bowers Avenue
Santa Clara, CA 95051
(408) 985-0700

Gould Inc., Measurement System Div.
2230 Statham Blvd.
Oxnard, CA 93030
(805) 487-8511

Gulton Industries S-C Division
1644 Whittier Avenue
Costa Mesa, CA 92627
(714) 642-2400

Helm Instrument Co., Inc.
4511 South Avenue
Toledo, OH 43615
(419) 531-0146

Hewlett Packard Santa Clara Div.
5301 Stevens Creek Blvd.
Santa Clara, CA 95050
(408) 246-4300

Hottinger Baldwin Measurement Inc.
17 Mercer Road
Natick, MA 01760
(617) 655-0950

Humphrey Inc.
9212 Balboa Avenue
San Diego, CA 92123
(714) 565-6631

IRD Mechanalysis Inc.
6150 Huntley Road
Columbus, OH 43229
(614) 885-5376

Impact-O-Graph Div. Torq Eng. Products
32 W. Monroe Street
Bedford, OH 44146
(216) 232-1880

Impact Register Inc.
W. Springfield Avenue
P.O. Box 3097
Champaign, IL 61820
(217) 352-4129

International Scientific Instr. Inc. (ISI)
3255-6C Scott Blvd.
Santa Clara, CA 95050
(408) 249-9840

Ithaco, Inc.
Box 818
735 W. Clinton Street
Ithaca, NY 14850
(607) 272-7640

KDO Precision Products Inc.
3975 McMann Road
Cincinnati, OH 45245
(513) 943-2000

Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, CO 80933
(303) 599-1500

Kinetic Systems Inc.
70 Lincoln Street
Brighton, MA 02135
(617) 782-7800

Kistler-Morse Corporation
13277 Northrup Way
Bellevue, WA 98005
(206) 641-4200

Konigsberg Instruments Inc.
(see: Unimeasure Div.,
Konigsberg Inst.)

Kistler Instrument Corporation
2475 Grand Island Blvd.
Grand Island, NY 14072
(716) 773-3140

Kulite Semiconductor Products Inc.
1039 Hoyt Avenue
Ridgefield, NJ 07657
(201) 945-3000

L.A.B. Div., Mechanical Technology
Onondaga Street
Skaneateles, NY 13152
(315) 685-5781

Larson Aero Development
P.O. Box 135
Concord, CA 94522
(415) 228-7870

Ling Electronics Inc.
1515 S. Manchester Ave.
Anaheim, CA 92803
(714) 774-2000

Lion Precision Inc.
60 Bridge Street
Newton, MA 02195
(617) 969-4710

MBIS Inc.
25865 Richmond Road
Bedford Heights, OH 44146
(216) 282-5850

Mechanical Technology Inc.
MTI Instruments Division
968 Albany-Shaker Road
Latham, NY 12110
(518) 785-2211

Media Recovery Inc.
2550 Electronic Lane, Suite 205
Dallas, TX 75220
(214) 350-5725

Metrix Instrument Company
1711 Townhurst Drive
Houston, TX 77043
(713) 461-2131

Muirhead, Inc.
1101 Bristol Road
Mountainside, NJ 07092
(201) 233-6010

Nicolet Scientific Corporation
P.O. Box 159, 245 Livingston St.
Northvale, NJ 07647
(201) 767-7100

PCB Piezotronics, Inc.
P.O. Box 33
Buffalo, NY 14225
(716) 684-0001

Precision Filters Inc.
303 West Lincoln Street
Ithaca, NY 14850
(607) 277-3550

Production Measurement Corp.
(see: Scientific Energy Systems
Corp., PMC/Beta)

Robertshaw Controls Company
Industrial Instrumentation Div.
333 N. Euclid Way
Anaheim, CA 92803
(714) 535-8151

Robinson-Halpern Company
One Apollo Road
Plymouth Meeting, PA 19462
(215) 825-9200

Rhode & Schwarz Sales Company
14 Gloria Lane
Fairfield, NJ 07006
(201) 575-0750

Schaevitz Engineering
P.O. Box 505
Camden, NJ 08101
(609) 662-8000

Scientific-Atlanta Inc.
New Jersey Div. (QuanTech)
Randolph Park West, Rt. 10
Randolph Twp., NJ 07801
(201) 361-3100

Scientific Energy Systems Corp.,
PMC/Beta
4 Tech Circle
Natick, MA 01760
(617) 237-6920

Sensory Products Inc.
IKON Communications Consultants, Inc.
554 Washington St.
Wellesley, MA 02181
(617) 237-6060

Setra Systems Inc.
1 Strathmore Road
Natick, MA 01760
(617) 655-4645

The Singer Company, Kearfoot Div.
1150 McBride Avenue
Little Falls, NJ 07424
(201) 256-4000

Spectral Dynamics Corporation
P.O. Box 671
San Diego, CA 92112
(714) 565-8211

Sprengnether, W.F. Instrument Co.
4567 Swan Avenue
St. Louis, MO 63110
(314) 535-1682

Sundstrand Data Control Inc.
Overlake Industrial Park
Redmond, WA 98052
(206) 885-3711

Systems Consultants Inc.
410 Jericho Turnpike
Jericho, NY 11753
(516) 822-5500

Systron-Donner Corporation
14844 Oxnard Street
Van Nuys, CA 91409
(213) 786-1760

Team Corporation
9949 Hayward Way
So. El Monte, CA 91733
(213) 442-3240

Terra Technology Corporation
3018 Western Avenue
Seattle, WA 98121
(206) 682-9946

Time/Data Corporation
(see: GenRad, Time Data Div.)

Trig-Tek, Inc.
423 S. Brookhurst St., Bldg. E
Anaheim, CA 92804
(714) 956-3593

Unholtz-Dickie Corporation
6 Brookside Dr/Barnes Industrial Park, N
Wallingford, CT 06492
(203) 265-3929

Unimeasure Div., Konigsberg-Instruments
2000 E. Foothill Blvd.
Pasadena, CA 91107
(213) 795-9719

Universal Technology Inc., Optron Div.
30 Hazel Terrace
Woodbridge, CT 06525
(203) 389-5384

Validyne Engineering Corporation
19414 Londelius Street
Northridge, CA 91324
(213) 886-8488

Vibra-Metrics/Kistler
385 Potnam Avenue
Hamden, CT 06517
(203) 288-6158

Vibration Control Company
(see: Bouche Laboratories)

Vibration Instruments Company
1614 Orangethorpe Way
Anaheim, CA 92801
(714) 879-6085

Vibration Sales & Service, Inc.
P.O. Box 3851
Amity Station, New Haven, CT 06525
(203) 389-1527

Vibration Test Systems
10246 Clipper Cove
Aurora, OH 44202
(216) 562-5729

Vibra-Meter Corporation
22109 S. Vermont Avenue
Torrance, CA 90502
(213) 320-8410

Vibroscope Company, Inc.
70 Furnace Street
Kingston, NY 12401
(914) 331-4215

Vitec Incorporated
23645 Mercantile Road
Cleveland, OH 44122
(216) 464-4670

West Coast Research Corporation
P.O. Box 25061
Los Angeles, CA 90025
(213) 478-8833

Wilcoxon Research
12156-B Parklawn Drive
Rockville, MD 20852
(301) 468-0055

FORCE/MASS

Force and Mass Sensors

A.L. Design & Development Co.
2070 Niagara Falls Blvd.
Tonawanda, NY 14150
(716) 692-5272

Acrison Inc.
20 Empire Blvd.
Moonachie, NJ 07074
(201) 440-8300

Action Instruments Co., Inc.
8601 Aero Drive
San Diego, CA 92123
(714) 279-5726

Advance Weight System Inc.
715 West Smith
Medina, OH 44256
(216) 725-6409

Ailtech, A Cutler-Hammer Co.
19535 E. Walnut Drive
City of Industry, CA 91748
(213) 965-4911

Allegany Technology
143 Offutt Street
Cumberland, MD 21502
(301) 722-7330

American Scale Corporation
P.O. Box 299
Hartsdale, NY 10530
(914) 761-1745

Ametek, Controls Div.
P.O. Box 152
Feasterville, PA 18960
(215) 355-6900

Ametek, Hunter Spring Div.
Hatfield, PA 19440
(215) 822-2971

Analogic Corporation
Audubon Road
Wakefield, MA 01880
(617) 246-0300

Automatic Control Systems, Inc.
8515 Freeway Drive
Macedonia, OH 44056
(216) 467-2186

Automatic Packaging & Conveyor Co.
4010 Bluebonnet
Houston, TX 77025

Automatic Timing & Controls Co.
King of Prussia, PA 19406
(215) 265-0200

B&F Instruments Div., FX Systems
(see: FX Systems)

B&K Instruments Inc.
5111 W. 164th Street
Cleveland, OH 44142
(216) 267-4800

BLH Electronics
42 4th Street
Waltham, MA 02254
(617) 890-6700

Bay Labs, Inc.
20160 Center Ridge Road
Cleveland, OH 44116
(216) 333-3898

Bell & Howell, CEC Div.
360 Sierra Madre Villa
Pasadena, CA 91109
(213) 796-9381

Bitronics Inc.
732 Goepp Street
Bethlehem, PA 18018
(215) 866-0777

Borg-Erickson Corporation
1133 N. Kilbourn Avenue
Chicago, IL 60651
(312) 384-5600

Brewer Engineering Labs, Inc.
P.O. Box 288
Marion, MA 02738
(617) 748-0103

Brinkmann Instruments
Cantiague Road
Westbury, NY 11590
(516) 334-7500

CCS Systems, Inc.
15600 Megal Drive
Menomonee, WI 53051
(414) 255-5640

Cahn Instruments Div., Ventron Corp.
16207 S. Carmenita Road
Cerritos, CA 90701
(213) 926-3378

The Carlson Company
P.O. Box 174, Hwy. 9 West
Clinton, AZ 72031
(501) 745-4811

Celesco Transducer Products Inc.
P.O. Box 1457, 7800 Deering Ave.
Canoga Park, CA 91304
(213) 884-6860

Chatillon, John & Sons
83-30 Kew Gardens Road
Kew Gardens, NY 11415
(212) 847-5000

Cleveland Machine Controls, Inc.
7550 Hub Parkway
Cleveland, OH 44125
(216) 524-8800

Comptrol Inc.
9505 Midwest Avenue
Cleveland, OH 44125
(216) 587-5212

Consolidated Controls Corporation
15 Durant Avenue
Bethel, CT 06801
(203) 743-6721

D.J. Instruments Inc.
11-E Esquire Road, N.
Billerica, MA 01862
(617) 667-5301

Data Instruments
4 Hartwell Place
Lexington, MA 02173
(617) 861-7450

Data Scale Ltd.
4570 Enterprise Street
Fremont, CA 94538
(415) 651-7350

Detecto Scales, Inc.
103-00 Foster Avenue
Brooklyn, NY 11236
(212) 272-4500

Detroit Testing Machine Co.
9390 Grinnell
Detroit, MI 48213

Digimetric Co./Div. of Sybron Corp.
(see: National Controls Inc.)

Dillon, W.C. & Co., Inc.
14620 Keswick Street
Van Nuys, CA 91407
(213) 786-8812

Doric Scientific Co.
3883 Ruffin Road
San Diego, CA 92123
(714) 565-4415

Dovey Mfg. Co., Inc.
P.O. Box 2249
Anderson, IN 46011
(317) 649-2576

Dynamic Measurements Corp.
6 Lowell Avenue
Winchester, MA 01890
(617) 729-7870

Electro-Numerics Inc.
1811 Reynolds Street
Irvine, CA 92714
(714) 549-8821

Electronic Scales International
P.O. Box 1087
San Gabriel, CA 91776
(800) 423-4384

Electronic Systems Design, Inc.
317 W. University Drive
Arlington Heights, IL 60004
(312) 398-0550

Electroscale Corporation
15 Third Street
Santa Rosa, CA 94501
(707) 546-6785

Emery, A.H., Company
70 Pine Street
New Canaan, CT 06840
(203) 966-4551

Enerpac, Div. of Applied Power
  Ind. Inc.
Butler, WI 53007
(414) 781-6600

Entran Devices, Inc.
10 Washington Ave.
Fairfield, NJ 07006
(201) 785-4060

FX Systems Corporation
CPO Box 818
77 Cornell Street
Kingston, NY 12401
(914) 338-0515

Fairbanks Weighing Div., Colt Industries
711 E. Street, Johnsbury Road
St. Johnsbury, VT 05819
(800) 451-4107

Fatigue Dynamics Inc.
P.O. Box 2533
Dearborn, MI 48123
(313) 273-8270

The Foxboro Company
Dept. 120, 38 Neponset Ave.
Foxboro, MA 02035
(617) 543-8750

GCA/Precision Scientific
3737 W. Cortland Street
Chicago, IL 60647
(312) 227-2660

GSE Inc.
23640 Research Drive
Farmington Hills, MI 48024
(313) 476-7875

Genisco Technology Corp.
18435 Susana Road
Compton, CA 90221
(213) 537-4750

Gentran Inc.
1290 Hammerwood Avenue
Sunnyvale, CA 94086
(408) 734-5060

Gould Inc., Measurement Systems Div.
2230 Statham Blvd.
Oxnard, CA 93030
(805) 487-8511

Guardian Electric Mfg. Co.
1550 W. Carroll Avenue
Chicago, IL 60607
(312) 243-1100

Hardy Scales Company
4075 Ruffin Road
San Diego, CA 92123
(714) 565-7701

S. Himmelstein & Company
2500 Estes Avenue
Elk Grove Village, IL 60007
(312) 439-8181

Hi-Speed Checkweigher Company Inc.
P.O. Box 314
Ithaca, NY 14850
(607) 273-5121

Hitec Corporation
Nardone Industrial Park
Westford, MA 01886
(617) 692-4793

Honeywell Inc., Process Control Div.
1100 Virginia Drive
Fort Washington, PA 19034
(215) 643-1300

Hottinger Baldwin Measurements Inc.
17 Mercer Road
Natick, MA 01760
(617) 655-0950

Houston Controls Packaging Inc.
P.O. Box 45873
Houston, TX 77045

Houston Instrument/Div. Bausch & Lomb
One Houston Sq. at 850 Cameron Road
Austin, TX 78758
(512) 837-2820

Howe Richardson Scale Co.
680 Van Houten Avenue
Clifton, NJ 07015
(201) 471-3400

Industrial Nucleonics Corp.
650 Ackerman Road
Columbus, OH 43202
(614) 261-2000

Instron Corporation
100 Royall Street
Canton, MA 02021
(617) 828-2500

Intech, Inc.
282 Brokaw Road
Santa Clara, CA 95050
(408) 244-0500

Intec Inc.
81 Chimney Road Rd.
Bridgewater, NJ 08807
(201) 356-8112

Interface Inc.
7401 E. Butherus Drive
Scottsdale, AZ 85260
(602) 948-5555

IRAD Gage, Inc.
14 Parkhurst Street
Lebanon, NH 03766

K-Tron Corporation
Warrick & Grillo Street
Glassboro, NJ 08028
(609) 881-6500

Kay-Ray Inc.
516 W. Campus Drive
Arlington Heights, IL 60004
(312) 259-5600

Kelk, George Ltd.
48 Lesmill Road
Don Mills, Ontario M3R 7R2, Canada
(416) 445-5850

King, J.A. & Co., Inc.
2620 High Point Road
P.O. Box 21225
Greensboro, NC 27420
(919) 292-0511

Kistler-Morse Corporation
13227 Northrup Way
Bellevue, WA 98005
(206) 641-4200

Konigsberg Instruments
(see: Unimeasure)

Kistler Instrument Corp.
75 John Glenn Drive
Amherst, NY 14126
(716) 691-5106

Kulite Semiconductor Products
1039 Hoyt Avenue
Ridgefield, NJ 07657
(201) 945-3000

Lebow Associates Inc.
1728 Maplelawn Road
Troy, MI 48084
(313) 643-1220

Litton Industries Potentiometer Div.
226 E. 3rd Street
Mt. Vernon, NY 10550
(914) 664-7733

Magnaflux Corporation
Champion Spark Plug Co.
7328 W. Lawrence Avenue
Chicago, IL 60656
(312) 867-8000

Marshall Electronics Inc., Clayton Div.
7440 N. Long Avenue
Skokie, IL 60076
(312) 583-6060

Martin-Decker Corporation
1928 S. Grand
Santa Ana, CA 92705
(714) 540-9220

Merrick Scale Mfg. Co.
180 Autumn Street
Passaic, NJ 07055
(201) 779-0697

Metron Corporation
928 W. Ninth Street
Upland, CA 91786
(714) 981-4981

Mettler Instrument Corp.
Box 100
Princeton, NJ 08540
(609) 448-3000

Micro-Measurements Div.
Vishay Intertechnology Inc.
P.O. Box 306, 38905 Chase Rd.
Romulus, MI 48174
(313) 941-3900

Micro-Strain Inc.
Spring City, PA 19475
(215) 948-4550

Milltronics Inc.
2409 Avenue J
Arlington, TX 76011
(817) 649-8540

Morehouse Instrument Co.
1742 Sixth Avenue
York, PA 17403
(717) 843-0081

National Controls Inc.
1160 Hopper Lane
Santa Rose, CA 94501
(707) 527-5555

Ohaus Scale Corporation
29 Hanover Road
Florham Park, NJ 07932
(201) 377-9000

Ohmart Corporation
4241 Allendorf Drive
Cincinnati, OH 45209
(513) 272-0131

Orbitran, Inc.
11487 Woodside Ave.
Lakeside, CA 92040
(714) 448-5075

Ormond Inc.
11969 Rivera Road
Santa Fe Springs, CA 90670
(213) 698-8358

PCB Piezotronics Inc.
P.O. Box 33
Buffalo, NY 14225
(716) 684-0001

Phoenix Precision Instr. Co.
Div. Virtis
Rte. 208
Gardiner, NY 12525
(914) 255-5000

Photobell Company, Inc.
12 E. 22nd Street
New York, NY 10010
(212) 674-2121

Pittsburgh Brass Mfg. Co.
Sandy Hill Road, R.D. 6
Irwin, PA 15642
(412) 863-0550

Powers Fiat Div. Powers Regulator Co.
3400 Oakton Street
Skokie, IL 60076
(312) 673-6700

Princo Instruments
1020 Industrial Hwy.
Southampton, PA 18966
(215) 355-1500

Process Analyzers Inc.
1101 State Road
Princeton, NJ 08540
(609) 921-7330

Process Systems Inc.
Subsidiary of Powell Industries, Inc.
8550 Mosley Dr., P.O. Box 12818
Houston, TX 77017
(713) 944-6900

Productronix Inc.
2409 West Bond St.
Park Forest South, IL 60466
(312) 563-1850

Proximity Controls Inc.
Box 50
Fergus Falls, MN 56537
(218) 736-6072

Ramsey Engineering Co.
1853 W. Country Rd. C.
St. Paul, MN 55113
(612) 633-5150

Revere Corp. of America
845 N. Colony Road
Wallingford, CT 06492
(203) 269-7701

Rockwell Engineering Co.
2121 E. 45th St.
Indianapolis, IN 46205
(317) 251-9453

Ruska Instruments Corp.
6121 Hillcroft, P.O. Box 36010
Houston, TX 77036
(713) 774-2533

Schaevitz Engineering
P.O. Box 505
Camden, NJ 08101
(609) 662-8000

Scientech, Inc.
5649 Arapahoe Avenue
Boulder, CO 80303
(303) 444-1361

Sensotec Inc.
1200 Chesapeake Ave.
Columbus, OH 43212
(614) 486-7723

Soiltest Inc., Cenco
2205 Lee Street
Evanston, IL 60202
(312) 869-5500

Space Electronics Inc.
P.O. Box 2166
Meriden, CT 06450
(203) 265-2945

Sterling Scale Co., Inc.
20950 Boening Dr.
Southfield, MI 48075
(313) 358-0590

Straindyne Engineering Co.
P.O. Box 328
Los Altos, CA 94022
(415) 948-3227

Strainsert Co.
Union Hill Industrial Pk.
W. Conshohocken, PA 19428
(215) 825-3310

Streeter Amet, Div. Mangood Corp.
Dept. PBS, Slusser & Wickes Sts.
Grayslake, IL 60030
(312) 223-4801

Sundstrand Data Control Inc.
Overlake Industrial Pk.
Redmond, WA 98052
(206) 885-3711

Tensitron, Inc.
P.O. Box 185
Harvard Depot Rd.
Harvard, MA 01451
(617) 456-3511

Testing Machines Inc.
400 Bayview Avenue
Amityville, NY 11701
(516) 842-5400

Thayer Scale Div.
Thayer Park
Pembroke, MA 02359
(617) 826-2371

Thor Power Tool Co./Stewart-Warner Corp.
175 North State St.
Aurora, IL 60505
(312) 898-8000

Thurman Scale Company
1939 Regugee Road
Box 2179
Columbus, OH 43216
(614) 443-9741

Toledo Scale Div. of Reliance
Electric Co.
Dept. 941, P.O. Box 1705
Columbus, OH 43216

Toroid Corporation
P.O. Box 1435
Huntsville, AL 35807
(205) 534-1687

Torsion Balance Co.
125 Ellsworth St.
Clifton, NJ 07012
(201) 473-6900

Transducer Products Inc.
95 Wolcott Ave.
Torrington, CT 06790

Transducers Inc./ELDEC
12140 E. Rivera Road
Whittier, CA 90606
(213) 945-3741

Tyco Instrument Div. Tyco
Laboratories
(see: Data Instruments)

Unimeasure Div. Konigsberg Instr.
2000 E. Foothill Blvd.
Pasadena, CA 91107
(213) 795-9719

Voland Corporation
27 Centre Avenue
New Rochelle, NY 10802
(914) 636-2014

Wallace & Tiernan Div. Pennwalt
Corp.
25 Main Street
Belleville, NJ 07109
(201) 759-8000

Watson, Oliver H.
232 Millbridge Road
Riverside, IL 60546
(312) 447-1024

Webster Instrument Inc.
11856 Mississippi Ave.
Los Angeles, CA 90025
(213) 479-6770

Weigh & Test Systems Inc.
8850 N.W. 22 Ave.
Miami, FL 33147
(305) 691-2561

Weight Systems Inc.
10210 N. Interregional
Austin, TX 78753
(512) 836-5513

West Coast Research
S. Sepulveda Blvd., P.O. Box 25061
Los Angeles, CA 90025
(213) 478-8833

Western Load Cell Co.
17929 Ventura Blvd.
Encino, CA 91316
(213) 996-2700

Wilcoxon Research
12156-B Parklawn Drive
Rockville, MD 20852
(301) 468-0055

Torque Sensors

AOK Tool Corp.
82-21 Sutter Ave.
Ozone Pk, NY 11417
(914) 835-2740

AST Servo Systems Inc.
930 Broadway
Newark, NJ 07104
(201) 484-4233

A.V.D., B.V. of the Hague
c/o Netherlands Consulate General
Commercial Div. 571
One Rockefeller Plaza, NY 10020

Acurex Corp., Autodata Div.
485 Clyde Ave.
Mountain View, CA 94042
(415) 964-3200

Ametek/U.S. Gauge Div.
906 Clymer Ave.
Sellersville, PA 18960
(215) 248-3368

Apco Mossberg Co.
Lamb St.
Attleboro, MA 02703
(617) 222-0340

Asea Electric Inc.
4 New King St.
White Plains, NY 10604
(914) 428-6000

Brewer Engineering Labs, Inc.
P.O. Box 288
Marion, MA 02738
(617) 748-0103

The Carlson Co.
P.O. Box 174-Hwy 9 West
Clinton, AR 72031
(501) 745-4811

Chatillon & Sons, John
83-30 Kew Gardens Road
Kew Gardens, NY 11415
(212) 847-5000

Comstock & Wescott Inc.
765 Concord Avenue
Cambridge, MA 02138
(617) 547-2580

Data Instruments
4 Hartwell Place
Lexington, MA 02173
(617) 861-7450

Daytronic Corporation
2589 Corporate Place
Miamisburg, OH 45342
(513) 866-3300

Dillon & Company, W.C.
14620 Keswick Street
Van Nuys, CA 91407
(213) 786-8812
(212) 873-1354

Dynapar Corporation
1675 Delany Road
Gurnee, IL 60031
(312) 662-2666

Electronic Systems Design, Inc.
317 W. Washington Drive
Arlington Heights, IL 60004
(312) 398-0550

Fairlane Tool Company
31790 Groesbeck Hwy.
Fraser, MI 48026
(313) 293-0711

GSE Inc.
23640 Research Drive
Farmington Hills, MI 48024
(313) 476-7875

General Thermodynamics Corp.
210 South Meadow Road
P.O. Box 1105
Plymouth, MA 02360
(617) 746-0200

Gentran Inc.
1290 Hammerwood Ave.
Sunnyvale, CA 94086
(408) 734-5060

Himmelstein & Co. S.
2500 Estes Avenue
Elk Grove Village, IL 60007
(312) 439-8181

Hottinger Baldwin Measurements Inc.
17 Mercer Road
Natick, MA 01760
(617) 655-0950

Inductor Inc.
Union Grove, WI 53182
(414) 878-3707

Instron Corporation
100 Royall St.
Canton, MA 02021
(617) 828-2500

James Gear Mfg. Co.
1140 W. Monroe St.
Chicago, IL 60607
(312) 226-1800

Jo-Line Tools Inc.
P.O. Box 3186, 4225 E. LaPalma
Anaheim, CA 92806
(714) 524-3410

Kahn & Co., Inc.
885 Wells Road
Wetherfield, CN 06109
(203) 529-8643

Kavlico Electronics
20869 Plummer St.
Chatsworth, CA 91311
(213) 882-2400

Lebow Associates Inc.
1728 Maplelawn Road
Troy, MI 48084
(313) 643-0220

Link Engineering Co.
13840 Elmira
Detroit, MI 48227
(313) 933-4900

McFadden Electronics Co.
8953 Atlantic Blvd.
South Gate, CA 90280
(213) 564-5958

McNab Inc.
20 N. MacQuesten Parkway
Mt. Vernon, NY 10550
(914) 699-1616

Macotech Corporation
4104 W. Marginal Way S.W.
Seattle, WA 98106
(206) 932-4886

Magtrol
70 Gardenville Pkwy., W.
Buffalo, NY 14224
(716) 675-3333

Meridian Laboratory Inc.
Box 156
Middletown, WI 53562
(608) 238-3333

Morehouse Instruments
1742 Sixth Avenue
York, PA 17403
(717) 843-0081

Mountz Inc.
1080 N. 11th Street
San Jose, CA 95112
(408) 292-2214

Moxon, Inc.
222 Michelson Drive
Irvine, CA 92715
(714) 833-2000

Ono Sokki Co., Ltd.
27-4 Yaguchi 1-Chome
Ohta-ku, Tokyo, Japan

Owatonna Tool Co., Tools &
Equipment Div.
Eisenhower Drive
Owatonna, MN 55060
(507) 451-7163

Power Instruments Inc.
7352 N. Lawndale Avenue
Skokie, IL 60076
(312) 676-2300

RFD Instrument Co., Inc.
404 N. Main Street, Box 548
Elgin, TX 78621
(512) 285-3385

Raymond Engineering Inc.,
Power-Dyne Torque Products Div.
217 Smith St.
Middletown, CT 06457
(203) 632-1000

Sensotec, Inc.
1200 Chesapeake Ave.
Columbus, OH 43212
(614) 486-7723

Snap-On-Tool Corp.
8028 28th Avenue
Kinosha, WI 33140
(414) 654-8681

Stewart Warner Corp.
(see: Thor Power Tool Co./
Stewart-Warner)

Sunshine Scientific Inst. Inc.
1810 Grant Ave.
Philadelphia, PA 19115
(215) 673-5600

Sweeney Mfg. Co. B.K.
6300 Stapleton S. Dr.
Denver, CO 80216
(303) 320-4800

Thor Power Tool Co./
Stewart Warner Corp.
175 N. State St.
Aurora, IL 60505
(312) 898-8000

Torquemeters America Inc.
P.O. Box 8
Allegany, NY 14076
(716) 373-2383

Torvaal
524 Washington St.
Chagrin Falls, OH 44022
(216) 247-6066

Transducers Inc.
Sub. ELDEC
12140 E. Rivera Rd.
Whittier, CA 90606
(213) 945-3741

Tyco
(see: Data Instruments)

Utica Tool Company, Inc.
Cameron Road
Orangeburg, SC 29115
(803) 534-7010

Vibrac Corporation
11 Alpha Dr./Alpha Industrial Pk.
Chelmsford, MA 01824
(617) 256-6581

Waters Mfg. Inc.
Longfellow Center
Wayland, MA 01778
(617) 358-2777

West Coast Research
P.O. Box 25061, S. Sepulveda Blvd.
Los Angeles, CA 90025
(213) 478-8833

Level Sensors

Abtec Ltd.
133 Rushey Green
London SE6 4AA, England

Action Instruments Co. Inc.
8601 Aero Dr.
San Diego, CA 92123
(714) 279-5726

Agitronics Manufacturing Co.
756-C Lakefield Rd.
Westlake Village, CA 91361
(805) 495-0874

Almac Cryogenics Inc.
1108-26th St.
Oakland, CA 94607
(415) 832-1505

Amprodux Inc.
150 W. 28th St.
New York, NY 10001
(212) 242-1636

B/W Controls Inc.
2200 E. Maple Rd.
Birmingham, MI 48012
(313) 643-8800

Bailey Controls Co.
29801 Euclid Ave.
Wickliffe, OH 44092
(216) 943-5500

Bailey Scientific
P.O. Box 1245
W. Sacramento, CA 95691
(916) 371-1472

Bill Manufacturing Inc.
903 W. Center Street N
Salt Lake City, UT 84054
(801) 364-6451

Bell & Howell, CEC Div.
360 Sierra Madre Villa
Pasadena, CA 91109
(213) 796-9381

Bindicator Company
1915 Dove St.
Port Huron, MI 48060
(313) 987-2700

Bristol Div.
929 Connecticut Ave.
Bridgeport, CT 06607
(203) 335-2511

Brooks Instruments
Div. Emerson Electric Co.
407 W. Vine Street
Hatfield, PA 19440
(215) 368-2000

C-E Invalco Div. of Combustion
Engineering, Inc.
P.O. Box 556
Tulsa, OK 74101
(918) 932-5671

Chem-Tec Equipment Co., Inc.
Box 1030
Pompano Beach, FL 33061
(305) 946-6153

Coastal Data Service, Inc.
(see: Eppley Lab Inc.)

Columbia Controls
4545 Pine Timbers Bldg. 300
Houston, TX 77041
(713) 462-7800

Computer Inst. Corp.
100 Madison Ave.
Hempshead, LI, NY 11550
(516) 483-8200

Controlotron Corp.
155 Plant Ave.
Hauppauge, NY 11787
(516) 231-3600

Cooke Vacuum Products Inc.
13 Merritt St., S
Norwalk, CT 06854
(203) 853-9500

Curtis Industries Inc.
8000 West Tower Ave.
Milwaukee, WI 53223
(414) 354-1500

Custom Controls Co. Inc.
1005 Sussex Blvd.
Lawrence Industrial Park
Broomall, PA 19008
(215) 543-5000

Delaval Turbine Inc.
Gems Sensors Div.
Farmington, CT 06032
(203) 677-1311

Delavan Electronics Inc.
1441 N. 73rd St.
Scottsdale, AZ 85260
(602) 948-6350

R.B. Denison Inc.
(see Gould Inc., Circuit
Protection & Controls Div.)

Desgranges & Huot, F.R. Industries Inc.
556 Long Road
Pittsburgh, PA 15235
(412) 242-5903

Digilin Inc./Dynamic Sciences
(see: Dynamic Sciences Intl Inc/
Digilin)

Drexelbrook Engineering Co.
205 Keith Valley Road
Horsham, PA 19044
(215) 674-1234

Dynamic Sciences International Inc.,
Digilin
16150 Stagg St.
Van Nuys. CA 91406
(213) 893-6341

Electramtion
1099 Batavia
Orange, CA 92667
(714) 639-0832

Endress & Hauser Inc.
2350 Endress Place
Greenwood, IN 46142
(317) 535-7138

Epic Inc.
150 Nassau St.
New York, NY 10038
(212) 349-2470

Eppley Laboratory Inc.
12 Sheffield Ave.
Newport, RI 02840
(401) 847-1020

Ernst Gage Co.
250 S. Livingston Ave.
Livingston, NJ 07039
(201) 922-1400

Exactel Instr. Div.
(see: Technical Devices Co.)

F.R. Industries
(see: Desgranges & Huot)

Fluid Components Inc. (FCI)
870 Remmet Avenue
Canoga Park, CA 91304
(213) 341-7722

Fluid Products Co., Inc.
14740 Martin Dr.
Eden Prairie, NM 55343
(612) 941-8388

Foster Cambridge Ltd.
Howard Rd., Eaton, Socon,
Huntingdon, Cambridgeshire,
England

The Foxboro Co.
Dept. 120, 38 Neponset Avew.
Foxboro, MA 02035
(617) 543-8750

GPE Controls
6511 Oakton St.
Morton Grove, IL 60053
(312) 966-4000

Gagne Associates Inc.
1080 Chenango & Hillcrest St.
Binghamton, NY 13901
(607) 723-9556

Genelco Inc.
11649 Chairman Dr.
Dallas, TX 75243
(214) 341-8410

Gould Inc. Circuit Protection
& Controls Div.
103 Broadway
Bedford, OH 44146
(216) 232-8200

Great Lakes Instruments Inc.
8855 N. 55th Street, P.O. Box 23056
Milwaukee, WI 54223
(414) 355-3601

Harwil Corporation
1548 17th St.
Santa Monica, CA 90404
(213) 829-2310

Hersey Products Inc.
Industrial Measurement Div.
Old Valley Falls Rd.
Spartansburg, SC 29303
(803) 578-3800

Hi-G Electronics
580 Spring St.
Windsor Locks, CT 06096
(203) 623-2481

Honeywell Inc. Process Control Div.
1100 Virginia Drive
Fort Washington, PA 19034
(215) 643-1300

ITT Barton
Box 1882
City of Industry, CA 91749
(213) 961-2547

Instrumentation & Control Systems Inc.
520 Interstate Road
Addison, IL 60101
(312) 543-6200

Inventory Sciences Inc.
17728 15th Avenue NE
Seattle, WA 98155
(206) 363-0810

Inventron Industries Inc.
4005 W. Jefferson Blvd.
Los Angeles, CA 90016
(213) 731-2507

Jerguson Gage & Valve Co.
15 Adams St.
Burlington, MA 01803
(617) 272-3600

Jogler Inc.
2121 Governors Circle
P.O. Box 10899
Houston, TX 77018
(713) 681-4811

Kay-Ray Inc.
516 W. Campus Dr.
Arlington Heights, IL 60004
(312) 259-5600

Key Electro Sonic
Box 8
Milton-Freewater, OR 97862
(503) 938-5556

Knight Equipment Corp.
Box 1378
Costa Mesa, CA 92626
(714) 557-5400

Kodata Inc.
3621 McCart St.
Fort Worth, TX 76110
(817) 926-8483

Kolt Engineering Inc.
P.O. Box 1172
Los Gatos, CA 95030
(408) 356-7244

Konigsberg Instrument
(see: Unimeasure Div.,
Konigsberg Inst.)

LTI Corporation
P.O. Box 1828
Monterey, CA 93940
(408) 394-6775

Lake Shore Cryotronics Inc.
64 E. Walnut St.
Westerville, OH 43081
(614) 891-2243

Leeds & Northrup Company
Sumneytown Pike
North Wales, PA 19454
(215) 643-2000

Lenz Company
P.O. Box 1044, 3301 Klepinger Rd.
Dayton, OH 45401
(513) 277-9364

Liquid Level Lectronics Inc.
P.O. Box Drawer 788
Porter, TX 77365
(713) 354-2163

Liquidometer Corporation
19-29 Sheldon St.
Norwich, NY 13815
(607) 324-3939

Logicomp Electronics Inc.
895 Mamaroneck Avenue
Mamaroneck, NY 10543
(914) 698-9332

Lumenite Electronic Co.
2331 N. 17th Avenue
Franklin Park, IL 60131
(312) 455-1450

MSW Instruments Inc.
Bldg. 111, 8750 Katy Freeway
Houston, TX 77024
(713) 468-6100

Madison Company
P.O. Box 608
Madison, CT 06443
(203) 245-4280

Magnetrol International
5300 Belmont Road
Downers Grove, IL 60515
(312) 969-4000

Manning Environmental Corp.
120 DuBois Street, P.O. Box 1356
Santa Cruz, CA 95061
(408) 427-0230

Masoneilan International Inc.
63 Nahatan Street
Norwood, MA 02062
(617) 762-4600

Meriam Instrument Div/
The Scott & Fetzer Co.
10920 Madison Avenue
Cleveland, OH 44102
(216) 281-1100

Metrig Engineering
10 Charles Street
Auburn, NY 13021
(315) 252-5657

Metritape, Inc.
33 Bradford Street
W. Concord, MA 01742
(617) 369-7500

Milltronics Inc.
2409 Avenue J
Arlington, TX 76011
(817) 649-8540

Monitech, Inc. (Monitor Tech. Inc.)
630 Price Avenue
Redwood City, CA 94063
(415) 365-6550

Monitor Mfg. Inc.
Drawer AL
Elburn, IL 60119
(312) 365-9403

Monitor Technology Inc.
(see: Monitek, Inc., Monitor Tech Inc.)

NP Industries Inc.
P.O. Box 746
Niagara Falls, NY 14302
(716) 282-0022

National Sonics Div., Envirotech Corp.
250 Marcus Blvd.
Hauppague, NY 11787
(516) 273-6600

The Ohmart Corporation
4241 Allendorf Drive
Cincinnati, OH 45209
(513) 272-0131

Oil-Rite Corporation
2318 Waldo Blvd.
Manitowoc, WI 54220
(414) 682-6173

Optek Inc.
127 Holmes Street
Galena, OH 43021
(614) 965-1819

Orion, Alpha Corporation
2974 Scott Blvd.
Santa Clara, CA 95050
(408) 247-4237

Peripheral Industries, Ltd.
439 Washington
Woodbury, CT 06798
(203) 263-3444

Petrometer Corporation
P.O. Box 245, 1807 Gilford Ave.
New Hyde Park, NY 11040
(516) 488-5777

Petur Instruments Co.
(formerly Thordason Inc)
11300 25th Ave., NE
Seattle, WA 98125
(206) 365-0052

Princo Instruments Inc.
1020 Industrial Hwy.
South Hampton, PA 18966
(215) 355-1500

Qualitron Corporation
1385 Fairport Road
Fairport, NY 14450
(716) 586-1515

Rechner Electronics Industries Inc.
8651 Ave.
Niagara Falls, NY 14304
(716) 283-8744

Red Valve Co., Inc.
500 North Bell Ave.
Carnegie, PA 15106
(412) 923-2677

Rexnord Instrument Products
30 Great Valley Pkwy.
Malvern, PA 19335
(215) 647-2400

Robertshaw Controls Co.
Industrial Instrumentation Div.
1809 Staples Mill Road
Richmond, VA 23230
(804) 358-2301

Sangamo Electric Company
Energy Management Div.
P.O. Box 75
West Union, SC 29696
(803) 638-3601

Schaevitz Engineering
P.O. Box 505
Camden, NJ 08101
(609) 662-8000

Sensor Technology
21012 Lassen Street
Chatsworth, CA 91311
(213) 882-4100

Sensotec Inc.
1200 Chesapeake Ave.
Columbus, OH 43212
(614) 486-7723

Sirco Controls
2795 152nd Ave., NE
Redmond, WA 98052
(206) 885-5303

Skan-A-Matic
Rte. 5 West
Elbridge, NY 13060
(315) 689-3961

Stevens International Inc.
P.O. Box 619
Kennett Sq., PA 19348
(215) 444-0616

Taylor Instrument Company
Div. of Sybron Corp.
95 Ames St.
Rochester, NY 14601
(716) 235-5000

Technical Devices Company
11250 Playa Court
Culver City, CA 90230
(213) 870-3751

Temposonics Inc.
131 E. Ames Court
Plainview, NY 11803
(516) 935-4100

Texas Nuclear Div..Ramsey Engr. Co.
Box 9267
Austin, TX 78766
(512) 836-0801

Thordarson Inc.
(see: Petur Instrs. Co.)

Uehling Instrument Co.
461 Getty Avenue
Paterson, NJ 07509
(201) 742-8710

Unimeasure Div., Konigsberg Instr.
2000 E. Foothill Blvd.
Pasadena, CA 91107
(213) 449-0016

VEGA Controls US
P.O. Box 352
Wakefield, MA 01880
(617) 246-0026

W-K-M Valve Div., ACF Industries Inc.
P.O. Box 2117
Houston, TX 77001
(713) 499-1511

WeatherMeasure Corporation
P.O. Box 41257
Sacramento, CA 95841
(916) 481-7565

Wesmar, Western Marine Electronics
Industrial Systems Division
905 Dexter Avenue North
Box C19074
Seattle, WA 98109
(206) 285-2420

Western Gauge Service Co.
921 A Mt. View Ave.
Oxnard, CA 93030
(805) 486-2358

Zi-Tech Div., Aikenwood Corp.
2151 Park Blvd.
P.O. Box 26
Palo Alto, CA 94302
(415) 326-2151

Humidity and Moisture Sensors

Abbeon Cal, Inc.
123 Gray Avenue
Santa Barbara, CA 93101
(805) 966-0810

Agridustrial Electronics Inc.
1827-C St.
Bettendorf, IA 52722
(319) 359-1691

Alnor Instruments Company
7301 N. Caldwell Avenue
Niles, IL 60648
(312) 647-7866

American Instrument Co.
Div. of Travenol Laboratories, Inc.
8030 Georgia Avenue
Silver Spring, MD 20910
(301) 589-1727

Anacon
30 Main Street
P.O. Box 267
Ashland, MA 01721
(617) 881-3000

Atkins Technical Inc.
3401 S.W. 40th Blvd.
Gainesville, FL 32608
(904) 378-5555

Bacharach Instrument Company
625 Alpha Drive
RIDC Industrial Park
Pittsburgh, PA 15238
(412) 782-3500

Bacharach Instrument Company
West Coast Operation
2300 Leghorn Street
Mountain View, CA 94043

Batson, Louis P. Company
Box 3978
Greenville, SC 29608
(803) 242-5262

Beckman Instruments Inc.
Technical Information Services
Cedar Grove Operations
89 Commerce Road
Cedar Grove, NJ 07009
(201) 239-6200

Belfort Instrument Company
1600 S. Clinton Street
Baltimore, MD 21224
(301) 342-2626

Bendix Environmental & Process
Instr. Div.
1400 Taylor Avenue
Baltimore, MD 21204
(301) 835-5200

Blue M Electric Company
138th & Chatham
Blue Island, IL 60406
(312) 385-9000

C.W. Brabender Instruments Inc.
50 E. Wesley Street
South Hackensack, NJ 07606
(201) 343-8425

Breda Scientific Company
Suite 2225, One Sutter Street
San Francisco, CA 94104
(415) 788-4120

Bristol Div., ACCO
929 Connecticut Ave.
Bridgeport, CT 06607
(203) 335-2511

CTE Inc.
(see: Electromech Services)

Central Scientific Company
2600 S. Kostner Avenue
Chicago, IL 60623
(312) 277-8300

Chandler Engineering Co.
c/o John D. Mills & Associates
P.O. Box 45644
Tulsa, OK 74145

Climatronics
1324-A Motor Pkwy.
Hauppage, NY 11787
(516) 234-2772

Climet Instruments Co.
1320 W. Colton Ave., P.O. Box 151
Redlands, CA 92373
(714) 793-2788

Cosa Corp. (for Shaw Moisture Meters)
17 Philips Parkway
Montvale, NJ 07645
(201) 391-0200

Delmhorst Instrument Co.
P.O. Box 840
Boonton, NJ 07005
(201) 334-2557

H.W. Dietert Company
9330 Roselawn Ave.
Detroit, MI 48204
(313) 933-9790

Drexelbrook Engineering Co.
205 Keith Valley Road
Horsham, PA 19044
(215) 674-1234

EG&G Environmental Equipment Div.
151 Bear Hill Road
Waltham, MA 02154
(617) 890-3710

Electromech Services
1240C Mt. View-Alviso Road
Sunnyvale, CA 94086
(408) 744-1870

Electronic Automation Inc.
732 Crofton, SE
Grand Rapids, MI 49507
(616) 949-0779

Environmental Tectonics Corp.
Scott Environmental Systems Div.
County Line Ind. Pk.
Southhampton, PA 18966
(215) 322-5455

Epic Company
150 Nassau Street
New York, NY 10038
(212) 349-2470

Ernst Gage Company
250 S. Livingston Ave.
Livingston, NJ 07039
(201) 992-1400

Foster-Cambridge Ltd.
Howard Road
Eaton, Socon, Huntingdon,
Cambridgeshire, England PE193EU

The Foxboro Company
Neponset Avenue
Foxboro, MA 02035
(617) 543-8750

General Eastern Instrs. Corp.
50 Hunt Street
Watertown, MA 02172
(617) 2386

Gulton Industries Inc.
Measurement & Control Systems Div.
Middle Rd & Rte. 2
E. Greenwich, RI 02818
(401) 884-6800

H-B Instruments
4319 N. American St.
Philadelphia, PA 19140
(215) 329-9125

Haake, Inc.
244 Saddle River Road
Saddle Brook, NJ 07662
(201) 843-7070

Honeywell Inc., Process Control Div.
1100 Virginia Drive
Ft. Washington, PA 19034
(215) 643-1300

Howard Engineering Company
P.O. Box 3164
Bethlehem, PA 18017
(215) 694-0939

Humidial Corporation
465 N. Mt. Vernon
Colton, CA 92324
(714) 825-1793

Hy-Cal Engineering Co.
12105 Los Nietos Road
Santa Fe Springs, CA 90670
(213) 698-7785

Impact Register Inc.
W. Springdfield Ave., P.O. Box 3097
Champaign, IL 61820
(217) 352-4129

Industronics Inc.
489 Sullivan Avenue
S. Windsor, CT 06074
(203) 289-1594

Ionics Inc.
65 Grove Street
Watertown, MA 02172
(617) 926-2500

Kahn & Company Inc.
885 Wells Road
Wethersfield, CN 06109
(203) 529-8643

Kay-Ray Inc.
516 W. Campus Drive
Arlington Heights, IL 60004
(312) 259-5600

Lab-Line Instruments Inc.
15th & Bloomingdale Ave.
Melrose Park, IL 60160
(312) 345-7400

Land Instruments Inc.
P.O. Box 1623
Tullytown, PA 19007
(215) 943-7882

Leone Engineering
117 Third Street
Newton, PA 15089
(412) 872-5189

Liebert Corporation
P.O. Box 29186
Colubmus, OH 43229
(614) 888-0246

Lockwood & McLorie, Inc.
P.O. Box 113
Horsham, PA 19044
(215) 675-8718

Luft Instruments
Old Winter Street
Lincoln, MA 01773
(617) 259-9215

Meteorology Research Inc.
Box 637
Altadena, CA 91001
(213) 791-1901

Moisture Register Co.
Div. of Berwind Corp.
6934 Tujunga Ave.
N. Hollywood, CA 91605

Moisture Systems Corp. (MSC)
P.O. Box 97
Hopkinton, MA 01748
(617) 435-6881

Monarch International Inc.
Columbia Drive
Amherst, NH 03031
(603) 883-3390

Motorola Inc., Semiconductor
Products Div.
P.O. Box 20912
Phoenix, AZ 85036
(602) 244-3464

Multiform Desiccant Products Inc.
1418 Niagara Street
Buffalo, NY 14213

Ohaus Scale Corporation
29 Hanover Road
Florham Park, NJ 07932
(201) 377-9000

The Ohmart Corporation
4241 Allendorf Drive
Cincinnati, OH 45209
(513) 272-0131

Omega Controls Corp.
1542 Moulton Parkway
Tustin, CA 92680
(714) 731-2233

Ondyne Inc.
P.O. Box 6302
Concord, CA 94524
(415) 825-8282

Panametrics Inc.
221 Crescent St.
Waltham, MA 02154
(617) 899-2719

Photovolt Corporation
1115 Broadway
New York, NY 10010
(212) 989-2900

Phys-Chemical Research Corp.
36 West 20th Street
New York, NY 10011
(212) 924-2070

Praxis Corporation
5420 Jackwood
San Antonio. TX 78238
(512) 684-3231

Princo Instruments Inc.
1020 Industrial Hwy.
Southampton, PA 18966
(215) 355-1500

Procema Ltd.
38 Hampton Road
Twickenham, Middlesex,
England TW2 5QB

Raeco, Inc.
550 Armory Drive
South Holland, IL 60473
(312) 331-6001

Refinery Supply Co., Div. of
Central Scientific
P.O. Box 15628, E. Twelfth St.
Tulsa, OK 74112
(918) 836-4681

Scientific Systems Corp.
9020 S. Choctaw
Baton Rouge, LA 70815
(504) 926-6950

Seaman Nuclear Corporation
3846 W. Wisconsin Avenue
Milwaukee, WI 53208
(414) 342-1030

Shaw Moisture Meters
Rawson Roads, Westgate
Bradford, England, BD135 Q

Sonic Development Corporation
3 Industrial Avenue
Upper Saddle River, NJ 07458
(201) 825-3030

Strandberg Engineering Labs, Inc.
Industrial Elec. Division
1001 S. Elm Street
Greensboro, NC 27406
(919) 274-3775

Taylor Instr. Co., Div. of
Sybron Corp.
95 Ames Street
Rochester, NY 14601
(716) 235-5000

Tenney Engineering Inc.
1104 Springfield Road
Union, NJ 07083
(201) 686-7870

Testing Machines Inc.
400 Bayview Avenue
Amityville, NY 11701
(516) 842-5400

Tewwipe Company
P.O. Box 278
Hillside, NJ 07642
(201) 664-0555

Thunder Scientific Corporation
623 Wyoming, SE
Albuquerque, NM 87108
(505) 265-8701

Totco Div., Baker International Corp.
506 Paula Ave., P.O. Box 3885
Glendale, CA 91201
(213) 245-7411

Tierice, H.O. Company
12950 Eight Mile Road
Detroit, MI 48237
(313) 399-8000

United Exporters Co.
World Trade Center
San Francisco, CA 94111
(415) 433-0771

Vaisala Oy (Industrial Sales)
PL 26, SF-00421
Helsinki 42, Finland

Volumetrics
1025 W. arbor Vitae
Inglewood, CA 90301
(213) 641-3747

Watlow Winona, Inc.
1265 E. Sanborn
Winona, MN 55987
(507) 454-5300

Watrous & Company, Inc.
110 East 23rd Street
New York, NY 10010
(212) 473-7789

Waynco Inc.
(see: Watlow-Winona, Inc.)

WeatherMeasure Corporation
P.O. Box 41257
Sacramento, CA 94841
(916) 481-7565

Weathertronics, Inc.
2777 Del Monte Street
West Sacramento, CA 95691
(916) 371-2660

Weksler Instruments Corporation
80 Mill Rd., P.O. Box 3040
Freeport, NY 11520
(516) 623-0100

Wescor Inc.
459 South Main St.
Logan, UT 84321
(801) 752-6011

Yellow Springs Instr. Company
P.O. Box 279
Yellow Springs, OH 45387
(513) 767-7242

11.2 Sensor Calibration and Evaluation Resources

As far back as 1951, the Office of the Assistant Secretary of Defense, recognizing the need for standardization of instrumentation systems and activities, established the Range Commanders Council. This group, composed of the commanders of the National Military Test Ranges, created a consulting organization called the Inter-Range Instrumentation Group. The latter was to cover areas of range instrumentation through working groups which ultimately produced a variety of standards documents. The Telemetry Working Group (IRTWG) concerned with the uniform and accurate transmission and reception of information (flight test data) from flight vehicles, in turn, established several committees to cover sub-areas.

At the eleventh meeting of the Inter-Range Telemetry Working Group in April 1958, a committee on transducers was established at the request of the National Bureau of Standards. The purpose of this committee was to provide effective feedback and guidance to the NBS Interagency Transducer Project [1] by IRTWG, as well as to provide IRTWG with information of significant developments in the field of telemetry sensors. Close liaison between the NBS project and IRTWG was desirable to assure maximum usefulness to the sponsors and to telemetry users generally.

Workshops sponsored by the Transducer Committee and characterized by a free exchange of information in an informal atmosphere have opened avenues of communication among those having a direct interest in transducer developments. These workshops have encouraged efforts to improve sensor performance, to standardize telemetry transducer terminology, specifications, evaluation, and calibration procedures, and to establish a clearinghouse for sensor calibration and evaluation reports. Workshop proceedings were published after the meetings held in 1967, 1969, 1972, 1975, 1977, and 1979. Those still in print may be obtained from the Secretariat, Range Commanders Council, White Sands Missile Range, NM 88002. (Non-government agencies must obtain authorization from a sponsoring government agency.)

The Transducer Committee produces a "Directory of Transducer Users" [56] which lists sensor resources (laboratories and experts) throughout the United States. A summary of the Directory appears below, divided into government installations and private industry facilities. The listing, based on voluntary submission of information on sensor usage, expertise, and facilities is probably not complete. The Directory was issued early in 1978 and may not be totally up to date, but will be revised in the future. Nevertheless, it should provide useful contacts for sensor experts.

Another source of information on federal metrology and calibration facilities not specifically directed towards sensors, however, is the "Catalog of Federal Metrology and Calibration Facilities," NBS SP 546 [57].

11.2.1 Government Sensor Laboratories, Contacts and Functions

The comments under each facility listing were furnished by laboratory staff.

Air Force Flight Dynamics Laboratory

Charles E. Thomas
AFFDL/FBG
Wright-Patterson AFB, OH 45433

Phone: (513) 255-2543
Autovon: 785-2543

Richard Talmadge
AFFDL/FBG
Wright-Patterson AFB, OH 45433

Phone: (513) 255-4684
Autovon: 785-4684

Comments:

"Acoustic, pressure and vibration sensors are used extensively in laboratory, ground and flight tests. We have a good calibration facility and maintain a moderate inventory of acoustic and vibration sensors. Two self-contained mobile laboratories are available for making on-site dynamics measurements at remote test sites. In addition, we have a quick response data acquisition system for ground and flight tests."

Air Force Weapons Laboratory

Terry Courthayn
Civil Eng. Research Div.
AFWL/DEO
Kirtland AFB, NM 87118

Phone: (505) 264-0358
Autovon: 964-0358
FTS: 475-0358

Comments:

"Acceleration, motion, pressure and structural strain are measured in and around high explosives tests. High level transient pressure and motion measurements and related data recovery are achieved."

Armament Development and Test Center

Herbert W. Brown
Armament Dev. and Test Center
3246 Test W/TETT
Eglin AFB
FL 32569

Phone: (904) 882-2785
Autovon: 872-2785

Harold D. Nation
Armament Dev. and Test Center
3246 Test W/TETT
Eglin AFB
FL 32569

Phone: (904) 882-2785
Autovon: 872-2785

J.W. Kronmiller
Armament Dev. and Test Center
3246 Test W/TEEAS
Eglin AFB
FL 32542

Phone: (904) 882-2461
Autovon: 872-2461

Sid Shelley
Armament Dev. and Test Center
3246 Test W/TEERS
Eglin AFB
FL 32542

Phone: (904) 882-4461
Autovon: 872-4461

Comments:

"The 3246th Test Wing is the responsible agency at Eglin for all testing and test facilities. An assortment of ground-based range instrumentation and transducers are used to obtain performance profiles on conventional and experimental munitions. Typical measurements include blast pressure, acceleration, temperature, strain, fragment weight, fragment velocity and dispersion. Air and ground tests can be performed. A sled track exists. The ADTC maintains a complete sensor calibration and evaluation facility."

Army Aeromechanics Laboratory

Robert E. George
U.S. Army Aeromechanics Lab
NASA Ames Research Center
MS-N215-1
Moffett Field
CA 95129

Phone: (415) 965-5835
Autovon: 586-5651

Comments:

"The Army Aeromechanics Lab is a multi-test facility which uses a number of transducers, including pressure (static and dynamic), temperature, acceleration and position. The facilities include both wind and water tunnel operations. Static and dynamic model rotor tests, plus some flight tests, are performed."

Army Ballistic Research Laboratory

Arpad A. Juhasz
Ballistic Research Lab
DRDAR-BLP
Aberdeen Proving Ground
MD 21005

Phone: (301) 278-4153
Autovon: 283-4153

Charles D. Bullock
Ballistic Research Lab
DRDAR-BLP
Aberdeen Proving Ground
MD 21005

Phone: (301) 278-3340
Autovon: 283-3340

Willis F. Jackson
Ballistic Research Lab
DRDAR-BLT
Aberdeen Proving Ground
MD 21005

Phone: (301) 278-2040
Autovon: 283-2040

Comments:

"Internal pressure measurements are made for large caliber weapons and free-field overpressure measurements are taken during high explosives detonations. Piezoelectric and strain gage type ballistic pressure gages are used for artillery, small arms and closed bomb applications. Primary standard (deadweight) calibrations to 100 000 psi and secondary standard calibrations to 150 000 psi, plus development of capability for primary standard calibrations to 150 000 psi are available.

Army Metrology and Calibration Center

J.R. Miller, III
U.S. Army Metrology and Calibration Center
Bldg. 5435, DRSMI-MMP
Redstone Arsenal
AL 35802

Phone: (205) 876-2876
Autovon: 746-2876

Comments:

"The U.S. Army Calibration Program managed by USAMCC, provides calibration support for sensors throughout the Army. Three tiers of accuracy are available in the various laboratories. Interest exists in the application of microprocessors to sensor calibrations in order to develop automated transfer standards."

NASA-Marshall Space Flight Center

W.T. Escue
EC-23
NASA-MSFC
Huntsville
AL 35812
Phone: (205) 453-4627
FTS: 872-4627

Marlan S. Harman
ES-23
NASA-MSFC
Huntsville
AL 35812
Phone: (205) 453-4627
FTS: 872-4627

Comments:

"Aerospace applications of sensors to Saturn, Space Shuttle, and similar programs. Calibration and test capabilities exist to evaluate sensors in areas of pressure, temperature, force, flow, liquid level, vacuum, remote sensing vibration."

National Aviation Facilities Experimental Center

Jack J. Shrager, (ANA-410)
Airworthiness Branch
Aircraft & Airports Safety Division
National Aviation Facilities Experimental Center/FAA
Atlantic City
NJ 08405

Phone: (609) 641-8200 Ext 2665/3718
FTS: 346-2665/3718

Comments:

"Sensors are used in the development of aircraft and airport testing, and test equipment. They are also used in the development of devices for both airborne and ground-based operational equipments for aircraft navigation, guidance and control."

National Bureau of Standards

Paul S. Lederer
Electrosystems Division
National Bureau of Standards
Washington
D.C. 20234
Phone: (301) 921-2727

John D. Ramboz
Electrosystems Division
National Bureau of Standards
Washington
D.C. 20234
Phone: (301) 921-3121

Comments:

"NBS-Interagency Transducer Project from 1951 to 1979 developed calibration and evaluation techniques with emphasis on dynamic calibration methods for pressure sensors and accelerometers, durability and thermal transient tests."

Charles R. Tilford
A149 Met.
Pressure and Vacuum Section
National Bureau of Standards
Washington
DC 20234
Phone: (301) 921-2121

Vern E. Bean
A149 Met.
Pressure and Vacuum Section
National Bureau of Standards
Washington
DC 20234
Phone (301) 921-2121

Comments:

"The Pressure and Vacuum Group of NBS provides calibration services for pressure standards and sensors over the range of 1 Pa to 420 MPa. In the pressure sensor characterization service, a battery of tests over a period of several months are used to determine such parameters as zero drift, voltage dependence, pressure and temperature hysteresis, relaxation, short- and long-term stability, precision, temperature effects on zero and span, effects of pressure cycling, attitude dependence, etc. Training courses in the use of piston gages, piston gage data evaluation services and consultations are also available."

National Parachute Test Range Test Facility

Lt. David G. Leupp
DORSI
6511th Test Squadron
National Parachute Test Range
El Centro
CA 92243
Phone: (714) 339-2474
Autovon: 958-8474

Comments:

"We primarily utilize strain gages (foil), accelerometers and rate transducers to determine parameters of parachute recovery systems. FM-FM and PAM-FM telemetry systems provide information during test drops."

Naval Air Test Center

William D. Anderson
Head, Airborne Instr. Branch
Technical Support Directorate
Naval Air Test Center
Patuxent River
MD 20670
Phone: (301) 863-4271
Autovon: 356-4271

Harry W. Clarke
Head, Aero Calibration Labs
Technical Support Directorate
Naval Air Test Center
Patuxent River
MD 20670
Phone: (301) 863-4557
Autovon: 356-4557

Comments:

"NATC utilizes sensors for the instrumentation of Navy aircraft. Tests include: flying qualities, structural tests, engine performance, vibration measurements, weapons release, avionics performance and temperature surveys. Major types of sensors utilized are: pressure, strain gage, accelerometers, vibration pickups, rate gyros, thermocouples and position sensors. NATC maintains compelte sensor calibration facilities and is engaged in sensor evaluations. NATC operates and maintains the NAVAIRSYSCOM Instrumentation Pool which loans sensors to Navy activities and contractors holding NAVAIR contracts."

Naval Ordnance Station

Eugene J. Stekfo
Ballistic Test Division
Code 3024, Bldg. 1576
Naval Ordnance Station
Indian Head
MD 20640
Phone: (301) 743-4387
Autovon: 364-4387

Ronald P. Denton
Ballistic Test Division
Code 3024A, Bldg. 759
Naval Ordnance Station
Indian Head
MD 20640
Phone: (301) 743-4477
Autovon: 364-4477

Comments:

"The Division performs testing during the development, qualification, pre-production and production phases of solid and liquid propulsion weapon systems, components and devices. These tests subject the specimens to conventional fleet/field use environments. Evaluation test equipment includes shock machines, shakers, centrifuges, temperature/humidity/altitude chambers, etc. Static test firings are conducted measuring strain, acceleration, displacement, pressure, thrust and temperature. Pressure levels to 50 000 psi, thrust levels to 200 000 lb., accelerations to 1000 g, and temperatures to 2500 °F are measured. Information is recorded by an automated data acquisition system which provides on-line, real-time, data reduction."

Naval Ship Weapons System Engineering Station

Leroy Bates
NSWSES, Code 6340
Port Hueneme
CA 93043
Phone: (805) 982-4104
Autovon: 360-4104

Wes Paulson
NSWSES, Code 6310
Port Hueneme
CA 93043
Phone: (805) 982-4159
Autovon: 360-4159

Comments:

"A wide variety of accelerometers, pressure sensors, thermocouples, microphones, etc., are used to support shipboard weapon (missile and gun) system test and evaluation programs. NSWSES is responsible for engineering, logistics and evaluation of operational weapon systems for surface ships. Weapon systems include Tartar, Terrier, SM-1, SM-2, Harpoon, Aegis, Point Defense, CISW, 76mm gun and 5- and 8-inch guns. Specially tailored instrumentation systems are temporarily installed for tests at sea."

Naval Surface Weapons Center

Dr. Philip M. Aronson
Naval Surface Weapons Center
Bldg. 427, Room 419
White Oak, Silver Spring
MD 20910
Phone: (202) 394-1920
Autovon: 290-1920

Comments:

"NSWC, A prime Navy R&D laboratory, is heavily involved in the development and testing of underwater and air ordnance. Measurements are made of pressure, acceleration and temperature with emphasis on transient phenomena. Data transmissions make use primarily of hard-wire telemetry systems.

The center has a wide variety of facilities and equipment including: airblast facilities, hydroballistic tanks, wind tunnels, shock tubes, air guns, shock tunnels, dynamic pressure and accelerometer calibrations, shockless pressure-step generators, electrodynamic shakers and piezoelectric and strain gage type pressure sensors."

Naval Weapons Center

Kenneth D. Cox
Code 6213
Naval Weapons Center
China Lake
CA 93555
Phone: (714) 939-7427
Autovon: 245-7427

William Francis
Code 6213
Naval Weapons Center
China Lake
CA 93555
Phone: (714) 939-7404
Autovon: 245-7404

Franklin R. Hartzler
Instrumentation Division
Code 6243
Naval Weapons Center
China Lake
CA 93555
Phone: (714) 939-5551. 5554, 5586
Autovon: 245-5551, 5554, 5586

Jim Rieger
Instrumentation Division
Code 6243
Naval Weapons Center
China Lake
CA 93555
Phone: (714) 939-5551, 5554, 5586
Autovon: 245-5551, 5554, 5586

Comments:

"The Naval Weapons Center is the principal Navy RDT&E Center for air warfare and missile weapon systems. To perform its mission, the Center establishes and maintains the primary in-house research and development capability and appropriate documentation for an important series of Navy and Marine Corps aircraft weapons, tactical missiles, weapon subsystems, and technologies.

The instrumentation branch designs or specifies sensors for airborne and ground-based (wired and wireless) instrumentation systems for a variety of customers.

Measurement experience exists in areas of free-flight, fires, explosions, sled tracks and aircraft. Sensor types include infrared sensing, light sensing, accelerometers, microphones, strain and displacement, electrometry and non-contact motion sensing.

In-house facilities can design and produce signal-conditioning circuitry for networking, including nonlinear processing and charge amplification.

The Transducer Calibration Laboratory in the Propulsion Development Department has equipment to calibrate pressure sensors from 0.01 psi to 40 000 psi, load cells from 1 lb to 400 000 lb compression and 200 000 lb tension. We make temperature measurements from -250 °F to approximately 3000 °F in various ranges using thermocouples."

Navy Metrology Engineering Center

Dale W. Rockwell
Metrology Engineering Center
Naval Plant Representative
P.O. Box 2505, MZ 3-18
Pomona
CA 91766
Phone: (714) 629-5111 Ext 3662
Autovon: 360-2811 Sta 6

Comments:

"The Metrology Engineering Center serves as technical director to the Navy's Standards and Calibration Program. As such the Center writes calibration procedures, develops/evaluates calibration techniques, and develops/evaluates calibration systems and standards. It procures calibration equipment required for use at Navy calibration and standards laboratories supporting various test instruments (including transducers). The actual use of sensors by this Center is restricted to evaluation of calibration systems and to evaluations of sensors for use as standards. The Metrology Engineering Center does not perform evaluations or calibrations for other activities, but Navy calibrations and standards are equipped to perform a wide range of calibrations depending on the capability of each individual laboratory. They are, typically, capable of calibrating sensors used in the measurement of force, pressure, temperature, humidity, and vibration. In addition, several laboratories are capable of providing calibration of gas and liquid flowmeters, anemometers, dynamic pressure sensors, viscometers, densitometers, and shock accelerometers."

Test Track Division

Joe A. Haden
6585th Test Group
Test Track Division (TKIA)
Holloman AFB
NM 88330
Phone: (915) 679-2038
Autovon: 349-2038

Robert C. DeRoy
6585th Test Group
Test Track Division (TKIA)
Holloman AFB
NM 88330
Phone: (915) 679-2611
Autovon: 349-2611

Comments:

"The Test Track Division instruments a wide variety of systems and subsystems for sledborne testing. These include guidance systems, crew escape systems, missile warheads, projectiles, parachute systems, airfoils, etc. The test equipment is realized by utilization of rocket propelled test-bed vehicles (sleds) with the sled and propulsion being designed to meet specific test parameters. RF telemetry links are used for data transmission.

The Test Track Division makes a wide variety of measurements including pressure, acceleration, vibration, stress and strain, velocity, temperature, roll, pitch, and yaw."

Tooele Army Depot

Jerry R. Miller
Commander
Tooele Army Depot
SDSTE-AEO
Tooele, UT 84074
Phone: (801) 833-2825
790-2825

Kenneth T. Smith
Commander
Tooele Army Depot
SDSTE-AEO
Tooele, UT 84074
Phone: (801) 833-2825
790-2825

Comments:

"Meaasurements are made of air blast pressures in the 1 to 100 psi range, also of pneumatic and hydraulic pressures to 5000 psig, and thermocouple temperature measurements to 2000 °F. Strain gages are also used. This facility has a 40-ft semi-trailer instrumentation van, 100-pound (maximum) explosive test bays, an explosives test range, and high-speed (500 to 10 000 fps) movie cameras."

11.2.2 Private Industry Sensor Laboratories, Contacts and Functions

The comments under each listing were furnished by laboratory staff.

Boeing Aerospace Company

John D. Favour
Boeing Aerospace Company
P.O. Box 3999 M/S 86-14
Seattle
WA 98124
Phone: (206) 773-4802

Norman G. Ray
Boeing Aerospace Company
P.O. Box 3999 M/S 86-12
Seattle
WA 98124
Phone: (206) 773-8594

Comments:

"The Engineering Labs within the Boeing Aerospace Company are involved in the static and dynamic testing of aerospace systems and components, such as defense systems and components, commercial aircraft components, and various commercial and civil oriented products and components. The wide range of testing capability has led to a wide diversity of instrumentation requirements necessitating "in-house" development of transducers and associated calibration techniques. Primary parametric measurements are motion (X, X, X), force, pressure, temperature, strain, and time. Areas of expertise are in the development of strain gage instrumentation, high temperature strain measurement techniques, structural modal analysis, the -S/N- Fatigue Life Gage, composite instrumentation techniques, dynamic calibration of accelerometers, velocimeters, and pressure transducers through transient excitations, wind tunnel instrumentation techniques, and transient test and analysis techniques."

Boeing Commercial Airplane Company

Albert E. Davis
Boeing Commercial Airplane Company
P.O. Box 3707 M/S 1W-04
Seattle
WA 98124
Phone: (206) 655-1369

Comments:

"Pressure sensors and hot wire/hot film anemometer sensors are used for test instrumentation. A variety of calibration and testing facilities exists."

Boeing Vertol Company

A. Miller
Boeing Vertol Company
Flight Test Instrumentation
P.O. Box 16858 M/S P37-14
Philadelphia
PA 19142
Phone: (215) 522-7135

Hans F. Pauls
Boeing Vertol Company
Flight Test Instrumentation
P.O. Box 16858 M/S P37-14
Philadelphia
PA 19142
Phone: (215) 522-7234

Comments:

"We are concerned with all sensors utilized in the typical flight testing of helicopters. The company maintains a calibration lab for flight-test sensors. A real-time computer is available for on-line computing, plotting, and hard copy of data from two aircraft simultaneously telemetering stress and vibration measurements to a ground station."

Civil Engineering Research Facility, University of New Mexico

Stephen F. Pickett
University of New Mexico
CERF Campus, P.O. Box 25
Albuquerque
NM 87131
Phone: (505) 264-4644
Autovon: 964-4644

Neal P. Baum
University of New Mexico
CERF Campus, P.O. Box 25
Albuquerque
NM 87131
Phone: (505) 264-4644
964-4644

Comments:

"Pressure, triaxial stress, acceleration, velocity, displacement, strain and angular motion instrumentation are used. Explosive-induced high pressures, motion, and stress transients are measured."

EG&G, Incorporated, Las Vegas

Roger P. Noyes
EG&G, Inc.
P.O. Box 1912 M/S N-28
Las Vegas
NV 89101
Phone: (702) 647-5340
FTS: 545-5340

Lee E. Davies
EG&G, Inc.
P.O. Box 1912 M/S N-28
Las Vegas
NV 89101
Phone: (702) 647-5261
FTS: 545-5261

Comments:

"The EG&G Special Measurements Group calibrates and installs transducers utilized in measuring pressure, temperature, acceleration and velocity in support of the Lawerence Livermore Laboratory (LLL) Underground Nuclear Test Program at the Nevada Test Site. A calibration laboratory exists for testing pressure sensors, temperature sensors, variable reluctance velocity gages, and accelerometers. This group has extensive field experience with both dual-constant-current excitation and carrier-demodulation signal conditioning."

EG&G, Incorporated, San Ramon

M.A. Hatch, Jr.
EG&G, Inc.
2801 Old Crow Canyon Road
San Ramon
CA 94583
Phone: (415) 837-5381

J.A. Kalinowski
EG&G, Inc.
2801 Old Crow Canyon Road
San Ramon
CA 94583
Phone: (415) 837-5381

Comments:

"EG&G, San Ramon, in conjunction with the Lawrence Livermore Laboratory, uses a variety of transducers to measure the dynamic and static behavior of gases in line-of-sight pipes coupled to nuclear detonations. Measurements are also made of the dynamic behavior of the pipe and other mechanical structures during the detonation using transducers to sense temperature, pressure, velocity, acceleration, strain, stress, ionization, and illuminosity."

"EG&G/San Ramon has a gas-gun shock-tube facility which is used for evaluating pressure, temperature and acceleration sensors. It is capable of producing planewave impact stresses in solids ranging from 0-100 k-bar. It is capable of subjecting small structures, i.e., an accelerometer, to levels in excess of 50 000 g. The system can produce step pressure changes and rapidly changing pressure impulses of several milliseconds duration in the 0-2000 psi range."

Grumman Aerospace Corporation, Bethpage

Methody Sirkot
Grumman Aerospace Corporation
Department 802
Plant 12
Bethpage
NY 11714
Phone: (516) 575-5754

Comments:

"Grumman Aerospace Corporation makes extensive use of a large variety of sensors for both flight and ground test programs. These include angular and linear accelerometers, acoustic, displacement, liquid and gaseous flow, force, pressure and temperature sensors. A modern sophisticated calibration laboratory exists to calibrate and maintain these instruments.

Familiarity with most of the pressure sensors presently being manufactured has come through calibration of the same. Units calibrated vary from very low differential pressure to those measuring 20 000 psi, inlet rake pressure sensors, air data sensors and high frequency crystal types. Generally, units are independently calibrated in the lab, but some system calibrations are performed, in situ."

Grumman Aerospace Corporation, Calverton

G. Rosen (Temperature)
Grumman Aerospace Corp.
Flight Test Dept.
M/S B28-07
Calverton
NY 11933
Phone: (516) 369-7471

H. Weiss (Flight Dynamics)
Grumman Aerospace Corp.
Flight Test Dept.
M/S B28-07
Calverton
NY 11933
Phone: (516) 369-7471

T. Harmon (Air Data & Dynamic Press.)
Grumman Aerospace Corp.
Flight Test Dept.
M/S B28-07
Calverton
NY 11933
Phone: (516) 369-7472

M. Keitel (General Pressure)
Grumman Aerospace Corp.
Flight Test Dept.
M/S B28-07
Calverton
NY 11933
Phone: (516) 369-7472

Comments:

"Sensor usage at Calverton chiefly involves the instrumentation of aircraft for development flight testing. Sensors are utilized in the acquisition of data relative to aerodynamic and power plant performance, structural dynamics and thermodynamic surveys. Test requirements usually dictate high accuracy sensors suited to hostile environments and compatible with on-board tape recording systems and telemetry. Sensors typically used include crystal accelerometers, strain gage accelerometers, all types of pressure sensors, rate and attitude gyros, turbine flowmeters, thermocouples, resistance thermocouples and thermometers, tach generators, and synchros.

A separate group, dedicated to sensor applications, exists in the Grumann Flight Test Organization. This group specializes in the selection of sensors and the development of probes, rakes and novel application techniques. Substantial knowledge and experience has been accrued in the areas of air data sensors (air-speed/altitude), dynamic pressure sensing (low range-high frequency), general purpose sensing (absolute and differential, from fractions to thousands of psi), flow measurements (liquid and gas) and flight dynamics (rates, acceleration, etc.)."

<u>Lawrence Livermore Laboratory, University of California</u>

Henry S. Freynik
Lawrence Livermore Laboratory
Transducer Lab.
P.O. Box 808, L-342
Livermore
CA 94550
Phone: (415) 422-6988
FTS: 532-6988

Comments:

"Measurements are made of strain and temperature, both static and dyanmic, also of strain principally as stress, with some special sensor development. Surface and gas temperature measurements cover a wide range and with very fast rise times. Most applications are in conventional environmental tests and in nuclear field tests. Other tests involve the long-term stability (2 years plus) of installation, and special bonding techniques for gaging hostile (radio-active) materials used in adverse environments."

Thomas B. Miller
Lawrence Livermore Laboratory
Transducer Lab.
P.O. Box 808, L-342
Livermore
CA 94550
Phone: (415) 422-7040
FTS: 532-7040

Comments:

"Our principal use of transducers is in conventional environmental testing, with some applications in tests using sheet explosives, flyer plates and nuclear detonations.

Parameters measured and relative frequency range requirements are these: acceleration, vibration, and shock (high), displacement, quasi-static (medium); pressure, mostly static (medium); force, mostly static (low). Calibration facilities exist for the sinusoidal calibration of accelerometers (20 Hz to 10 kHz; to 50 kHz for surveys), displacement sensors by the interferometric method, pressure sensors (0.2 psia to 200 k psi), and force sensors (to 60 1-1b)."

Bill Shay
Lawrence Livermore Laboratory
Materials Engineering Div.
P.O. Box 808, L-342
Livermore
CA 94550
Phone: (415) 422-7044
532-7044

Ray Cornell
Lawrence Livermore Laboratory
Materials Engineering Div.
P.O. Box 808, L-342
Livermore
CA 94550
Phone: (415) 422-6933
532-6933

Comments:

"We supply or use instruments for all types of testing on individual parts to completed assemblies. The testing ranges from static to dynamic with the test environments from ambient to high explosive and underground nuclear detonations. The types of sensors used are: pressure sensors, accelerometers, thermocouples, strain gages, and load cells.

We evaluate and calibrate pressure, load cell, displacement and accelerometers used by the laboratory. Special areas of expertise are: gas gun work, measurement of thermophysical properties, calorimetry, strain gaging of special materials, strain, and temperature measurement for reactor experiments and high explosive blast measurements."

David C. Holten
Nuclear Explosives Eng. Div.
Lawrence Livermore Laboratory
P.O. Box 808, L-122
Livermore
CA 94550
Phone: (415) 422-8836
FTS: 532-8836

Arthur W. Hampton
Nuclear Explosives Eng. Div.
Lawrence Livermore Laboratory
P.O. Box 808, L-508
Livermore
CA 94550
Phone: (415) 422-9596
FTS: 532-9596

Richard T. Hasbrouck
Field Test Systems Division
EE Department
Lawrence Livermore Laboratory
P.O. Box 808, L-218
Livermore
CA 94550
Phone: (415) 422-3977
FTS: 532-3977

Comments:

"We are principally a user of sensors in extensive field tests, laboratory experiments and portable high pressure gas systems applications. Pressure ranges from vacuum to 20 000 psi, in both absolute and differential pressures. Heavy emphasis is placed on sensor mechanical integrity and signal conditioning electronics reliability under difficult test conditions. Expertise exists in areas of mechanical quality control, specification, evaluation, certification, and performance testing of absolute pressure sensors. There is an on-going program to develop special sensor materials. Experience exists in high reliability signal conditioning electronics, digital readout portable transfer standards, and end-to-end static calibration via PCM/microwave telemetry link."

Lockheed California Company

Ed Kaufman
Lockheed California Company
74/94 B6-360
P.O. Box 551
Burbank
CA 91520
Phone: (213) 847-4092

Comments:

"The Lockheed Flight Test Laboratory uses sensors in its data acquisition systems for flight and demonstration programs to measure pressure, acceleration, flow, temperature, rpm, etc. Nearly all data is multiplexed on 1" magnetic tape reels.

The Flight Test Lab, in addition to providing, servicing and maintaining the data acquisition systems for flight test aircraft, conducts numerous ground tests in support of flight and demonstration programs. These involve all of the sensors previously mentioned in such tests as ground vibration of components and of the complete aircraft, engine tests, structural (strain gage) calibrations, control surface response and free play, and other systems tests. Digital sensors have been used for the measurement of air-speed, altitude, and other critical parameters."

McDonnell-Douglas Corporation

D.D. Crompton
McDonnell-Douglas Corporation
M.S. 41-59
3855 Lakewood
Long Beach
CA 90846
Phone: (213) 593-2482

P.M. Mumford
McDonnell-Douglas Corporation
M.S. 41-59
3855 Lakewood
Long Beach
CA 90846
Phone: (213) 593-3268

J.H. Gault
McDonnell-Douglas Corporation
M.S. 41-52
3855 Lakewood
Long Beach
CA 90846
Phone: (213) 593-8969

Comments:

"DAC Flight Development uses large quantities of sensors for flight testing of aircraft and for ground support equipment. They measure pressures from 0.1 psi to 10 000 psi, accelerations from 0.1 g to 500 g (frequency range 1 to 10 000 Hz), forces, temperature, position, airspeed, altitude, proximity and frequency. Telemetry coverage via radio and microwave is from Baja, California to Reno, Nevada.

Facilities include wind tunnels, fatigue and endurance testers, aircraft simulators, seat ejection tests and flight testing of military and commercial aircraft. Also there are facilities for pneumatic, hydraulic, acoustic, and vibration measurements."

Pratt & Whitney Aircraft, East Hartford

Howard P. Grant
Pratt & Whitney Aircraft, CPD
XT2
400 Main Street
E. Hartford
CT 06108
Phone: (203) 565-3355

Comments:

"We are engaged in aircraft gas turbine engine development testing (occasionally flight testing). There are instrumentation development laboratories for strain gages, slip rings, near-field telemetry and optical systems."

Pratt & Whitney Aircraft Group, West Palm Beach

James C. Birdsall
Pratt & Whitney Aircraft Group
P.O. Box 2691 M/S 3-87
West Palm Beach
FL 33402
Phone: (305) 844-7311
ext 2733

Peter V. Bechman
Pratt & Whitney Aircraft Group
P.O. Box 2691 M/S E-87
West Palm Beach
FL 33402
Phone: (305) 844-7311
ext 2733

Comments:

"Military jet engine (F100) pressures are monitored in the following environment: -65° to 468 °F, up to 600 g at 20 kHz random vibration, and 20 g to 2 kHz random vibration.

We have deadweight calibration facilities for pressure and force sensors. Development of silicon-on-sapphire solid-state pressure sensors in ranges from 25 to 1000 psia (in conjunction with Conrac Systems West Division) was undertaken."

Sandia Laboratories, Albuquerque

P.L. Walter
Sandia Laboratories
Division 9486
Albuquerque
NM 87115
Phone: (505) 264-5226
Autovon: 964-5226

Frederick Schelby
Sandia Laboratories
Division 9486
Albuquerque
NM 87115
Phone: (505) 264-3907
Autovon: 964-3907

Comments:

"Sandia Laboratories, Albuquerque, instruments a variety of components/assemblies for design verification testing. These include electromechanical devices, mechanical structures, projectiles and parachutes. Test environments utilized are vibration exciters, centrifuges, drop towers, ballistics, rocket sleds, sheet explosives, flyer plates, shock tubes and underground nuclear detonations. Both radio-link and hard-wire telemetry are employed.

We make a large quantity of acceleration measurements in impact-type environments where levels in the tens of thousands of g are frequently encountered. Expertise exists in measuring blast and ballistic type pressure environments where very short pressure rise-times are encountered and pressure levels from a few hundred to tens of thousands of psi are experienced."

<u>Sandia Laboratories, Livermore</u>

R.D. Culy
Sandia Laboratories
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P.O. Box 969
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CA 94550
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D.C. Stoner
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Phone: (415) 422-3119
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Comments:

"Sandia Laboratories, Livermore, instruments a variety of components/assemblies for design verification testing. These include electromechanical devices, mechanical structures, projectiles, parachutes, etc. Test environments utilized are vibration exciters, centrifuges, drop towers, ballistics, rocket sleds, sheet explosives, flyer plates, shock tubes, and underground nuclear detonations. Both radio-link and hard-wire telemetry are employed.

We make acceleration, vibration, pressure, temperature and angular velocity measurements on flight test vehicles, laboratory test assemblies, and special test units. The latter two range from single components to full-scale models."

<u>Stein Engineering Services</u>

Peter Stein
Stein Engineering Services, Inc.
5602 E. Monte Rosa
Phoenix
AZ 85018
Phone: (602) 945-4603
(602) 946-7333

Comments:

"Consultant collects, evaluates and organizes literature on transducer performance and behavior, especially in hostile environments. He has an extensive library and develops educational programs specifically oriented to transducers construction, evaluation and application. Consultant on measurement problems."

Systems, Science and Software

Russell Wilson
Systems, Science & Software
P.O. Box 1620
LaJolla
CA 92038
Phone: (174) 453-0060
ext 217

Comments:

"Personnel in the Shock Physics program at S^6 use accelerometers, stress gages, pressure sensors, and laser interferometer systems to study dynamic environments produced by explosives (conventional and nuclear), light-gas guns and flash x-ray tubes.

S^3 has the facilities and expertise to design, manufacture, calibrate, and install quartz and ytterbium stress gages, particle velocity instruments, and laser velocity interferometers usable at stresses of several k-bar, accelerations above 10 000 g and velocities over 100 meters per second. Special facilities at S^3 include an explosive test site, a flash x-ray generator, a light-gas gun, and a dropbar stress and velocity calibrator."

TRW Systems

Ken Bushey
TRW Systems
P.O. Box 10
San Clemente
CA 92672
Phone: (714) 492-4157
ext 370

Comments:

"The Metrology Lab at TRW calibrates, evaluates and assists in design and usage of a wide variety of pressure, force, flow, temperature, and vibration sensors and their associated electronics. These sensors and associated electronics are employed in tests ranging from rocket engine firings to measurement of the pulsations of the human heart.

"Metrology at TRW is capable of special accuracies of low liquid flow and accuracies in minipressures down to 1 to 2 inches of water within 0.01% of the reading. Improvements in speed and accuracy of pressure sensor calibrations through automation have been accomplished."

Vought Corporation

J.V. Kelly,, Jr.
Vought Corporation
Unit 2-59150
P.O. Box 5907
Dallas
TX 75222
Phone: (214) 266-3260

W.E. Dryer
Vought Corporation
Unit 2-59150
P.O. Box 5907
Dallas
TX 75222
Phone: (214) 266-3260

Comments:

"We use sensors in the ground and flight tests of missiles and aircraft."

11.2.3 Miscellaneous Sensor Information Resources

11.2.3.1 Periodicals

(The following periodicals present articles on sensors and related matters and advertise new sensors.)

Instrumentation Technology (monthly)
Instrument Society of America
67 Alexander Drive
Research Triangle Park, NC 27709

ISA Transactions (quarterly)
Instrument Society of America
67 Alexander Drive
Research Triangle Park, NC 27709

Measurements and Control (bi-monthly)
Measurements and Data Corporation
2994 West Liberty Avenue
Pittsburgh, PA 15216

Instruments and Controls Systems (monthly)
Chilton Company
Radnor, PA 19089

Electronic Design (bi-weekly)
Hayden Publishing Comapny, Inc.
50 Essex Street
Rochelle Park, NJ 07662

Machine Design (bi-monthly)
Penton/IPC
Penton Plaza
Cleveland, OH 44114

Control Engineering (monthly)
666 Fifth Avenue
New York, NY 10109

Review of Scientific Instruments (monthly)
American Institute of Physics
345 East 45th Street
New York, NY 10017

IEEE Transactions on Instrumentation and Measurement
IEEE Service Company
445 Moes Lane
Piscataway, NJ 08854

11.2.3.2 Courses

Some universities and colleges at times offer courses related to sensors. Special inquiries should be made.

Short courses on measurements are currently being offered as:

"Measurement Systems Engineering" and
"Measurement Systems Dynamics" by
Stein Engineering Services, Inc.
5602 East Monte Rosa
Phoenix, AZ 85018

11.2.3.3 Conferences

The Instrument Society of America sponsors a number of meetings and conferences:

- Annual Conference and Exhibit, fall
- International Instrumentation Symposium, special
- Flow, Its Measurement and Control, every few years
- Temperature, Its Measurement and Control, every few years

The Range Commanders Council through the Transducer Committee of the Telemetry Group sponsors a transducer workshop every second year. Information may be obtained from Range Commanders Council, White Sands Missile Range, NM 88002.

12. INDEX

APPENDIX A

TABLES OF COMMERCIALLY AVAILABLE SENSORS

The following tables were compiled from current sensor manufacturers' literature. This sampling of commercially available sensors is included to indicate the types, ranges, characteristics, and operational environments that such sensors encompass.

No conclusions should be drawn as to the quality of performance of any of the listed devices. Listing of a particular sensor does not constitute endorsement, nor does the absence of a device or manufacturer indicate disapproval. The tables only serve to indicate approximately the scope of commercial sensors.

Manufacturers of sensors should be contacted directly to get the most up-to-date information on available sensors.

Key to Manufacturer's Codes

AKC	Ametek Controls Division
ANL	Analog Devices
AVL	AVL Gesellschaft (Austria) - distributed by Degamo, Inc.
BAH	Bell and Howell
BLE	BLH Electronics
BBN	Bolt, Beranek, and Newman, Inc.
BRN	Bourns, Inc.
CCC	Consolidated Controls Corp.
CEL	Celesco Transducer Products, Inc.
COL	Columbia Research Laboratories, Inc.
CNT	Controlotran Corporation
CXI	Cox Instrument
DGS	Degussa Inc., Metals Div.
DII	Data Instruments Inc.
DMI	Datametrics Inc.
DRC	Dynamics Research Corp.

END	Endevco, Dynamic Instruments Div.
ENT	Entran Devices, Inc.
FAR	Farrand Controls
FDN	Fluidyne Instrumentation
FTI	Flow Technology, Inc.
FWL	Fenwal Electronics
FXB	Foxboro/I.C.T. Inc.
GLD	Gould Inc.
GTN	Gulton
HBM	Hottinger Baldwin Messtechnik
HFC	Hoffer Flow Controls Inc.
HLS	Haliburton Services
HMS	Hamilton Standard
IGI	IRAD Gage, Inc.
KAG	Kistler Instrument Corporation - subsid. of Kistler Instrumente AG
KEY	Keystone Carbon Company
KLT	Kulite Semiconductor Products, Inc.
KMN	Kaman Sciences Corporation
KSM	Kistler-Morse
LBW	Lebow Associates, Inc.
MRL	Marlin Manufacturing Corp.
MNC	Minco Products, Inc.
MSG	Measurements Group, Vishay Intertechnology, Inc.
MTX	Metrix Instrument Co.
OMG	Omega Engineering Group
PCB	PCB Piezotronics, Inc.
PSE	Precise Sensors, Inc.

RES	Research, Inc.
SCV	Schaevitz Engineering
SNT	Sensotec Incorporated
SSS	Systems, Science, and Software
STN	Strainsert Company
STR	Setra Systems, Inc.
SUN	Sunstrand Data Control, Inc.
SYC	Systems Corporation
TGY	Teledyne Gurley
THR	Teledyne Hastings-Raydist
TMP	Temposonics Incorporated
UDT	United Detector Technology, Inc.
UNM	Unimeasure Div., Konigsberg Instruments
VLD	Validyne Engineering Corp.
VNT	Vernitech Division, Vernitron Corp.
VTN	Viatran Corporation
WAT	Waters Manufacturing, Inc.
WLX	Wilcoxon Research

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** *(See instructions)*	1. PUBLICATION OR REPORT NO. NBS SP 615	2. Performing Organ. Report No.	3. Publication Date October 1981

4. TITLE AND SUBTITLE

SENSOR HANDBOOK FOR AUTOMATIC TEST, MONITORING, DIAGNOSTIC, AND CONTROL SYSTEMS
APPLICATIONS TO MILITARY VEHICLES AND MACHINERY

5. AUTHOR(S)
Paul S. Lederer

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered
Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*
U.S. Army Material Command
CORADCOM/DRDCO-TCS
Fort Monmouth, NJ 07703

10. SUPPLEMENTARY NOTES

The preparation of this document was one of the objectives of Subtask 20602 of the Joint Logistics Commanders Panel on Automatic Testing (Department of Defense).

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The Sensor Handbook is intended as a guide for those who design, specify, use, and test military automatic test equipment containing sensors. The handbook addresses measurands and principles of measurement, data acquisition, sensor calibration and testing, environmental considerations, stability, durability, reliability, and error assessment. Sensor manufacturers and sensor calibration and evaluation resources are included, as is an annotated bibliography. The handbook is based largely on the present, proved state-of-the-art. Possible future trends are briefly discussed. The handbook is addressed to the general engineer, system designer, or manager with an engineering background. It does not provide the highly detailed technical information needed by the measurement engineer, although ample references are included for further study.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

automatic test equipment; ATE; calibration; data acquisition; durability; dynamic calibration; environmental testing; evaluation; measurand; reliability; sensor; transducer.

13. AVAILABILITY

☒ Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☒ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

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☆ U.S. GOVERNMENT PRINTING OFFICE : 1981 -354-868/9172

TABLE A-1

COMMERCIALLY AVAILABLE PRESSURE SENSORS

TRANSDUCTION	FULL SCALE RANGES (PSI) from 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴ 10⁵ 10⁶	FULL RANGE OUTPUT (mV)	FULL RANGE OUTPUT (mA)	SENSITIVITY (pC/PSI)	SENSITIVITY (mV/PSI)	ACCURACY LINEARITY (%)	ACCURACY HYSTERESIS (%)	ACCURACY REPEATABILITY (%)	FREQUENCY RANGE MINIMUM (Hz)	FREQUENCY RANGE MAXIMUM (kHz)	RESONANT FREQUENCY (kHz)	OPERATING TEMP RANGE (°C) −200 0 +200 +400	EXCITATION (V)	EXCITATION (mA)	WEIGHT (kg)	COMMENTS	MANUFACTURER
CAPACITIVE - DIAPHRAGM	D A D	10,000 DC				0 05 to 0 15 OF READING +0 001 F S					3		18-35 DC or 20-33 AC @ 75		TO		OMI
CAPACITIVE - DIAPHRAGM	0 to or ± A D D	5000 or ±2,500				0 T	0 1	0 03			2		24 DC	6 0	0 23	WET/DRY, STAINLESS STEEL #440 to #660	STR
CAPACITIVE - DIAPHRAGM	0 to A C	6000				0 00							10 to 24 DC			BAROMETRIC	STR
CAPACITIVE - DIAPHRAGM	0 to A D	0-5000 DC				0 T	0 05	0 02			2 to 30		22 to 30 DC	6 0	0 26	#250 to #505	STR
PIEZOELECTRIC DIAPHRAGM	0 01-20 to			0 2 to 1 0		1 0 to 2 0					130 to 500		SELF GENERATING			6 4 TO 11mm DIA , INVAR DIAPHRAGM, #275 to #510	PCB
PIEZOELECTRIC DIAPHRAGM	0 004 to			120	150								SELF GENERATING			ABOUT THE SIZE OF A DIME. #206	CEL
PIEZOELECTRIC - DIAPHRAGM	0 to			0 12 to 0 26		1 0 to 2 0					100 to 170		SELF GENERATING		0 014 to 0 020		KAG
PIEZOELECTRIC - DIAPHRAGM	VACUUM to			0 15 to 0 34		1 0					175 to 180		SELF-GENERATING			6 4 TO 11mm DIA	AVL
PIEZOELECTRIC - DIAPHRAGM	to (100 to 205 dB)									600			SELF-GENERATING			51mm LONG, HYDROPHONE	CEL
PIEZORESISTIVE (SEMICONDUCTOR STRAIN GAGE)	0 to A	50 to 200				±0 25 to 0 5					10 to 275		12 AC DC			19mm DIA., STAINLESS STEEL; #355	ENT
PIEZORESISTIVE (SEMICONDUCTOR STRAIN GAGE)	0 to G A		4-20			±0 5							14 to 50 DC			INTEGRAL AMPLIFIER FOR USE WITH LONG TRANSMISSION LINES	DII
PIEZORESISTIVE (SEMICONDUCTOR STRAIN GAGE)	0 to A G S	35 to 100				±0 5 to 1 0					20 to 50		10 DC		0 035 to 0 040	STAINLESS STEEL	KLT
PIEZORESISTIVE (SEMICONDUCTOR STRAIN GAGE)	A G	100				1 0							5 DC or AC$_{RMS}$		0 057	LOW COST	
PIEZORESISTIVE (SEMICONDUCTOR STRAIN GAGE)	0 to G	100				±0 5 to 1 0							10 to 24 DC or 5		0 020 to 0 11		FXB
	0 to G	500				±1 2 to 2 0		±0.1 to 0.7			>500		10 DC		0 011		END

A Absolute
D Differential
G Gage
S Sealed Standard

TABLE A-2

COMMERCIALLY AVAILABLE PRESSURE SENSORS

TRANSDUCTION	FULL SCALE RANGES (PSI) = from 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}		FULL RANGE OUTPUT (mV)	FULL RANGE OUTPUT (mA)	SENSITIVITY (pC/PSI)	SENSITIVITY (mV/PSI)	ACCURACY LINEARITY (%)	ACCURACY HYSTERESIS (%)	ACCURACY REPEATABILITY (%)	FREQUENCY RANGE MINIMUM (Hz)	FREQUENCY RANGE MAXIMUM (kHz)	RESONANT FREQUENCY (kHz)	OPERATING TEMP RANGE (°C) −200 0 +200 +400	EXCITATION (V)	EXCITATION (mA)	WEIGHT (kg)	COMMENTS	MANUFACTURER
STRAIN GAGE - UNBONDED, DIAPHRAGM	±	D*	35 to 40				±0.5						(COMPENSATED)	10 AC-DC		0.17 to 0.31	GEN PURPOSE	GLO
STRAIN GAGE - UNBONDED; DIAPHRAGM	0 to	A	±20				±0.5					14 to 60		10 DC		0.20		DAH
STRAIN GAGE - UNBONDED, DIAPHRAGM	0 to	A G	40				±0.35					10 to 50		10 DC		0.11	GEN PURPOSE LOW COST	DAH
STRAIN GAGE - UNBONDED; DIAPHRAGM	0 to	D G	20				±0.5 to ±0.75					8		5 DC		0.054 to 0.080	NUCLEAR RADIATION ENVIRON	BAH
STRAIN GAGE - BONDED; DIAPHRAGM	0 to	D G V	30, 5000, or	2 to 20			±0.4			DC	0.002 to 0.15			10 AC-DC or 12 to 40 AC		0.60	STAINLESS STEEL	VTN
STRAIN GAGE - BONDED; DIAPHRAGM	±	D	5000				0.5	0.2	0.1			0.21 to 1.4		28 DC		5.4	STAINLESS STEEL HIGH LINE PRESS WET/WET	OLE
STRAIN GAGE - BONDED; DIAPHRAGM	0 to	A S	30				±0.25					5 to 35		10 DC		0.14	STAINLESS STEEL CRYOGENIC	BAN
STRAIN GAGE - BONDED; DIAPHRAGM	0 to	A S	30				±0.25					5 to 50		10 DC		0.14	STAINLESS STEEL	DAH
STRAIN GAGE - BONDED; DIAPHRAGM	0 to	A S	5000				0.15 to 0.25	0.05 to 0.10	0.05			3 to 50		20 DC		0.48 or 0.79	STAINLESS STEEL BUILT-IN AMP	OLE
STRAIN GAGE - BONDED; DIAPHRAGM	0 to OR	A S D	10 to 30				0.2 to 0.5	0.1 to 0.2	0.1 to 0.15				OR	10			STAINLESS STEEL WET/WET	SNT
STRAIN GAGE - BONDED; DIAPHRAGM	0 to		20				±0.25 to 0.35		±0.08			45 to 632		10		0.54	STAINLESS STEEL	PSE
STRAIN GAGE - BONDED, DIAPHRAGM	0 to	S	4.5 to 6				±0.25 to 0.5	±0.1	±0.5			13 to 20		6 AC DC		14	STAINLESS STEEL RUGGED	BLH
STRAIN GAGE - BONDED, DIAPHRAGM	0 to	S	6				±0.5	±0.75	±0.1			18.6 to 20		6 AC-DC		0.91	STAINLESS STEEL	BLH
POTENTIOMETRIC	0 to	D					±0.1 to 1.0		±0.1				OR	AC or DC		0.40	FOR FLOW PRESSURE MEAS	VNT
POTENTIOMETRIC	0 to OR ±	A D					±0.9										WET/WET	GTN

A-Absolute
D-Differential
G-Gage
S-Sealed standard

TABLE A-3

COMMERCIALLY AVAILABLE PRESSURE SENSORS

TRANSDUCTION	FULL SCALE RANGES		FULL RANGE OUTPUT		SENSITIVITY		ACCURACY			FREQUENCY RANGE		RESONANT FREQUENCY (kHz)	OPERATING TEMP RANGE (°C)	EXCITATION		WEIGHT (kg)	COMMENTS	MANUFACTURER
	(PSI) × from 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}		(mV)	(mA)	(pC/PSI)	(mV/PSI)	LINEARITY (%)	HYSTERESIS (%)	REPEATABILITY (%)	MINIMUM (Hz)	MAXIMUM (kHz)		−200 0 +200 +400	(V)	(mA)			
LVDT w/ CAPSULE	0 to	A D	±2500 DC or 250 to 320 (AC OPEN)				±0 5 to 1 0					0 16 to 2		15 DC or 5 AC$_{RMS}$ @ 2 5 kHz	30	0 25 to 0 43	CORROSION RESIST #220 #568	SCV
LVDT w/ DIAPHRAGM, CAPSULE, OR BOURDON		V C					±0 25	0 15						2 to 4 WATTS AC		1 2	TRANSMITTER	AKC
LVDT w/ DIAPHRAGM, CAPSULE, OR BOURDON	0 to ± 0 to	D A G	0-1000 AC$_{(RMS)}$				±2 0				2000 @ 35g			26 AC @ 400 Hz	30	0 11 to 0 17	STAINLESS STEEL & NiSPAN OR INCONEL FOR NUCLEAR RAD ENV	GTN
LVDT w/ BOURDON TUBE	0 to	G	2500 DC or 1000 to 1600 AC$_{(RMS)}$	2 5			±0 5	±0.1				0 05 to 0 375		±15 DC 5 AC$_{(RMS)}$ @ 2 5 kHz	3 0	1 2	#255 #453	SCV
VARIABLE RELUCTANCE	±	D	400				±0 5(BSL)	0 5 to 1 0						10 AC @ 3 kHz		0 34 to 1 1	FOR LOW FLOW PRESSURES	VLD
VARIABLE RELUCTANCE	±	D	400				±0 5(BSL)	0 5						10 AC @ 3 kHz		0 9	LINE PRESSURES TO 10 000 PSI	VLD
VIBRATING CYLINDER w/ MAGNETIC DRIVE & COIL PICKUP	0 to	A						0 (Calibration error=±0 015)	±0 0001					±15 DC		0 75 to 1 3	DIGITAL, TRANSFER STAND ACCURACY	HMS
VIBRATING WIRE w/ COIL-MAGNET, DIAPHRAGM	0 to		REQUIRES SPECIAL DIGITAL READOUT											12 TYPE AA BATTERIES FOR READOUT			DIA 18 to 44 OR 225 mm FOR UNDERGROUND USE	IGI
RESISTANCE YTTERBIUM FOIL SANDWICH			DEPENDS ON SUPPLY VOLT							DC	HIGH MHz						25 4 × 38 × 0 038 mm	SSS

A Absolute
C Compound
D Differential
G Gage
V Vacuum

TABLE A-4

COMMERCIALLY AVAILABLE DISPLACEMENT SENSORS

TRANSDUCTION	FULL SCALE RANGES (mm) × from 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}	FULL RANGE OUTPUT (V)	SENSITIVITY (mV/V/mm)	ACCURACY LINEARITY (%)	ACCURACY HYSTERESIS (%)	ACCURACY REPEATABILITY (%)	FREQUENCY RANGE MINIMUM (Hz)	FREQUENCY RANGE MAXIMUM (kHz)	OPERATING TEMP RANGE (°C) 0 +200 +400	EXCITATION (V)	DIMENSIONS CORE, O DIA (mm)	DIMENSIONS BORE DIA (mm)	DIMENSIONS OTHER	COMMENTS	MANUFACTURER
LVDT (LINEAR VARIABLE DIFFERENTIAL TRANSFORMER) (AC)	±			0.2 to 0.5				20		1 (RMS)	1.8	2.03		SUB-MINIATURE STAINLESS STEEL HOUSING	SCV
LVDT (AC)	±		30 to 335	0.1 to 0.75			400	20		3 (RMS)	2.7	3.2		MINIATURE, LIGHTWEIGHT CORE MAGNETIC STAINLESS STEEL HOUSING	SCV
LVDT (AC)	±		4 to 51	0.5			400	5		3 (RMS)	4.6	4.8		CRYOGENIC APPLICATIONS	SCV
LVDT (AC)	±		4 to 51	0.5			400	5		3 (RMS)	4.6	4.9		NUCLEAR RADIATION RESISTANT, WITHSTANDS PRESSURES TO 175 BAR @ 350°C, HERMETICALLY SEALED STAINLESS STEEL SHELL	SCV
LVDT (AC)	±		3 to 250	0.1 to 1.3			50	10		3 (RMS)	0.4	0.5		GENERAL PURPOSE HIGH RELIABILITY, LARGE CORE-TO-BORE CLEARANCE, MAGNETIC STAINLESS STEEL CASE	SCV
LVDT (AC)	±		1.4 to 10	2			50	3		3 (RMS)	0.4	6.6		LONG STROKE-TO-BODY LENGTH	SCV
LVDT (DC)	±	5 into 10 kΩ		0.5						10 DC, (40 to 60 mA)	2.7		LENGTH 18mm	INTEGRATED PACKAGE OF TRANSDUCER AND OSCILLATOR-DEMODULATOR CARRIER FREQUENCY - 3 or 5 kHz	AKC
LVDT (DC)	±		(0.04 to 8 V/mm)				200	0.5		±15 DC; ±20 mA	4.0	8.0		THICK FILM CARRIER GENERATOR/SIGNAL CONDITIONING MODULE	SCV
LVRT (LINEAR VARIABLE RELUCTANCE TRANSFORMER)	±		7.0 to 59										OVERALL LENGTH 64 to 256mm	\$130 to \$336	AKC
	±												LENGTH, 74 to 838mm	HEAVY DUTY, WITHSTANDS SEVERE SHOCK, \$195 to \$607	AKC
POTENTIOMETRIC	0 to			0.35					(AIR COOLED)	30			WEIGHT 0.27kg	INCLUDES ABOUT 1.5 m OF TEFLON COATED CONNECTOR WIRE	RES
POTENTIOMETRIC	0 to			0.5									LENGTH 84 to 215mm	15 g VIBRATION LIMIT (1970 DATA)	BRN
POTENTIOMETRIC				1.0									DIAMETER 9.5 to 25.4mm	AC INPUT, HIGH LEVEL AC OUTPUT, INFINITE LIFE, 50 g VIBRATION LIMIT (1970 DATA)	BRN
POTENTIOMETRIC				0.2									LENGTH RANGE PLUS 55mm	10 g VIBRATION LIMIT (1970 DATA)	BRN
POTENTIOMETRIC	0 to			0.5										100 GRAM OPERATING FORCE, 0.75 W/25 mm TRAVEL	WAT
POTENTIOMETRIC	0 to			0.1 to 0.7					(AIR COOLED)	25 to 40			WEIGHT 0.93kg	RUGGED	RES
POTENTIOMETRIC	To ·			0.1						AC or DC			LENGTH ≈130mm	CABLE ACCELERATION RATES UP TO 100 g, RUGGED	CEL

TABLE A-5

COMMERCIALLY AVAILABLE DISPLACEMENT SENSORS

TRANSDUCTION	FULL SCALE RANGES (mm) × from 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³ 10⁴	FULL RANGE OUTPUT (V)	SENSITIVITY	ACCURACY LINEARITY (%)	ACCURACY HYSTERESIS (%)	ACCURACY REPEATABILITY (%)	FREQUENCY RANGE MINIMUM (Hz)	FREQUENCY RANGE MAXIMUM (kHz)	OPERATING TEMP RANGE (°C) 0 +200 +400	EXCITATION (V)	DIMENSIONS	WEIGHT (kg)	COMMENTS	MANUFACTURER
RESISTANCE (SOLID STATE)	0 to	20mA AC or DC	200Ω/mm	1.0								0.24	UNIVERSAL MEASURING TRANSDUCER $135 (1975)	UNM
STRAIN GAGE (SEMICONDUCTOR)	0 to ±	.033 to .066/V		0.1	0.01	0.01	0	1.5				0.025	'UNIVERSAL' MEASUREMENTS	KSM
INDUCTIVE	±									2 to 6 @ 5 or 50 kHz			STAINLESS STEEL, CONTACTLESS	HBM
INDUCTIVE	±	0.08/V		0.2 or 0.4						2 to $5_{(RMS)}$ @ 5 kHz			SPRING LOADED PROBE STAINLESS STEEL	HBM
INDUCTIVE	±	0.08/V		0.2 or 0.4						2 to $5_{(RMS)}$ @ 5 kHz			PLUNGER SCREWS INTO OBJECT, STAINLESS STEEL	HBM
MAGNETO-STRICTIVE	0 to	±10		0.05			50	0.2		±15 DC or 115 @ 60 Hz			SOLID STATE, SEALED, STAINLESS STEEL, WITHSTANDS 3000 PSI	TMP
EDDY CURRENT	0.001 to		4 to 8 V/mm				0	3		−18 to −24 @ 5 mA			NON CONTACTING, MEASURES RADIAL VIBRATION OR AXIAL POSITION OF MOTOR SHAFTS	MTX
EDDY CURRENT (VARIABLE IMPEDANCE)	0 to		0.1 to 1 V/mm	1.0			0	50		12 DC @ 70 mA			NON-CONTACTING	KMN
ULTRASONIC (PULSE TRAVEL TIME)	0 to	10		0.05			DC	0.075 to 0.2		±15 DC or 115 @ 60 Hz			SOLID STATE, QUARTZ CRYSTAL TIME REFERENCE	TMP
POSITION														
PHOTO DIODE (PHOTOCONDUCTIVE)	0 to			1.0							ACTIVE AREA 2.5×100 mm		DETECTS POSITION OF SPOT OF LIGHT	UDT
PHOTO DIODE (PHOTOVOLTAIC)	0 to			3 to 10							ACTIVE AREA 63 or 100 mm²		DETECTS X AND Y POSITION OF SPOT OF LIGHT	UDT
ANGULAR DISPLACEMENT														
RVDT (ROTARY VARIABLE DIFFERENTIAL TRANSFORMER)	±60 DEG		1.1 to 2.9 mV per V per DEG.	1.6 to 3			400	20		$3_{(RMS)}$	DIAMETER 25 to 37 mm			SCV

TABLE A-6

COMMERCIALLY AVAILABLE DIGITAL ENCODERS (DISPLACEMENT SENSORS)

	TRANSDUCTION	RANGES	RESOLUTION	ACCURACY (ARC SEC.)	OPERATING TEMPERATURE	EXCITATION	DIMENSIONS	COMMENTS	MANUFAC-TURER
ROTARY	INDUCTION			±1 TO ±4		CARRIER FREQ. FROM 2.5 TO 100kHz	DIAMETER 3, 7, OR 12 INCHES	ROLLED STEEL OR ALUMINUM DISK	FAR
	VARIABLE RELUCTANCE		"GOOD"		800°C MAXIMUM			MAXIMUM RADIATION DOSE — 10^{14}n/cm²; SIMPLE	
	CAPACITIVE		"GOOD"					PERFORMANCE DETERIORATED BY NEUTRON FLUX, SIMPLE	
	EDDY CURRENT		"FAIRLY GOOD"					MAXIMUM RADIATION DOSE — 10^{15}n/cm², SIMPLE	
	PERMANENT MAGNET GENERATOR		"GOOD"					SELF-GENERATING; MAXIMUM RADIATION DOSE — 10^{14}n/cm²	
	OPTICAL		UP TO 10,000 COUNTS/REVOLUTION			5, 5, 12, OR 15 VOLTS	WEIGHT 17 OZ.	3000 RPM — MAXIMUM CONTINUOUS SHAFT SPEED, LED LIGHT SOURCE, RUGGED	ORC
	OPTICAL		1024 TO 5400 LINE PAIRS			5 V DC	DIAMETER 1. TO 3 25 IN, LENGTH — 1 TO 4 IN		TGY
	MICROWAVE		"VERY GOOD"		200°C MAXIMUM			REQUIRES ELABORATE SOURCE, WAVEGUIDE, AND DETECTOR SYSTEM; MAXIMUM RADIATION DOSE — 10^{14}n/cm²	
LINEAR	INDUCTION	TO 250mm — (SCALE) AND TO 30,000mm — (TAPE)		± 0.0025 TO 0 005mm		CARRIER FREQ. FROM 2.5 TO 100kHz		NOT ROLLED STEEL; SCALES MAY BE PLACED END TO END	FAR
	OPTICAL	2 OR 4 INCHES	100 μ INCHES	± 100 μ INCHES ± 1 BIT DIGITIZING ERROR		5 V DC, 150 ma	6.5 OR 10.5 x 2 4 x 1.5 INCHES		ORC

TABLE A-7

COMMERCIALLY AVAILABLE ACCELERATION SENSORS

TRANSDUCTION	FULL SCALE RANGES (0) × 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} FROM	FULL RANGE OUTPUT (mV)	SENSITIVITY		ACCURACY			FREQUENCY RANGE		RESONANT FREQUENCY (kHz)	OPERATING TEMPERATURE RANGE (°C) 0 +200 +400 +600	EXCITATION		WEIGHT (kg)	COMMENTS	MANUFACTURER
			(pC/g)	(mV/g)	LINEARITY %	HYSTERESIS %	REPEATABILITY %	MAXIMUM (Hz)	MINIMUM (kHz)			(V)	(mA)			
PIEZOELECTRIC	±			0.2 TO 100				2	6			+18 TO +28 DC		0.02 TO 0.05	STAINLESS STEEL, BUILT-IN AMPLIFIER, $245 TO $395	COL
PIEZOELECTRIC	0.01 TO 1.0 TO.			0.1 TO 1000				0.05 TO 1.0	1.0 TO 5.0	5 TO 60		+18 TO +24 DC	2 TO 20	0.0045 TO 0.10	QUARTZ; STAINLESS STEEL, BUILT-IN AMPLIFIERS; INCLUDES TRIAXIAL MODEL; $195 TO $650	PCB
PIEZOELECTRIC				100				2 (2dB DOWN)	8			24 DC		0.07	TITANIUM CASE, BUILT-IN AMPLIFIER, FOR UNDERWATER USE, TO 3000PSI	WLX
PIEZOELECTRIC	8 TO.			10	±1.0			5.0 4.0	6.0 18				+1 TO +20	0.0003 TO 0.0045	SHEAR TYPE, INTEGRAL ELECTRONICS	END
PIEZOELECTRIC	V S		0.1 TO 30	0.15 TO 50		1.0		2.8	20	25 TO 100		SELF-GEN		0.009 TO 0.016	GENERAL PURPOSE; STAINLESS STEEL; $155 TO $225	COL
PIEZOELECTRIC	0 TO: (2·5)		2.5 TO 10					20 2	3 6		TO	SELF-GEN.		0.016 TO 0.030	"ISO BASE" OR SHEAR TYPES	END
PIEZOELECTRIC	0.006 TO.		6.5	1.6	1.6				23 (1 dB DOWN)			SELF-GEN		0.0001	ALUMINUM, ELECTROSTATIC SHIELD REQUIRED	WLX
PIEZOELECTRIC	0 TO: S		0.0035 TO 0.7					5 20	15 50	80 TO 250		SELF-GEN		0.0013 TO 0.013	SHEAR TYPE — SHOCK MEAS	END
STRAIN GAGE UNBONDED	±	20		4 TO 28	±0.75					20 TO 250		5 DC		0.125		BAH
STRAIN GAGE UNBONDED	± L	20			±0.75					0.36 TO 3.5		5 DC OR AC (RMS)		0.085	INCLUDES TRI-AXIAL MODEL	GLO
STRAIN GAGE UNBONDED	±	15 TO 20			±0.75					0.3 TO 2.9		5 DC		0.085		BAN
PIEZO RESISTIVE	± L	50 PER VOLT EXCITATION				±0.5		DC	0.05 TO 0.30			TO 30 DC		0.85 (MAX)	SINGLE AXIS; STAINLESS STEEL $150	KSM
PIEZO RESISTIVE	±			0.01 TO 30				DC	6.2 TO 30	1.0 TO 180		28 DC		0.001 TO 0.005		END
PIEZO RESISTIVE	± S			0.12 TO 20		±0.5		DC	0.75 TO 6.0	2.5 TO 45	(COMPENSATED RANGES)	28 DC		0.028	GENERAL PURPOSE; SHOCK	
PIEZO RESISTIVE	± V S			0.025 TO 0.1				DC	6.0 TO 15	40 TO 100	(COMPENSATED RANGES)	10 DC		0.010	TRIAXIAL; SHOCK; VIBRATION	END

L = LINEAR
S = SHOCK
V = VIBRATION

TABLE A-8

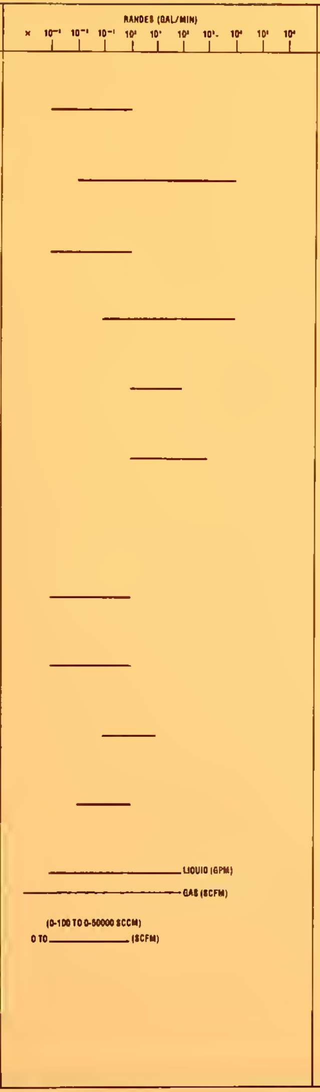
COMMERCIALLY AVAILABLE ACCELERATION SENSORS

TRANSDUCTION	RANGES (g) 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}	FULL RANGE OUTPUT (mV)	SENSITIVITY (pC/g)	SENSITIVITY (mV/g)	ACCURACY (%) LINEARITY	ACCURACY (%) HYSTERESIS	ACCURACY (%) REPEAT-ABILITY	DYNAMIC RANGE MIN (Hz)	DYNAMIC RANGE MAX (kHz)	RESONANT FREQUENCY (kHz)	OPERATING TEMPERATURE RANGE (°C) 0 +200 +400	EXCITATION (V)	EXCITATION (mA)	WEIGHT (kg)	COMMENTS	MANU-FACTURER
VARIABLE CAPACITANCE	± — V S I	± 1500 DC			± 1.0	±0.1		DC	0.004 TO 3	0.045 TO 5	—	6 DC	30	0.48	ALUMINUM. VIBRATION, SHOCK; IMPACT; INTERNAL CALIBRATION SIGNAL; $475 TO $575	STR
VARIABLE CAPACITANCE	± — V S I	± 500 OR ± 1000			± 0.5 TO ± 3	±0.1	±0.05	DC	0.22 TO 3	0 35 TO 6 5	—	10 DC OR 28 DC	5 10	0.03	STAINLESS STEEL. VIBRATION, SHOCK, IMPACT; EXTERNAL CALIBRATION, $400	STR
SERVO	± —	TO ± 5000		0.1 TO 10 (ADJUSTABLE)	±0.05			DC	0.15 TO 0.48	0.3 TO 0.8	—	+ 25 DC	40	0.098	EXTERNAL RANGE ADJUSTMENT, TELEMETRY; $675 TO $1050	SUN
				(mV/IN/SEC)												
MAGNETIC	0.001 TO 5 OR (0.01 TO 60 IN/SEC-VEL.) V			110 (10 k Ω LOAD)	± 5 @ 100Hz			8	0 7	0 005	— OR —	SELF-GEN.		0 4	VIBRATION, DISPLACEMENT, OR AVERAGE VELOCITY; FOR DYNAMIC BALANCING, PIPELINES; AIRCRAFT ENGINES	5AH
MAGNETIC	1.0 TO 5 OR (0.4 TO 30 IN/SEC-VEL.) V			105 OR 145 (10 k Ω LOAD)	± 1 @ 200Hz			45	1.5	13 TO 15	—	SELF-GEN.		0.23	VIBRATION; DISPLACEMENT; AVERAGE VELOCITY; REPAIRABLE; AIRCRAFT; LONG LIFE	OAN
FORCE BALANCE MAGNETIC	± —	± 5000			± 0 05	±0.0001				0.08 TO 0.12	—	± 15 DC		0 21	HIGH RESOLUTION; LIQUID DAMPED; $425	SCV
FORCE BALANCE MAGNETIC	± —	± 5000			± 0.1	±0.02 TO 0 04				0.04 TO 0.2	—	± 15 DC		0.015 TO 0.085	LINEAR, $350 TO $385	SCV
ANGULAR	RAD/SEC²															
FORCE BALANCE	± —	5000 DC			± 0.1	± 0.02				0.03 TO 0.13	—	± 15 DC		0.057 TO 0.085	ANGULAR, $350 TO $385	SCV

I = IMPACT
S = SHOCK
V = VIBRATION

TABLE A-9

COMMERCIALLY AVAILABLE FLOW SENSORS (VOLUME)



TRANSDUCTION	RANGES (GAL/MIN)	RANGEABILITY	ACCURACY			MATERIAL MEASURED			OPERATING TEMPERATURE RANGE (°C)	POWER REQUIRED	COMMENTS	MANUFACTURER
			OVERALL (±%)	LINEARITY (%)	REPEATABILITY (±%)	LIQUID	GAS	SLURRY				
TURBINE (TANGENIALLY DRIVEN)			0.1			X (VOLATILE, CORROSIVE OR CRYOGENIC)	X		CRYOGENIC (AVAILABLE)		MODELS AVAILABLE FOR CORROSIVE; CRYOGENIC, OR VOLATILE FLUIDS	FTI
TURBINE (AXIAL)			0.1			X	X				GENERAL PURPOSE	FTI
TURBINE		10.1			0.1	X	X				STAINLESS STEEL; MINIATURE	HFC
TURBINE			0.25 TO 0.8			X	X				STAINLESS STEEL, 1000 PULSES/42 GAL BARREL	HFC
TURBINE		7.8:1				X (ABRASIVE OR CORROSIVE)					FIELD REPLACEABLE ROTOR ASSEMBLY, LOW COST; ELECTRONIC PULSE OUTPUT	FTI
TURBINE			0.25 TO 0.5		0.02	X					STAINLESS STEEL; CD4m Cu; AND TUNGSTEN CARBIDE; UNI- OR BI-DIRECTIONAL	HLS
TURBINE			0.5(H_2O) 1.0 (CRYO.-LIQ.)			X (H_2O OR CRYOGENIC)			CRYOGENIC		MAGNETIC PICK-UP	CXI
HELICAL ROTOR		150.1	0 25 TO 0 4			X TO 50,000 (CPS) VISCOSITY (EXCEPT H_2O)			TO		2500psig POCKETLESS AND SANITARY VERSIONS AVIAL. BI-DIRECTIONAL	FDN
PISTON			0 5			X FUEL				10 TO 38 VDC @ 10 mA	FUEL CONSUMPTION MONITOR	STC
GEAR						X MEDIUM TO HIGH VISCOSITY					2000psi; ALUMINUM HOUSING	FDN
VORTEX			1.0		0.25	X	X			9-18 VDC	STAINLESS STEEL, BUILT-IN CIRCUITRY TO DIGITAL READOUT EQUIP.	CXI
VARIABLE AREA	LIQUID (GPM) GAS (SCFM)		0 25 TO 1.0 (LIQ.) 1.0 (GAS)			X	X				GLASS TUBE, SINGLE OR MULTISTAGE	CXI
THERMOELECTRIC	(0-100 TO 0-50000 SCCM) 0 TO (SCFM)		1.0				X (INCL. UF_6 AND OTHER CORROSIVES)			115-230 VAC; 15W @50-60 Hz	OUTPUT 0-1 VOLT	TNR
PRESSURE DIFFERENTIAL BY SEMICONDUCTOR RESISTANCE			1.8 TO 2 0							0-20 mA AC OR DC	"UNIVERSAL" TYPE TRANSDUCER	UNM

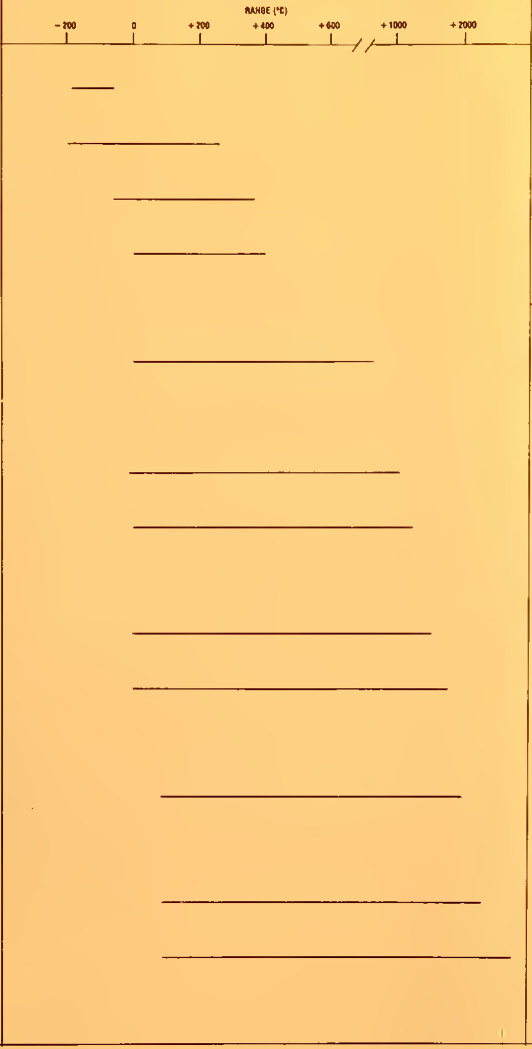
TABLE A-10

COMMERCIALLY AVAILABLE FLOW SENSORS (VELOCITY)

	RANGES (FT/MIN.)	RANGEABILITY	ACCURACY			MATERIAL MEASURED			OPERATING TEMPERATURE RANGE (°C)	POWER REQUIRED	COMMENTS	MANUFACTURERS
	10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}		OVERALL (± %)	LINEARITY (%)	REPEATABILITY %	LIQUID	GAS	SLURRY	−200 0 +200 +400 +600			
PRESSURE VARIATION BY PIEZOELECTRIC MEANS						X	X			22 TO 27 VDC (FOR MOTOR)	STAINLESS STEEL; PRESSURED FROM 0.1 TO 1 PSI RMS	SUN
EDDY CURRENT			10.0FS		3.0	X (METALS)					CAN BE USED IN BREEDER REACTORS	KMN
TURBINE	GAS LIQUID	10:1				X (CRUDE, DISTILLATE, PRODUCT; OR GAS)	X				RETRACTABLE PROBES USED IN PIPELINES, ETC.	FTI
TURBINE	GAS LIQUID	10:1				X (EXHAUST GAS OR EFFLUANT LIQUIDS)	X				PROBE FOR PERMANENT OR TEMPORARY INSERTION IN EXHAUST STACKS, ETC. (FOR EPA MEAS.)	FTI
TURBINE	GAS LIQUID	10:1				X	X				RETRACTABLE PROBE	FTI
ULTRASONIC (DOPPLER)	0 TO ±		2.0 (FOR METER)	0.1		X (W/ENTRAINED GASES)		X		120 or 220 VAC @50-60 Hz PLUS 10W (FOR COMPUTER)	EXTERNAL, CLAMP-ON TYPE - PORTABLE; WEATHER-PROOF, AND EXPLOSION-PROOF MODELS AVAILABLE	CNT
ULTRASONIC (TRANSIT TIME)		20,000:1	0.5			X					EXTERNAL, CLAMP-ON TYPE	CNT
THERMAL (SOLID STATE) SWITCH	0.6 (H_2O), (GASOLINE) 0.3 (OIL) 30.0 (AIR)					X	X	X ALSO: GRANULATED SOLIDS		90 TO 130 VAC @ 60Hz	0-3000 PSI; PRESSURE SWITCH	CEL

TABLE A-11

COMMERCIALLY AVAILABLE TEMPERATURE SENSORS



TRANSDUCTION	ACCURACY		TIME CONSTANT		RESISTANCE		TYPE OR COMPOSITION	DIMENSIONS		EXCITATION (V)	COMMENTS	MANUFACTURER
	LINEARITY	INTERCHANGEABILITY (°C)	(SEC.)		(Ω)	(@°C)		DIAMETER (mm)	LENGTH (mm)			
THERMOCOUPLE	±1.0 (SP) ±2.0 (ST)						T (CU-CONST.)				METAL SHEATHED OXIDE INSULATED CABLE	MRL
THERMOCOUPLE		±0.28	0.5 OR FASTER								FLEXIBLE RIBBON — PLAIN OR SELF-ADHERING	MNC
THERMOCOUPLE	±0.4°C OR 0.38% (SP) ±0.8°C OR 0.75% (ST)						T				METAL SHEATHED OXIDE INSULATED CABLE	MRL
THERMOCOUPLE	±0.38 TO 1% (SP) ±0.75 TO 2% (ST)				0.038 TO 3993 PER DBL METER	20	T	0.012 TO 4.1			RECOMMENDED FOR MILDLY OXIDIZING OR REDUCING OR FOR MOIST ATMOSPHERES AND LOW TEMPS	OMG
	LIMIT OF ERROR (%)											
THERMOCOUPLE	±0.30 (SP) ±0.75 (ST)				0.046 TO 4659 PER DBL METER		J (IRON-CONST.)	4.1 TO 0.012			RECOMMENDED FOR REDUCING ATMOSPHERES. (LARGEST DIAMETERS ONLY FOR HIGHEST TEMPERATURES)	OMG
THERMOCOUPLE							K (CHROMEL-ALUMEL)			115 AC @60Hz	HIGH SHOCK AND VIBRATION RESISTANCE	CCC
THERMOCOUPLE	±0.38 (SP) ±0.75 (ST)				0.075 TO 7898 PER DBL METER		K	4.1 TO 0.012			FOR USE IN CLEAN OXIDIZING ATMOSPHERES (LARGEST DIAMETERS ONLY FOR HIGHEST TEMPERATURES)	OMG
THERMOCOUPLE	±0.25 (SP) ±0.25 TO 0.5 (ST)				0.023 TO 2427 PER DBL METER	20	S (PT-PT 10% RH) AND R (PT-PT 13% RH)	4.1 TO 0.012			HIGH RESISTANCE TO OXIDATION AND CORROSION	OMG
THERMOCOUPLE	±0.25 (SP) ±0.28 TO 0.5 (ST)						B (PT, 6% RHo-PT, 30% RH)				HIGH RESISTANCE TO OXIDATION AND CORROSION	
THERMOCOUPLE							IR + RH				RECOMMENDED FOR VACUUM OR INERT ENVIRONMENTS	MRL
THERMOCOUPLE							W-RE AND PT-PT				SHEATHED PROBES; GROUNDED, UNGROUNDED, AND EXPOSED JUNCTIONS	OMG
							W-RE ALLOYS				POOR OXIDATION RESISTANCE — FOR USE IN VACUUM, HYDROGEN, OR INERT ENVIRONMENTS	OMG

SP = SPECIAL
ST = STANDARD

TABLE A-12

COMMERCIALLY AVAILABLE TEMPERATURE SENSORS

TRANSDUCTION	RANGE (°C)		ACCURACY		TIME CONSTANT		RESISTANCE		TYPE OR COMPOSITION	DIMENSIONS (mm)		EXCITATION (V)	COMMENTS	MANUFACTURER
	−200 0 +200 +400 +600 +1000 +2000		LINEARITY	INTERCHANGEABILITY (°C)	(SEC.)		(Ω)	(@°C)		DIAMETER	LENGTH			
RESISTANCE				±0 25 TO 0 03	0 4 TO 0 5	IN H_2O	10 OR 50	0	"KELTIC"	2.0	13 OR 20		AVAIL WITH STAINLESS STEEL SHEATH, BENDABLE HEMETICALLY SEALED, ANY LENGTH LEADS	OGS
RESISTANCE				±0 28	0 8 OR FASTER		78 TO 604	0	VARIOUS METALS				FLEXIBLE RIBBON — PLAIN OR SELF-ADHERING	MNC
RESISTANCE					"FAST"				NICKEL				GRID HIGH SENSITIVITY, SHUNT CALIBRATION, $22 TO $32 PER PACKAGE OF 6	MSG
RESISTANCE				±0.65			120	0	NICKEL	(CASE) 4 8 TO 6 4	T1 TO 1 220		TIP-SENSITIVE PROBE	MNC
RESISTANCE		GAS LIQUID VAPOR	0 12°C OR 0 25%									24 OR 48 DC	ZERO MAINTENANCE TRANSMITTER, FOR IMMERSION OR THERMOWELL USE	GLO
RESISTANCE							100	0				28 DC	SHOCK AND VIBRATION RESISTANT	CCC
RESISTANCE							100, 200, 400, 500, 1000, or 2000		PLATINUM	1 TO 8.7 (WIDTH)	2.3 TO 12		THIN FILM, FLAT OR CYLINDRICAL PACKAGES, $21 to $50	OMG
RESISTANCE				±0 3	7 5	IN H_2O			PLATINUM	4.3	UP TO 1 118		PROBES	MHC
RESISTANCE					0 6 TO 2 3 (00%)	IN H_2O	50, 100, 200, OR 300	0	PLATINUM	1.5 TO 4 8	30 TO 50		SHEATHED IN CERAMIC, $13 TO $48	OMO
THERMISTOR		LIQUID O_2, N_2, H_2, &He)					6,500 TO 3,000,000			2 5 OR 1.5 (SQUARE)	1 0 7.0		USEFUL FOR DETECTION OF CRYOGENIC LIQUID LEVELS	KEY
THERMISTOR			±0 08 TO 0 15	0.1						3 2	7 1	3.5	LINEAR, COMPOSITE OF 3 THERMISTORS AND 3 RESISTORS	OMO
THERMISTOR		SENSITIVITY (μ A/°C) 1.0	±2.0, OR 0.8										SILICON	ANL
		TEMPERATURE COEFFICIENT (%/°C)	RESISTANCE TOLERANCE (%)											
THERMISTOR		−2.81 TO −0.83 @400°C	±20		4 (FOR GLASS BEAD) 25 (FOR PROBE)		1000	400		0 76 TO 1.14	1 27 TO 1 65 (μm)		GLASS BEAD OR PROBE	FWL
THERMISTOR		−1.0@ 750°C					10,000 (DC) 8,300 (AC)			2 54	12.7		ALUMINA ENCAPSULATED	FWL
THERMISTOR	SWITCHING TEMPERATURES (°C) 	+4 T TO +33	±20 TO 30				0 5 TO 3,300			5 TO 15			SWITCHING THERMISTOR	TOK

TABLE A-13

COMMERCIALLY AVAILABLE FORCE SENSORS

TRANSDUCTION	FULL SCALE RANGES (LBS) × from 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}	UNIVERSAL	COMPRESSION	TENSION	FULL RANGE OUTPUT (mV/V)	ACCURACY LINEARITY (%)	ACCURACY HYSTERESIS (%)	ACCURACY REPEATABILITY (%)	OPERATING TEMP RANGE (°C) −200 0 +200	EXCITATION (V)	WEIGHT (kg)	COMMENTS	MANUFACTURER
STRAIN GAGE (BONDED FOIL)	0 to	X	X		1 to 2	0.15 to 0.7				3 to 10		MINIATURE, VARIETY OF CONFIGURATIONS AVAILABLE	SNT
STRAIN GAGE (BONDED FOIL)	0 to	X	X	X	2 or 3	0.1 to 0.2	0.08 to 0.1	0.08 to 0.1		10 to 15		LOW PROFILE, STAINLESS STEEL	SNT
STRAIN GAGE	0 to	X			2	0.03 to 0.075				4 to 12			HBM
STRAIN GAGE	0 to	X	X		2 or 3	0.1 to 0.25	0.1 to 0.15	0.05		15 (AC or DC)	0.27 to 450	LOW PROFILE	STN
STRAIN GAGE (BENDING BEAM)	0 to		X		2	0.03	0.02					PLATFORM TYPE, LOW COST	HBM
STRAIN GAGE (BENDING BEAM)	0 to	X			2	0.02				4 to 12	0.5 or 2.3		HBM
STRAIN GAGE (SHEAR BEAM)	0 to		X		2	0.03	0.02					LOW PROFILE & PLATFORM APPLICATIONS	HBM
SEMICONDUCTOR STRAIN GAGE (CANTILEVER BEAM)	±			X BI-DIRECTIONAL	25	±1.0				10 (DC or AC(RMS))	0.001	MINIATURE	KLT
SEMICONDUCTOR STRAIN GAGE (CANTILEVER BEAM)	0 to		X		15 or 30	0.15	0.05	0.1		10 to 20 (DC)	0.23	STAINLESS STEEL	KAG
SEMICONDUCTOR STRAIN GAGE (CANTILEVER BEAM)	0 to	X			83.3 (1V@ 12V input)	0.35	0.10	0.05		12 (DC)			BLH
LINEAR VARIABLE DIFFERENTIAL TRANSFORMER	0 to	X	X	X		0.2		0.1		1 to 5 AC @ 0.4 to 10 kHz or +15 DC @ 15ma			SCV
PIEZOELECTRIC	0 to	X			(pC/LB) 17	±1.0				SELF-GENERATING	0.011 to 2.6	DYNAMIC OR QUASI-STATIC FORCES RES. FREQ. 22 to 75 kHz	KAG
PIEZOELECTRIC	0 to				5 to 19	±1.0				SELF-GENERATING	0.003 to 1.5	DYNAMIC OR QUASI-STATIC FORCES RES. FREQ. 30 to 80 kHz	KAG
TORQUE SENSORS STRAIN GAGE (BONDED FILM)	(LB-FT)				(mV/V) 3	0.25				20 DC or AC RMS		SOCKET WRENCH TORQUE SENSOR	LBW

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sive in scope or definitive in
serve as a vehicle for final
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