NBSIR 75-929

A Study of the National Force Measurement System

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National Bureau of Standards
Washington, D. C. 20234

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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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EXECUTIVE SUMMARY

This study outlines the detailed structure of the National Measurement System as it pertains to force, and assesses the economic, social, and technological impacts of force measurements in the United States.

Force, as a unit of measurement defined by Newton's Second Law of Motion, is derived from the basic units of mass, length, and time. The most precise standards of force are realized in deadweight calibration machines such as those maintained by the National Bureau of Standards, a few government laboratories, one commercial calibration laboratory and a few industrial metrology organizations. The deadweight facilities at NBS are widely accepted as the national standards of force.

In practice, deadweight machines are used to provide a few precisely known forces for the calibration of high quality force transducers such as load cells and proving rings. These secondary standards are used to calibrate the multiplicity of devices for field measurements. Accuracy requirements in the measurement system range from the 0.002 percent accuracy of primary standards to about 10 percent for rough measurements such as crane overload indicators.

The principal impact of force measurements can be classified as both social and economic. The determination of the strength of a material of the determination of its weight is often made to guarantee the equity in trade in a commercial transaction. However, the safety implications of accurate measurements is obvious. The measurement is made to guarantee two parties that the product is delivered in accordance with a contractual agreement. Very often these agreements refer to one or more voluntary consensus standard methods of test. These standards are the result of the economic needs of the manufacturing community to agree upon a common method for making a measurement. If the standards of force measurement had not existed. the cost of doing business would have increased to cover the cumulative uncertainties resulting from inaccurate measurements. In addition, with the current and anticipated growth in mandatory safety regulations, many of which require that products be stronger than ever before, the traditional regulatory requirements of product purity are being amended or even supplanted by force measurement. Clearly, however, these regulations are resulting in increased product cost to the consumer and the government must weigh the social benefits against the economic penalties paid.

The history of NBS and of force measurement in this country are closely linked, beginning in the 1830's with the distribution of mass standards by the Office of Weights and Measures, and continuing today, with the development of proving rings, deadweight machines, and load cells and test methods. In addition NBS has participated in the formulation of many of the measurement test methods now in use. The role of NBS at the primary standards level in the measurement system is to provide adequacy, stability and consistency to the system. No other organization is so uniquely placed to provide that function.

Our assessment of the National Force Measurement System is that, while some aspects of it are stable and adequately maintained, other needed parts of the system scarcely exist. The historical areas of effort in static force measurement, over the range from 0.5 newtons (0.1 lbf) to 5×10^7 newtons (1×10^7 lbf), are fully adequate with the level of accuracy now provided and will remain so for the foreseeable future. They require only continued routine support and maintenance. In the areas of dynamic force, very small static forces, information transfer and metrication, however, the measurement system shows serious weaknesses. The measurement system for dynamic force does not exist. The standards and test methods that are needed to assure the accuracy of dynamic measurements and the reliability, efficiency and safety of load carrying systems under dynamic conditions such as impact and fatigue are not available. A similar condition exists for the measurement of very small forces down to 10^{-7} newtons (10^{-7} lbf). Measurements in this range are

needed in such areas as biomedical research and ultrasonic, nondestructive testing of manufactured parts.

The information transfer sector of the system is quite cumbersome. This is a result of the diversity of groups performing force measurements. In conjunction with the adoption of a new method for the calibration of force measurement devices, the system is now beginning to establish the lines of information return from the end user to the source of primary calibration. NBS is actively promoting this exchange through round robin calibration of devices and by measurement workshops.

The anticipated metrication of force measurements has become an area of increasing concern. In the field of force measurements, the foreseeable problems of education of professionals and large, long-lived capital equipment, have been compounded by the confusion about the unit of force which will evolve in common usage. The SI unit of force is the newton. However, European common usage is the kilogram-force. This usage has evolved in much the same way as the pound-force unit did in the U.S. This confusion will delay the acceptance of the SI unit of force and, as a result, the newton may be one of the last SI units which is accepted in common usage.

This study has served to verify many of the current concepts of the condition of the force measurement system. Several strengths and weaknesses have been discovered and studied. NBS, through its standards and calibration activities, will continue to have a stabilizing and unifying effect on the system. NBS should increase its efforts in areas of the system where weaknesses have been found.

1. INTRODUCTION

A thing of beauty is not always a joy forever. All too often, stunning fabrics fray or rip and new appliances fail inexplicably at precisely the wrong time. To help insure that these failures, which tend to discourage a repeat customer market, do not occur before a reasonable lifetime is achieved from the product, manufacturers are testing the strengths of their materials to a greater and greater extent before committing them to production. For example, a major automobile manufacturer tests upholstery and trim materials before approval is granted for their use. Samples of velours, brocades, leathers, vinyls and other materials are scraped, flexed, torn and pulled thousands of times to insure that they will resist wear for the lifetime of the vehicle. This is a typical example of physical testing which is brought on by an increasing consumer concern with the durability of products being sold. We are just now entering an era where the importance of mechanical testing is coming to the attention of legislators, regulators, and others making public interest decisions.

What, then, are force measurements? They are the direct result of the need to know strength or weight. We are generally familiar with the concept of "push or pull" involving a force and that some measurements are indeed made to quantify such things as the thrust of a rocket. More often, however, force measurements are used to provide knowledge of the strength of something, such as a piece of wire, string or an automobile bumper or of the weight of apples in a produce bag or the accuracy of the bathroom scale. In this light, the question of the adequacy of the standards of physical measurement in meeting the needs of industry and the public grows in importance and is relevant to any examination of the performance by the National Bureau of Standards of its basic statutory obligations.

NBS management has long recognized the necessity for analyzing the physical measurements performed in this country, with respect to the quality of measurements being made and the development of optimum dissemination procedures for the needs of the system. This paper describes the concept and utilization of force measurement standards and their everyday use, both implicitly and explicitly, in science, industry, commerce, health, safety, etc. The network of standards, procedures, and day-to-day measurements at all levels of accuracy is called the National Force Measurement System.

At first glance, the National Force Measurement System appears to be fairly limited and well defined. This is misleading and the current study, reported upon here, shows that, in our technological society, force measurements play a major role in the nation's industry and commerce and in our daily lives. This report will not dwell on each of the types of force measurements which are being made but will outline the scope of the measurement system and detail a few of its specific impact areas.

2. STRUCTURE OF THE MEASUREMENT SYSTEM

Before we begin any discussion of primary standards and accuracy requirements of the force system, it will be useful to outline its structure. As can be seen from figure 1 the system is stratified according to the degree of accuracy required in a measurement. Each block on a level of the system has approximately the same accuracy requirements and lesser requirements than the level above it from which it derives its traceability to a primary standard. At the bottom of the system are the two major end user categories of the system; weighing system users and testing machine users.

The major user groups derive their force standard traceability from several sources. Standards laboratories, such as those maintained by large industrial firms, the military services, and commercial calibration services provide a calibration for force devices by using deadweight machines or the transfer standard techniques to be discussed later. Secondary or working calibration devices are then used to calibrate the testing machines or scale systems.

The entire hierarchy of the measurements in the force measurement system might be assembled within a large corporation. A metrology or standards assurance department which is responsible for all force standards in the company submits a calibration kit, consisting of one or more load cells or proving rings, to NBS or another deadweight facility for a "primary" calibration. After the kit is returned, all the secondary and/or working standards are calibrated against the kit using a back-to-back technique. The secondary standards are used by the several departments in the company to calibrate testing machines, hardness machines, etc. Load cells are removed from the scale weighing systems and calibrated against either the primary or secondary calibration kits. The testing machines are used on the production line to assure quality

NATIONAL FORCE MEASUREMENT SYSTEM

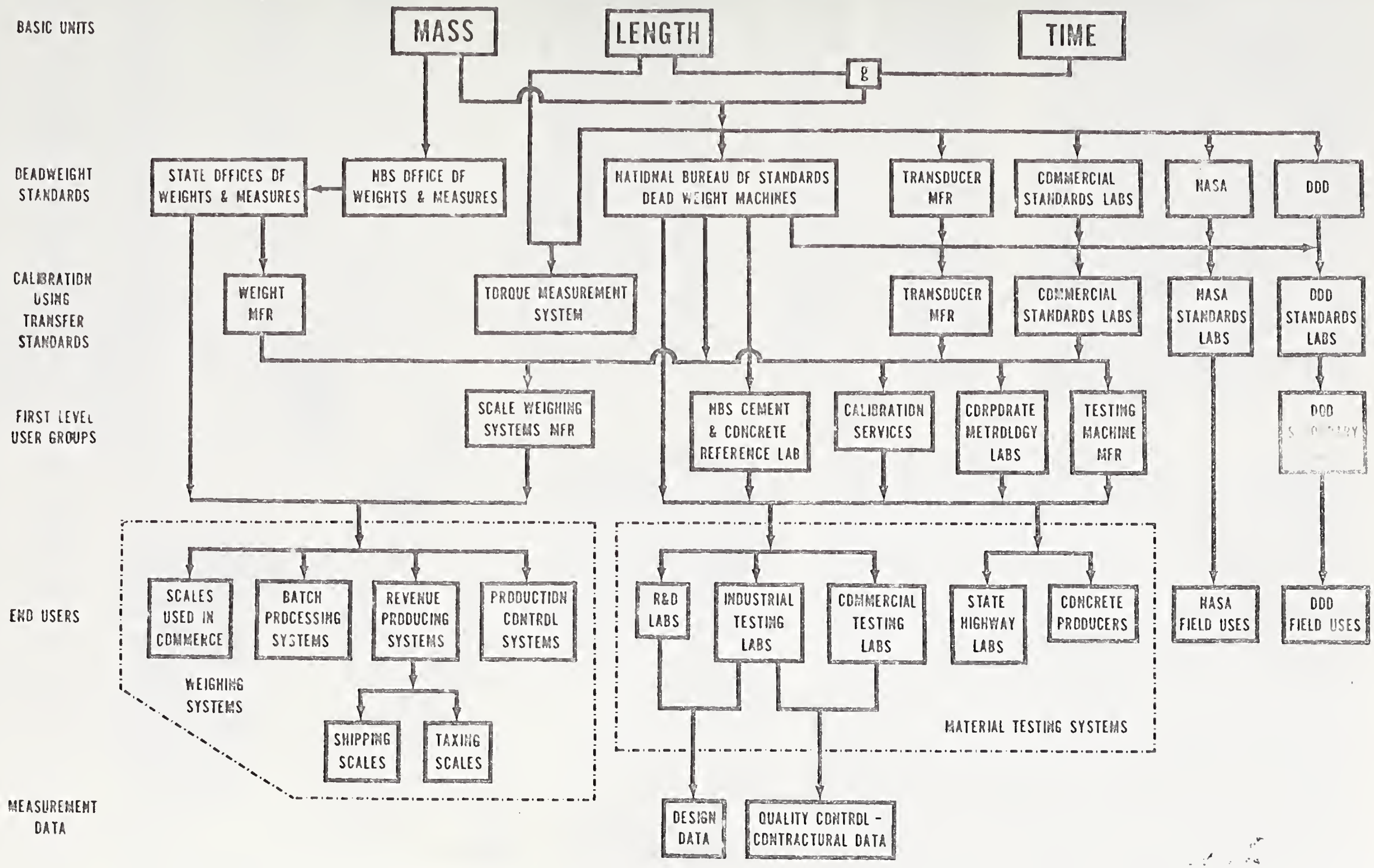

Figure 1 - National force measurement system

control of the product and in the R & D department in the development of new products. In addition, the company purchases new scales or testing machines or requires repair of existing equipment. In these cases, a preliminary calibration is provided by the scale or testing machine manufacturer. If disputes arise over the quality of a product between the company and a buyer, a commercial testing laboratory is contracted to referee the dispute. The commercial testing laboratory has derived its traceability in much the same way the company has. Perhaps a testing machine calibration service has been employed or the testing lab may own its own primary calibration kit.

Smaller companies derive traceability in a similar manner with various services of the system purchased from testing machine manufacturers, calibration services commercial standards labs, and NBS.

Discussions of the effects of many of these elements on the system structure will be presented in later parts of this document.

2.1 Conceptual System

Tradition tells us that the physical concept of force occurred to Isaac Newton on a fine fall day in 1686 while he was resting under the apple tree in his garden. As a measurement quantity, force is defined by the action of the Third General Conference of the International Committee on Weights and Measures, October 1901. Force may be defined by the simplified form of Newton's Second Law of Motion, F = kma, and can be most precisely determined from the attraction of the earth's gravitational field on a known mass with an appropriate correction for the buoyancy of the displaced air. In this way, the standards of force are directly traceable to the national standards of mass, length and time. Since the local value of the acceleration due to gravity and mass values can both be determined to a few parts per million, primary force standards with good precision are available, e.g., deadweight calibration machines with uncertainties of less than 20 ppm (0.002 percent) without accounting for temporal changes in air density. In the measurement system, force quantities are measured over the range from 5×10^{-7} newtons the force exerted by a single muscle fiber, to 5×10^{7} newtons for the Apollo Launch Vehicle (fig. 2). Over that force range of 14 decades, the accuracy requirement ranges from the 0.002 percent uncertainty of primary deadweight force standards to the 10 percent needed by metal rolling mills (fig 3).

Early force measurements were made using a combination of weights and multiplying levers. An early practical portable force measurement instrument, the proving ring, was developed by Petrenko and Whittemore at NBS in 1927 [1] (fig. 4). This was an elastic steel ring developed for the calibration of hardness machines. In the next year, the first deadweight force standards were placed in service at NBS.

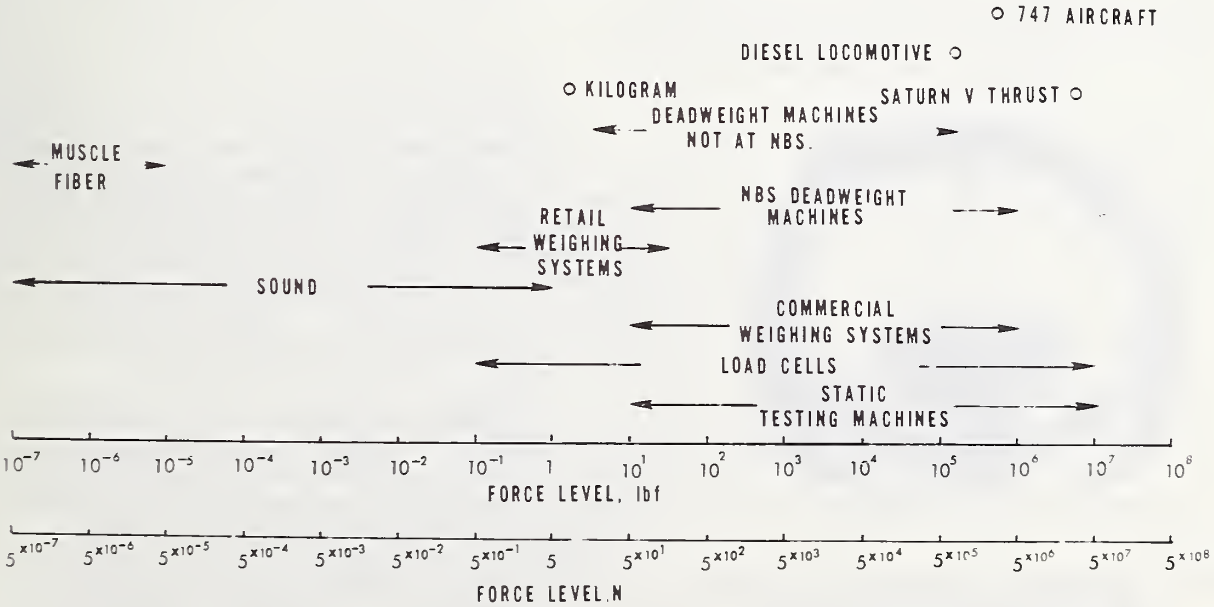

Figure 2 - Ranges of forces measured in the measurement system

Table 1 - Summary of Principal Domestic Deadweight Force Standards

Organization	DWM Capacity lbf	Accuracy percent	Notes
National Bureau of Standards	1,000,000	0.002	
	300,000	.002	
	112,000	.002	
	112,000	.002	
	25,300	.002	11,500 kgf
	6,100	.002	3,050 kgf
	500	.002	
Other US Government Laboratories			
US Army Redstone Arsenal	1,000	.005	
White Sands Missile Range	133,000	.005	
US Navy Eastern Standards Lab	10,000	.002	Surplus NBS DWM
US Air Force Edwards AFB	200,000	(a)	Not The Primary USAF Standard
NASA Marshall SFC	496,000	.005	Actually 225,000 kgf
Lawrence Radiation Lab	60,000	(a)	University of California
Commercial Laboratories in the US			
BLH Electronics	125,000	.005	Transducer Manufacturer
Interface Inc.	5,000	(a)	Transducer Manufacturer
Lebow Associates, Inc.	5,000	(a)	Transducer Manufacturer
Morehouse Instrument Co.	220	(a)	Transducer Manufacturer
Nat'l Standards Testing Lab	12,000	.002	Only Commercial Deadweight Calibration Lab
Revere Corp.	100,000	.005	Transducer Manufacturer
Toroid Corp.	12,000	(a)	Transducer Manufacturer

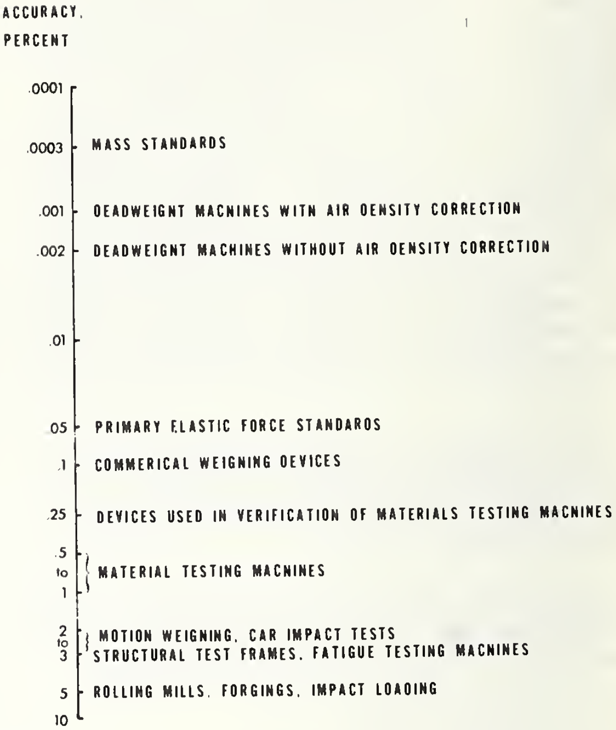

Figure 3 - Accuracy levels presently found in the measurement system

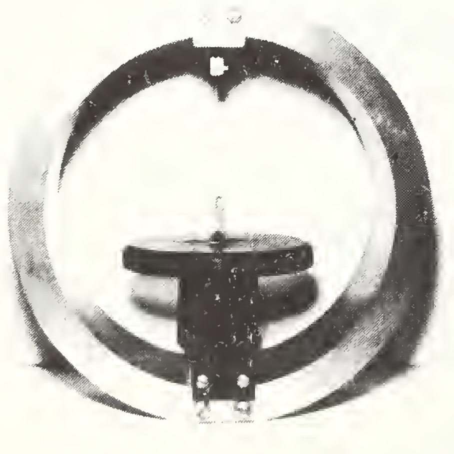

Figure 4 - Whittemore-Petrenko proving ring, the first practical transfer force standard, 1927

During World War II, with the rapid increase in the the number of measurements needed for aircraft weighings, a force transducer with an electronic read-out was developed. The development of these load cells reduced the physical size of the instruments and the training of the operator needed to measure large forces. With this, the number of force measurements increased significantly.

In the 1960's, deadweight force standards were installed at several other government laboratories, at the manufacturing plants of some transducer suppliers and by at least one commercial calibration laboratory (table 1). In 1965, six new standards with a capacity up to 4,500,000 N (1,000,000 lbf) were installed at NBS. During this same period, deadweight capability has also been developed in many other countries (table 2).

Table 2 - Summary of Foreign Force Standardization Equipment

Country	DWM Capacity[a]	Total Capacity
Austria	1 Machine, 4500 lbf	3 Machines up to 1,124,000 lbf with Hydraulic Multiplier
Canada	1 Machine, 100,000 lbf	
France	1 Machine, 56,000 lbf	3 Machines up to 56,000 lbf with Lever Multiplier
Federal Republic of Germany	14 Machines cover range from 660 lbf to 450,000 lbf	12 Machines up to 3,300,000 lbf with Lever or Hydraulic Multiplier
Hungary	1 Machine, 11,240 lbf	1 Machine, 225,000 lbf with Hydraulic Multiplier
Italy	1 Machine, 22,500 lbf	1 Machine, 225,000 lbf with Hydraulic Multiplier
Japan	1 Machine, 2,200 lbf	1 Machine, 1,100,000 lbf with Hydraulic Multiplier
Netherlands	2 Machines of 5,500 lbf and 125,000 lbf capacity	2 Machines up to 55,000 lbf with Lever Multiplier
Poland	1 Machine, 110,000 lbf	
Switzerland	1 Machine, 22,000 lbf	1 Machine, 200,000 lbf with Hydraulic Multiplier
United Kingdom	3 Machines of 500 lbf, 10,000 lbf and 100,000 lbf capacity	4 Machines up to 6,756,000 lbf with Hydraulic Multiplier

(a) All capacities have been converted to lbf for comparison with Table 1. One pound-force equals 4.448 newtons.

2.2 Basic Technical Infrastructure

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

Methods for the accurate measurement of forces and the calibration of force measurement devices have been promulgated by the American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), and by the International Standards Organization (ISO). These standard methods are referenced by most other standards-writing organizations (table 3).

2.2.1.2 Survey of Documentary Standards

Force measurement standards are generally incorporated into a contractual agreement between a purchaser and a vendor. The measurement standard is cited as a performance requirement by the purchaser and tests are performed in accordance with the standard by the vendor or a mutually agreed upon laboratory. The standards are written by many organizations and very often are redundant, i.e., several organizations have standards for testing the same product. ASTM, for example, has written voluntary standards for the performance of more than 20 physical tests requiring force measurement (table 4). These standards prescribe the test conditions for more than 50 materials and products (table 5). NBS participates in many of the organizations which develop voluntary standards.

Procedural specifications for the calibration of force-measuring instruments have followed an interesting development in this country. Shortly after the proving ring was invented, a Specification for Proving Rings was drafted at NBS. The specification included mandatory design features of the instrument as well as calibration procedures and performance requirements. Although NBS had no regulatory authority over the manufacturers of the rings, the policy was that rings submitted for calibration to NBS were tested under the document and awarded a certificate of calibration only if they complied with the requirements of the specification.

The NBS specification was immediately accepted by both industry and governmental agencies and, over the next few decades, became so thoroughly entrenched as the standard

Table 3 - Organizations Having Standards Specifications or Procedures Involving Force or Strength Measurement

Aerospace Industries Association
Air-Conditioning and Refrigeration Institute
Air Filter Institute
Aluminum Siding Association
American Carpet Institute
American Concrete Institute
American Dental Association
American Merchant Marine Association
American National Standards Institute
American Society of Civil Engineers
American Society of Mechanical Engineers
American Society for Testing and Materials
Asbestos Textile Institute
Asphalt Institute
Association of Iron and Steel Engineers
Clay Products Association
Concrete Reinforcing Steel Institute
Consumer Product Safety Commission
Cordage Institute
Department of Commerce
Department of Defense
Department of Transportation
Elastic Fabric Manufacturers Institute
Galvanized Ware Manufacturers Council
General Services Administration
Gummed Industries Association
Gypsum Association
Gypsum Roof Deck Foundation
Industrial Fasteners Institute
Metal Ladder Manufacturers Association
National Association of Chain Manufacturers
National Association of Corrosion Engineers
National Wooden Pallet Manufacturers Assoc.
Optical Manufacturers Association
Outdoor Power Equipment Institute
Prestressed Concrete Institute
Pressure Sensitive Tape Council
Rubber Manufacturers Association
Society of Automotive Engineers
Society of the Plastics Industry
Steel Bar Mills Association
Underwriters Laboratories

Table 4 - Tests Performed on Materials and Structures which Require Measurement of Forces

Abrasion Resistance
Bearing Test
Bond Strength
Bursting Strength
Climbing Drum Peel Test of Adhesives
Coefficient of Friction
Compressive Strength
Creep Resistance in Compression
Creep Resistance in Tension
Disk Shear
Fatigue
Flexural Strength
Hardness
High Speed Tensile Testing
Impact Resistance
Puncture Resistance
Residual Strength
Shear Strength
Stress Relaxation in Compression
Stress Relaxation in Tension
Tear Resistance
Tensile Strength

Table 5 - Representative Materials Covered by ASTM Standards which Require the Measurement of Force

Adhesives
Air-Conditioning Hose
Aluminum Foil
Asbestos
Bituminous Asphalt
Brake Hose
Brick and Structural Clay Tile
Carbon-Graphite Mat'ls
Cohesive Soil
Concrete Paving Mat'ls
Construction Mat'ls
Cooper Magnet Wire
Corrugated Carboard
Fiberous Composites
Glass Fibers
Glass Fiber Mat
Honeycomb Core
Ion Exchange Resin
Leather
Lime Mortar and Grout
Metallic Foil
Metallic Materials
Natural Building Stone
Package Cushioning Mat'ls
Paint Films
Paper
Paraffin Wax
Plastics
Plastics Film
Plastic Pipe
Plywood
Resin Mortar
Rigid Plastics
Rock Core Samples
Roofing Shingles
Rubber Belts
Rubber Cement
Rubber to Metal Bonds
Seals
Shipping Containers
Soil-Cement
Steel Spring Wire
Textile
Timber
Tire Cord
Tires
Urethane Foam
Vitrified Ceramic
Vulcanized Rubber
Whiteware Mat'ls
Yarn

for the nation that it completely overshadowed any other calibration procedures. It maintains that position today, after some forty years of use. In the 1940's an American Society for Testing and Materials document, Method E 74, was adopted following the same general outline as the NBS document, but without the mandatory design features. Many of the ASTM specifications for testing the materials listed above require that all calibration instruments comply with Method E 74. In spite of this requirement, only a few calibrations were ever performed under this Method E 74.

During the 1950's, the difficulties at NBS over possible conflicts of interest resulted in a policy decision to discontinue all certifications of calibrations except those required by law for State reference standards of mass, volume, etc. The policy also required that NBS would not issue specifications for proprietary products. The NBS specification for proving rings was withdrawn at that time and proving ring calibration reports subsequently carried merely the notation that the instrument complied with the requirements given in the appendix to NBS Circular 454, an old publication describing the rings. In spite of this, industry still regards the NBS "specification" as the definitive document in the field.

The NBS policy, while a necessary one, had the unfortunate effect of making it impossible to update the old specification to take full advantage of new ideas and new techniques. The design features of the document were put in to insure certain levels of performance that could not be verified from a calibration performance analysis in 1930. Today the information can be readily obtained using computer programs.

Attempts to update the ASTM Method E 74 document have been underway for the past four or five years but have suffered repeated set-backs because of the Society's policy of deferring to any objection. The feeling of some industry spokesmen that "It's not in the NBS specification" has been a repeated stumbling block. Recently, a new revision of Method E 74 [2] has been approved by the ASTM committees. NBS has changed its usual calibration procedures to conform to the new ASTM Method E 74.

2.2.2 Instrumentation System

2.2.2.1 Primary Standards

Deadweight Machine. A deadweight force calibration machine consists of a selection of masses and a means for using the masses to apply a direct load to the instrument under calibration (fig. 5). The masses of the weights are generally adjusted through multiplication of the mass standard to apply nominal force values, taking into account the local value of the acceleration due to gravity and the average buoyant effect of the displaced air. These nominal values may be in units of newtons, pounds-force or kilograms-force, but in this country, the U. S. Customary Unit, pound-force, is most commonly used. Deadweight machines do not measure loads, but supply a limited series of precisely known forces.

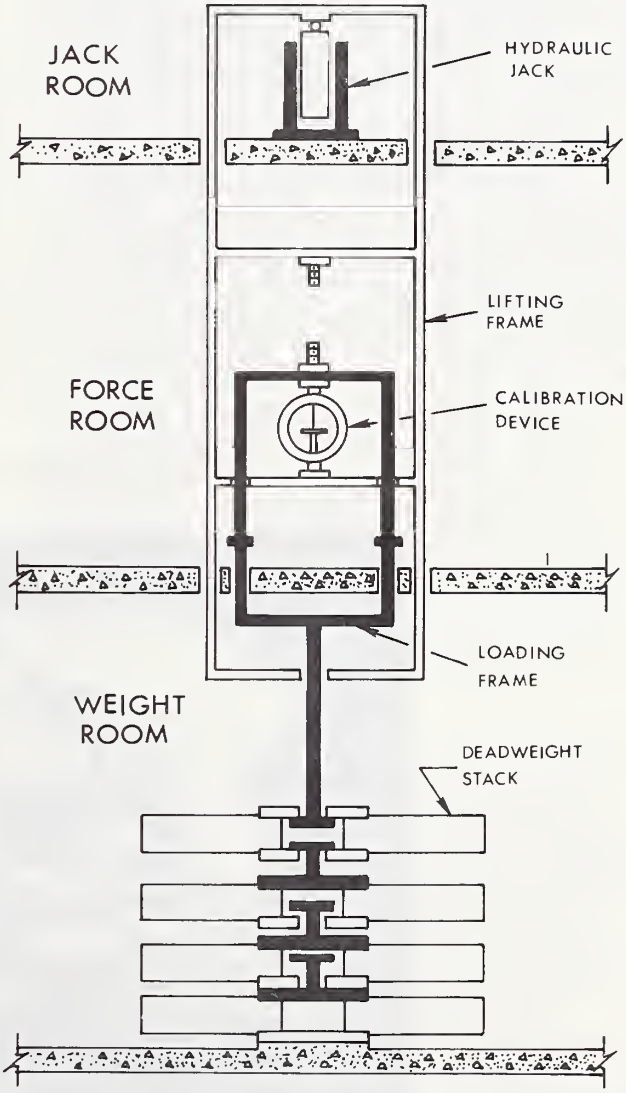

Figure 5 - Schematic of a deadweight calibration machine

The deadweight standards currently available at NBS (table 1) are undoubtedly the most important group of force standards in this country. Comparable standards covering the same force range are not known to exist elsewhere, although deadweight force calibration facilities in the lower load ranges (i.e., up to about 100,000 lbf or 450,000 N) are available in several countries. Apparently in these countries calibrations by means of combinations of several secondary standards or force multipliers suffice for the larger force ranges. In the NBS deadweight machines, the masses of the weights were adjusted to apply nominal force values, taking into account the measured local value of gravity [3] and the average buoyant effect of the displaced air. The uncertainty of loads applied with these machines is less than 0.002 percent and this uncertainty could be halved by using a value of air density measured at the time of each calibration.

Standard Weights. State and local Offices of Weights and Measures indirectly provide a significant portion of the force standards calibrations. This is done through the calibration of masses. The masses are then used as standards to calibrate scale systems, testing machines, etc., which actually measure force. The corrections for gravitational acceleration and air buoyancy are seldom required to meet the accuracy requirements imposed on these systems, but such corrections could be easily made using local gravity values obtainable from the National Oceanic and Atmospheric Administration, and average air density values.

2.2.2.2 Secondary Standards

As was noted above, the development of high-grade instruments for the accurate measurement of large forces, i.e., forces exceeding about 4,500 N (1,000 lbf), began shortly after the end of World War I. In 1928 the National Bureau of Standards began to provide accurate deadweight calibrations of force measuring instruments up to 450,000 N (100,000 lbf). A new instrument, the proving ring, was developed by two Bureau staff members [1] and provided a reliable means by which the accuracy of the deadweight standards could be transferred to other laboratories. Today, nearly half a century later, the proving ring is still one of the most reliable instruments available for the transfer of static force calibrations.

World War II brought a sharp increase in the demand for force measurements. The necessity of multiple weighings of heavily loaded aircraft by relatively unskilled personnel and the availability of reliable wire resistance strain gages prompted the development of the load cell. The use of this instrument has grown so that 95 percent

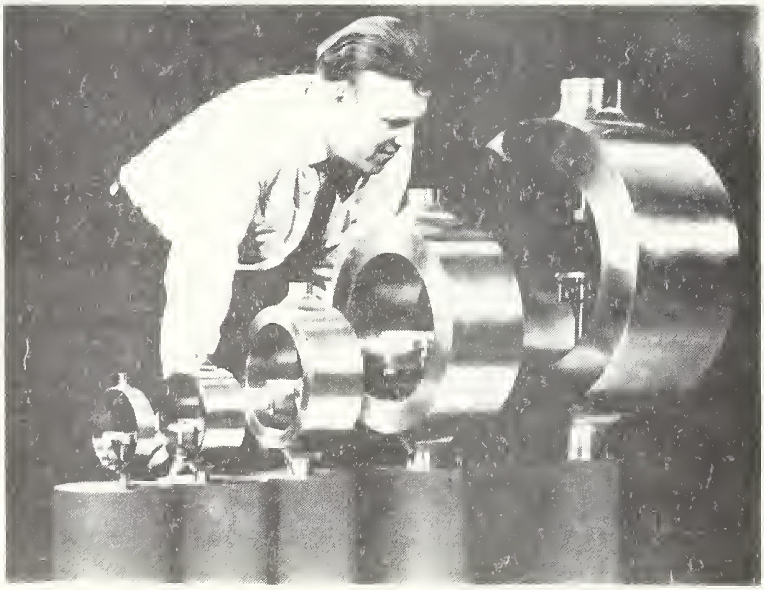

Figure 6 - Proving rings

of force measurements are now made with load cells.

A brief explanation of the characteristics of the principal types of force measuring instruments will assist in understanding the manner in which they tend to be used.

Proving Rings. The proving ring is a mechanical device in the form of a hardened steel ring or loop with well-defined loading points. Figure 6 shows several rings of the type now in use. The elastic deflection of the ring under load is measured with a micrometer screw and these measurements are then translated into load by use of a table or graph which summarize the calibration data. Other mechanical length measuring devices such as dial indicators can be substituted for the micrometer screw but usually result in poorer performance. Generally speaking, the mechanical instruments are rugged, exhibit excellent qualities of long-term stability, and require only minimal care and maintenance. They have the disadvantage of requiring the presence of an operator close to the point where the load is applied; they are not direct reading and the values read from the scale must be recorded manually and subjected to a moderate amount of calculation to determine the force value. In addition they are not suitable for measuring a rapidly changing load and require considerable operator skill and training to obtain satisfactory results.

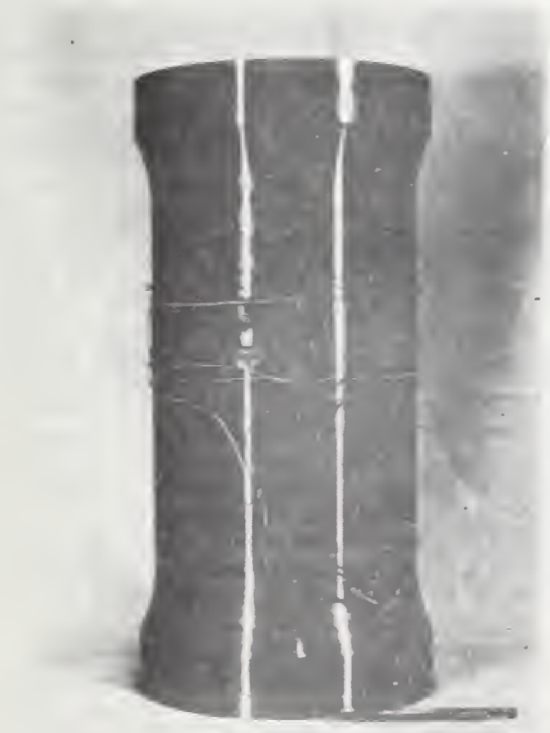

Figure 7 - Load cell showing the strain gage installation

Load Cells. The second type of device is the load cell (fig. 7) in which the elastic strain in a stressed member is sensed by a fine wire or foil strip cemented to the strained surface in such a manner that its electrical resistance changes with strain. Load cells offer an advantage in versatility by virtue of having an electrical signal as output. They also offer greater possibility for compensating for environmental and performance characteristics. They may be read by an operator located well away from the point of load application. They may be made as a direct reading instrument; the output may be recorded automatically or read manually or even fed directly into an information storage or computer system. They can follow rapidly changing or fluctuating loads when used with high speed recording equipment.

On the debit side, electrical instruments are more delicate, subject to damage in shipment, exhibit good short-term stability but are less reliable in long-term stability, and require frequent electrical checking and maintenance procedures.

Other Force Measurement Devices. Other instruments which are used as force measurement devices include rings or loops with differential transformers, a number of instruments using variable reluctance or piezoelectric sensing elements and hydraulic and pneumatic force capsules. These devices, to some degree, possess most of the advantages and disadvantages of strain gage type load cells.

2.2.2.3 Transfer Standards

When deadweight machines are not available, transfer devices can be used as calibration standards. Calibrations of this type are accomplished by loading the transfer standard and the instrument under calibration together, in series, in a press of suitable design. Since the conditions are static, the forces on the two instruments are the same and are measured by the transfer standard. This technique is frequently referred to as a "back-to-back calibration". A special case of this is the technique employed at the National Bureau of Standards and elsewhere for calibration at forces beyond the range of available deadweight standards (fig. 8). Here the load on the instrument under

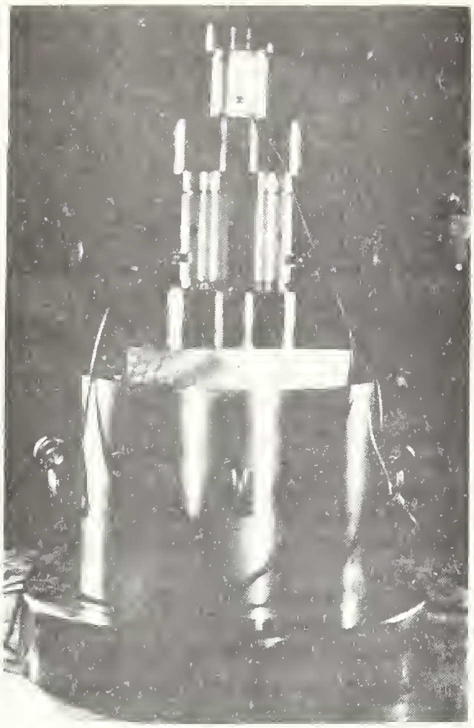

Figure 8 - Multiple load cell calibration setup

calibration is distributed among three or more transfer standards of lesser capacities. Uncertainties ranging up to 0.05 percent of load result from measurements using this technique.

Other mechanisms have also been used by standards labs as standards of force. The hydraulic multiplier is capable of very high precision and has been used successfully for some time. It has not been adopted to any extent in this country, even though one manufacturer has produced prototype models of very high quality. The multiplier consists of two free piston assemblies, the smaller one being essentially of the deadweight pressure calibration type. The larger unit consists of double piston in a rotating cylinder. The lower piston forms the base of the unit and the upper piston exerts the calibration force on the force-measuring instrument under test. The two piston-and-cylinder assemblies are usually connected through a pressure comparator. The deadweight load on the smaller piston is multiplied by the ratio of the areas of the two assemblies and applied to the instrument under test. Properly used, such a standard can approach the accuracy of deadweight loading. The method has the advantage that multiplication factor can be checked by loading the large piston assembly in a deadweight calibration machine.

Mechanical lever systems have also been used as transfer standards of force. In Europe, single levers have been used in a number of instances in conjunction with a small deadweight calibration machine. Multiplication of forces by five times is quite practical and the factor has even been extended to ten in one or two instances. In this country, a few lever systems have been constructed, mostly designed with a much higher multiplication factor so that the unit can operate with relatively small, hand-loaded weights. These designs usually require a multiple lever system and frequently employ flexure-plate pivots in lieu of knife-edge pivots because of the greater safety and stability. Unfortunately, the designers of these units have given little thought to formal methods of verifying the multiplication ratios as the systems are generally too large and cumbersome to mount in a deadweight machine. The mechanical lever systems are subject to the disadvantage that the multiplication ratio tends to change under increasing load because of the local deformations of the lever parts.

2.2.2.4 Instrumentation Industry

The instrumentation industry comprises those companies which supply transducers, testing machines and weighing scales to the measurement system.

Force Transducer. The industry which supplies instruments for the force measurement system is relatively small for the impact which its products have on other industry and commerce. The gross sales were $40 million in 1973 with almost no growth shown over the last several years. As could be inferred from the two principal transfer transducers available, the force transducer industry is divided into two almost exclusive parts. The small proving ring market is supplied by only two manufacturers (table 6). About 100 devices per year are marketed with a large majority of the market concentrated in one of the companies.

The load cell transducer market is supplied by about 60 manufacturers (table 6) including at least three importers. Many of these companies include load cells in their product line of physical measurement transducers.

In addition to sales of new transducers, the industry provides a significant recalibration service either through its own deadweight machines or by comparison with devices calibrated in deadweight machines using techniques discussed in Section 2.2.2.3.

Testing Machines. While the testing machine and scale industries appear as customers to the transducer industry, testing machines and scales are basic tools in the force measurement system. These industries, therefore, must be considered a major part of the instrumentation industry. Equipment manufactured by this $40 million industry [4] are the foundation of the measurement of strength of materials, quality control, and consumer safety section of the technology. Tables 4 and 5 list some of the interactions which the testing machine industry has with society. Mechanical tests are performed on a wide spectrum of materials from sewing thread, with a strength of only a few ounces, to high strength steel plates and cable, with strengths of millions of pounds. Testing machines vary in size and capacity from those capable of measuring the strength of a single fiber to the 12 million lbf capacity testing machine at NBS.

A partial list of testing machine manufacturers is also shown in table 6. There is a strong tie between the industry and the Office of Weights and Measures. This is especially true for calibration of machines with capacities less than a few hundred pounds. Of the eight manufacturers contacted during this study five use weights for calibration of at least some of the load ranges of their machines. For recalibration, however, the majority of users have the machines verified using load cells or proving rings which are themselves calibrated against a set of primary standards.

Scale Systems. Load cell scale systems vary in size from the scale used at the local supermarket to weigh produce to scale systems of more than 5 million newtons (1 million pounds force) capacity, capable of in-motion weighing of several freight cars simultaneously. Load cell based scale systems are typically used in batch processing operations to control the flow of materials in a production process and to weigh trucks in motion on highways for road tax enforcement.

The load cell weighing system market has grown from sales of 2700 units worth $3.4 million in 1963 to sales of 6400 units worth $11 million in 1972. It should be noted here, however, that the total market in scale systems was $140 million in 1972. This is divided among about 27 manufacturers, over half of which make load cell weighing systems of some type.

A relatively small number of scale systems are used by the railroads to determine transportation rates of goods shipped. The 600 railroads which belong to the Association of American Railroads operate 7000 track scales. About 500 of these are load cell systems. Such systems are being installed at ever increasing rates to replace older lever scale systems. These railroads moved approximately 2.5 billion revenue tons in 1972, worth about $12.6 billion in income to the railroads [8]. No attempt was made to estimate the retail value of the goods shipped by rail, but it includes everything from food and fuel to automobiles and heavy machine tools.

The load cell weighing systems are, for the most part, relatively large, stationary installations. Consequently the easiest way to recalibrate these systems is to bring a set of standard weights to the scale and calibrate it in place. Thus, the tie-in to the NBS Office of Weights and Measures is very strong for this branch of the measurement system.

2.2.3 Reference Data

Force data in the measurement system can also be the result of a mechanical property measurement and not a weight measurement. As such the end use of this data is reflected in the type of laboratory which makes the measurement. Tensile strength, fatigue strength, tear resistance, etc., measurements are made on materials by research laboratories. The results of these measurements are published in the open literature for the public use of design engineers. At another level, the corporate research department acquires data which is proprietary to the company. This is used by the company to improve existing products or in the planning and design of new products. Finally, tests are performed as a routine part of the quality control function on the production line. The greatest number of measurements are made at this level, and this data is basically contractual in nature. The buyer requires a certain performance from the material. The quality control tests are used to establish the compliance with the contract.

Table 6 - Force Instrumentation Manufacturers

Proving Rings

Morehouse Instrument Co.
York, Pa. 17403
Tinius Olsen Testing Machine Co.
Willow Grove, Pa. 19090

Load Cells

AESA Electric Inc.
White Plains, N.Y. 10602
AKO Inc.
Enfield, Conn. 06082
Alinco
Cumberland, Md. 21502
AST/Servo Systems Inc
Newark, N.J. 07104
Automatic Timing & Controls Co.
King of Prussia, Pa. 19406
B&K Instruments
Cleveland, Ohio 44101
BLH Electronics, Inc.
Waltham, Mass. 02154
Bofors Industries
Linden, N. J. 07036
Brewer Engineering
Marion, Mass. 02738
Cardinal Scale Manufacturing Co.
Webb City, Mo. 64870
Celesco Industries Inc.
Canoga Park, California 91304
Celtic Industries Inc.
Van Nuys, Cal. 91405
John Chatillon & Sons Inc.
Kew Gardens, N.Y. 11415
Comptrol Inc.
Cleveland, Ohio 44125
Comten Industries Inc.
St. Petersburg, Ill. 33701
Control Process Inc.
Plantsville, Conn. 06479
W. C. Dillon & Co., Inc.
Van Nuys, Cal. 91407
A. H. Emry Co.
New Canaan, Conn. 06840
Entran Devices, Inc.
Little Falls, N.J. 07424
Farr Measurements
East Lake, Cal. 80614
GSE Inc.
Farmington Hills, Mich. 48024
Gilmore Industries
Cleveland, Ohio 44122
Gould Inc., Statham Inst. Div.
Oxnard, Cal. 93030
S. Himmelstein & Co.
Elk Grove Village, Ill. 60007
Houston Scientific Industries Inc.
Houston, Texas 77018
Imtra Corporation
Medford, Mass. 02155
Instron Corporation
Canton, Mass. 02021
Intec Inc.
Bound Brook, N. J. 08805
Interface Inc.
Scottsdale, Ariz. 85260
Kistler-Morse Corp.
Bellevue, Wash. 98005
Kristal Instrument Corp.
Grand Island, N. Y. 14072
Lebow Associates, Inc.
Troy, Mich. 48084
Lion Precision Corp.
Newton, Mass. 02195
Marcan Products Corp.
S. Norwalk, Conn. 06856
Martin Decker Co.
Santa Ana, Cal. 92708
Metrodyne Corp.
Stamford, Conn. 06904
Microstrain Inc.
Spring City, Pa. 19475
Moxon Inc.
Irvine, Cal. 92664
Ormond Inc.
Santa Fe Spring, Cal. 90670
PCB Piezotronics Inc.
Buffalo, N. Y. 14225
Precision Force Measurement Inc.
Cinnamimson, N. J. 08077
Revere Corp. of America
Wallingford, Conn. 06492
Ruska Instrument Corp.
Houston, Texas 77036
Schaevitz Engineering
Camden, N.J. 08101
Scientech Inc.
Boulder, Col. 80303
Sensotec Inc.
Columbus, Ohio 43216
Space Corp.
Dallas, Texas 75040
Standard Controls Inc.
Seattle, Wash. 98144
Strainsert Co.
Bryn Mawr, Pa. 19010
Sundstrand Data Control Inc.
Redmond, Wash. 98052
Task Corp.
Anaheim, Cal. 92803
Tensitron Inc.
Harvard, Mass. 01451
Testing Machines Inc.
Amityville, N.Y. 11701
Thwing-Albert Instrument Co.
Philadelphia, Pa. 19154
Toledo Scale
Toledo, Ohio 43612
Torroid Corp.
Huntsville, Ala. 35804
Transducers Inc.
Whittier, Cal. 90606
Trans-Sonics Inc.
Lexington, Mass. 02173
West Coast Research Corp.
Los Angeles, Cal. 90025
Westinghouse Electric Corp.
Pittsburg, Pa. 15238

Testing Machines

ACCO
Bridgeport, Conn. 06602
ACG., Inc.
West Haven, Conn. 06516
Ametek
East Moline, Ill. 61244
Applied Test Systems, Inc.
Saxonburg, Pa. 16056
John Chatillon & Sons, Inc.
Kew Gardens, N.Y. 11415
Comten Industries, Inc.
St. Petersburg, Ill. 33701
Cosa Corp.
Montvale, N.J. 07645
Custom Scientific Instru., Inc.
Whippany, N.J. 07981
Detroit Testing Machine Co.
Detroit, Mich.
W. C. Dillon & Co., Inc.
Van Nuys, Cal. 91407
Duffers Associates, Inc.
Troy, N.Y. 12180
Fatigue Dynamics, Inc.
Detroit, Mich.
GCA/Precision Scientific Co.
Chicago, Ill. 60647
Gilmore Industries
Cleveland, Ohio
Claud S. Gordon Co.
Richmond, Ill. 60071
Hampden Engineering Corp.
E. Longmeadow, Mass. 01028
Harisonic Laboratories, Inc.
Stanford, Conn. 06902
Hunter Spring
Hatfield, Pa. 19440
Instron Corp.
Canton, Mass. 02021
Interface Inc.
Scottsdale, Ariz. 85260
Kinetic Systems, Inc.
Waltham, Mass. 02154
Lab Div., Mech. Technology, Inc.
Skaneateles, N.Y. 13152
Ladd Research Industries, Inc.
Burlington, Vt. 05401
Martin Decker Co.
Santa Ana, Cal. 92708
Mausner Equipment Co., Inc.
Carle Place, N.Y. 11514
Mechanical Technology, Inc.
Latham, N.Y. 12110
Micro-Strain, Inc.
Spring City, Pa. 19475
Monsanto Co.
Akron, Ohio 63166
MTS Systems Corp.
Minneapolis, Minn. 55440
Pacific Transducer Corp.
Los Angeles, Cal. 90064
Pegasus Div., Koehring, Inc.
Troy, Mich. 48084
Satec Systems, Inc.
Grove City, Pa. 16127
Testing Machines, Inc.
Amityville, N.Y. 11701
Thwing Albert Instrument Co.
Philadelphia, Pa. 19154
Tinius Olsen Testing Machine Co.
Willow Grove, Pa. 19090

2.2.4 Reference Materials

There are no system-wide standard materials in force measurement. The only reference materials are those occasionally established and maintained by a corporation. In such a case a well-characterized specimen material is used by the lab as a check test of the calibration of a quality-control testing machine. This is done once-per-shift or once-per-day to verify that a complete recalibration of the machine is not necessary.

2.2.5 Science and People

The education background of the people in the measurement system, both professional and technician, is best described as practical training. The differences in training between professional and technician are only a matter of degree, not of substance. A professional, usually an engineer, receives little formal education in physical measurement during his university education. What formal education he does receive usually ends with his undergraduate degree. All later training is gained on-the-job under the tutelage of his supervisors. Technicians receive almost no formal training, and training in force measurement may be combined with training in several other types of measurement which are being performed in the laboratory or on the production line.

The opportunity for formal training in measurement techniques is generally more available to people working in a research environment than to production workers.

The science in the measurement system includes the mechanical engineering sciences, i.e., the measurement of one or more of the physical properties of materials (table 4), physics, electronics, statistics, etc. Information about this science of physical measurement is transferred throughout the system through the journals of the professional societies, technical reports, professional opinions, etc. This mechanism tends to be limited by the specialized disciplinary nature of the journals and reports. The interdisciplinary transfer of information is carried out by the several abstract journals which draw from all available literature. The volume of this compilation task can be appreciated when the number of engineering society journals, university engineering schools, and corporate and government research laboratories are realized.

2.3 Realized Measurement Capabilities

An understanding of the range and accuracy capabilities of the measurement system can be derived from a review of figures 2 and 3 above. As might be expected the available accuracy is often in inverse proportion to the number of intermediate calibration stages between the final measurement and the primary standard.

The highest levels of accuracy necessary in the area of force measurements are those for the deadweight standards. Fortunately, the nature of a mass determination is such that the necessary accuracy can easily be obtained. A deadweight standard with an uncertainty of 0.005 percent of load is adequate for the calibration of the best elastic force measuring instruments available. The NBS deadweight standards are adjusted to be within 0.002 percent when used without correction. If corrections for daily variations in air density and for the measured masses of the individual weights were to be applied, the uncertainty of the NBS standard could be less than 0.001 percent of load. As can be seen from table 1, other deadweight calibration machines in use in this country are adjusted to comparable accuracy. All of these machines are considered adequate for present day needs.

At the next level of performance are the elastic force-measuring instruments such as proving rings and load cells and force-multiplying devices such as mechanical levers and hydraulic multipliers used as transfer force standards where an accuracy of 0.05 percent of load is adequate. These instruments and devices exhibit error characteristics that are somewhat different from those found in a deadweight system. The weights of a deadweight machine can be adjusted to be within a certain percentage of their desired values which is usually the same for all of the weights in a given machine. Indeed, the smaller weights may be adjusted to a somewhat closer percentage tolerance than the larger ones. As a consequence, the usable range of a deadweight calibration machine may be quite large. For instance, the 112,500 N (25,300 lbf) deadweight machine at the National Bureau of Standards may be used at a load as low as 900 N (200 lbf), less than 1/100 of its capacity. An elastic force-measuring instrument, on the other hand, has an inherent error band of nearly constant force amplitude throughout its entire range such that the error in percent of load increases markedly in the lower portion of its range. A force-measuring instrument used as a 0.05 percent reference standard may be useable only down to 1/3 of its capacity load. The same effect is present in lever systems and hydraulic multipliers where the constant-force error band is contributed by friction. As a consequence, a laboratory that depends on transfer force standards is obliged to maintain a substantial number of force measuring instruments in order to cover a sufficient range of loads to satisfy the needs of its customers. The initial cost of such an array of instruments and the annual cost of keeping them in calibration by deadweight standards appears to have discouraged the growth of commercial calibration laboratories Only one such laboratory is known to be operating at this time.

Outside of the calibration laboratories, there is a wide range of accuracy levels for general force measurements. Performance testing of aircraft engines and static weighing of aircraft, railway cars, and batch materials generally require accuracies comparable to the adjustment and maintenance standards for commercial weighing devices, about 1 part in 1000 or 0.1 percent of load. These needs are met very largely through the use of load cells. Load cell weighing scales of moderate capacity are usually calibrated in situ by the conventional means of scale calibration, using known masses, but many of the modern weighing applications require verification of the scale at loads well beyond the range of these techniques. The two NBS railway track scale test cars, for example, are limited to a maximum test load of 100,000 lb each. Modern railway weighing needs, on the other hand, frequently range up to loads as great as 3.3 MN (750,000 lb). A similar situation exists for many other weighing applications. As a result, there is a tendency to construct high capacity scales with load cell weighing elements, often predicated on the concept of calibrating the cells at some distant calibration laboratory before installing them in place.

At the next lower level of accuracy are the large number of measurements made to verify materials testing machines to an accuracy of one percent. The commonly accepted accuracy for verification devices is 0.25 percent of load. Currently, the bulk of these machine verifications are done with proving rings which seem to be preferred because of their ruggedness and long-term stability under adverse conditions.

Materials testing machines themselves represent the next level of accuracy in force measurement. Here the maximum uncertainty is 1 percent of load although some new testing machines are sold with a guarantee of 0.5 percent. The number of laboratories equipped with some form of compression or tension testing machine is very large, and many laboratories will have several such machines in full use throughout a working day. In a large steel mill, for example, five to ten machines may be in use, with tensile specimens being tested as fast as the operators can mount the specimens and remove the broken pieces.

Certain other types of materials or structural testing equipment can be operated at slightly lower levels of accuracy. Frequently portions of structures are tested in a loading frame, i.e., a rigid frame that constrains the external forces exerted on the structure by hydraulic jacks or similar mechanisms. Here the loads are measured with individual load cells or even elastic members equipped with dial indicators coupled in series with the hydraulic jacks. In this type of test there are usually no stated requirements for accuracy and an uncertainty of two to three percent of load is generally considered satisfactory and in line with the other parameters of the test.

A markedly different situation exists with regard to fatigue testing equipment. In fatigue tests as well as other dynamic tests the problem of inertial loading can be of great significance. The instrument used to verify the accuracy of the fatigue testing machine, usually a load cell, is customarily calibrated under static conditions, but is subject to dynamic loading during the verification of a fatigue machine. Because of interactions between machine components, the need to measure forces remote from the specimen under test, and possible changes in instrument performance under dynamic conditions, a dynamic uncertainty of two to three percent of load is about the best that one can be assured of in a fatigue testing machine.

In the field of motion weighing of railway cars, highway vehicles, and belt conveyers for industrial materials, forces are measured with uncertainties which range from one to ten percent. Again the problem is one of dynamic versus static force measurement. The frequencies of force fluctuation are low and probably the measurement made by the force transducer is little biased by the dynamic response of the instrument itself, but the error is due to the dynamic behavior of the scale platform structure and the dynamics of the vehicle being weighed.

At the lowest level of accuracy are the force measurements of such rough industrial quantities as forces between the rolls of a rolling mill, forces applied in forging presses or extrusion operations and other types of impact or non-repetitive loading. In these cases, repeatability of a measurement is more important than its accuracy and an uncertainty of five to ten percent is usually acceptable. Probably the future will require an improvement in this level of accuracy. The task of improving accuracy in all of the dynamic applications includes not only providing more accurate instrumentation, but also understanding the dynamic responses of the total system that is in motion.

2.4 Dissemination and Enforcement Network

2.4.1 Central Standards Authorities

The Force Measurement System has no internal regulatory functions. As a result, there is no absolute central standards authority, other than those required to disseminate the three base units which define force. In a sense, all the deadweight machines such as those at NBS and the Office of Weights and Measures constitute the central authority. The exceptions are the Department of Defense and the recently established Energy Research Development Administration, which require specific traceability to NBS for force measurement devices or material testing machines. The requirement is not for traceability to the deadweight machines, but to NBS. Many contractors provide acceptable traceability through the Department of Defense calibration laboratories or through weight sets calibrated by state and local Offices of Weights and Measures. The case of the ERDA is somewhat better defined. ERDA has inherited a well-established enforcement network which was established by AEC. All standards are traceable to a single set of transducers maintained by a contractor who provides the necessary calibrations to ERDA's suppliers and contractors.

In the most general case, however, the dissemination of force standards takes place through the voluntary recalibration of force transducers, scales, testing machines, etc. Because there is no central authority, dissemination of force standards is initiated at the user level and not from higher levels in the structure (fig. 1). A small study was made of the results of this voluntary enforcement network and this will be discussed later in section 4.2.

2.4.2 State and Local Offices of Weights and Measures

The position which the Office of Weights and Measures has in the Force Measurement System has been cited several times in this document. Their possession of one of the two types of primary standards for forces less than about 10,000 lbf, gives the OWM a co-equal position to those laboratories having the deadweight machine. As such, it is a major link in the dissemination network. The various state Offices of Weights and Measures also perform a regulatory function where retail commodities are sold by weight.

It is through this mechanism that the general public interacts most often with the force measurement system.

2.4.3 Standards Laboratories, Testing Laboratories and their Services

The role of standards and testing laboratories has also been discussed above, and their relationship to other parts of the system can be seen in figure 1.

With the exception of the few laboratories who have a deadweight capability (table 1), the role of the standards laboratories is limited to a back-to-back calibration of force instruments using secondary standards and the calibration of standard weight sets, a role similar to that of the Office of Weights and Measures cited above. In their case, however, their lack of statutory responsibility for equity in retail sales limits their impact with the general public.

Testing laboratories are divided into two sub-categories: industrial research and development laboratories and commercial testing laboratories. These categories are not absolute, as will be shown, but the titles of the two sub-groups are fairly descriptive of their functions.

Research and development laboratories are generally those operated by industrial organizations for product development purposes. In 1967, there were 1437 of these laboratories with a total funding of about $1.1 billion [5]. Research performed by a statistical sample (388) of these laboratories is broken down as follows [6]:

R & D on government contract	- $884 million
Miscellaneous R & D	- 554 million
Commercial testing	- 2.9 million
Other testing	- 51 million
Total	- 993 million

Testing laboratories are those set up and run for profit in the testing services performed. Seldom are they affiliated with a large corporation, but they often test products for such corporations and perform as referees in disputes between corporations. At the time of the 1967 industrial census, there were 1243 testing laboratories with gross revenues of $215 million [5]. Again, a representative sample (551) of these laboratories have revenues broken down as follows [6]:

R & D on government contract	-	$ 5 million
Other R & C	-	3 million
Commercial testing	-	143 million
Other testing	-	5.5 million
Total	-	156 million

As can be seen from figure 1, the DoD and NASA laboratories are almost a self-contained measurement system. This situation has evolved over the years primarily because of the size of the government's needs. It is instructive to trace the path of the measurement system in a government organization, namely the U. S. Navy as an illustration.

The Navy standards laboratory system is nominally headed by the Type 1 Laboratory, represented by the Eastern and Western Standards Laboratories. These labs maintain the U. S. Navy's force standards, in the form of deadweights or transfer standards which have been calibrated at NBS. Load cell kits are calibrated by the Type 1 Laboratories for six Type 2 Laboratories. These secondary standard load cell kits are used by the Type 2 Laboratories to calibrate load cell kits for the 7 shipyards, 15 floating laboratories, 3 missile tenders and 12 Naval Air Stations of the fleet. An estimate of the level of effort involved is provided by the following statistics. A single Type 2 Laboratory calibrates about 1000 force devices per year with a staff of 3 to 4 people. A shipyard lab, one of the direct users of the Type 2 Laboratory services, submits devices to the Type 2 Laboratory to be calibrated. Of these devices, a load cell kit containing 8 cells ranging from 12,000 N (3,000 lbf) to 1,200,000 N (300,000 lbf) is used to calibrate 4 tertiary sets of standards of 8 cells each. The 4 tertiary sets of standards are used to calibrate 50 ring dynamometers, 12 testing machines, 50 spring dynamometers, shipyard crane dynamometers and special test set-ups as required.

As noted above, extensive calibration facilities are maintained by the three military services and NASA. In addition, the NBS manages a testing machine calibration service for laboratories doing concrete and cement testing for the state highway departments. A staff of six are employed to calibrate testing machines used in about 250 state highway departments, concrete producer and contract testing laboratories per year. These calibrations are performed in accordance with ASTM Designation E329.

2.4.4 Regulatory Agencies

The regulatory control which the Department of Defense and the Energy Research Development Administration exercise over the force measurements made by their industrial contractors has been discussed above. These agencies explicitly require traceability to NBS.

The function of a regulatory agency is to prepare and enforce standards, regulations or codes to insure equity in trade and public safety. In the performances of this function several federal agencies are involved in the regulation of force measurements. The role of the Office of Weights and Measures in the regulation of the accuracies of retail scale systems has been discussed. Table 7 shows a list of several agencies involved in the enforcement of occupational and public safety codes which involve force measurement, generally involving the strength and safety of products and structures. In many cases, there exists a strong tie between these codes and the documentary standards discussed in section 2.2.1.2.

Table 7 - Regulatory Agencies Which Write Standards Specifying Force Measurements.

Consumer Product Safety Commission
Federal Aviation Administration
Federal Highway Administration
Federal Railroad Administration
Federal Trade Commission
Food and Drug Administration
Maritime Administration
Mining Enforcement and Safety Administration
National Highway Traffic Safety Administration
U. S. Coast Guard

2.5 Direct Measurements Transactions Matrix

2.5.1 Analysis of Suppliers and Users

The Force Measurement System encompasses the entire goods fraction of the domestic economy to some degree. As can be seen in figure 9, the impacts on manufacturing are much greater than those on trade or services. A more detailed picture of the impact areas can be seen through a breakdown of the Standard Industrial Classification (SIC) groups into the two digit SIC codes (fig. 10). Figures 9 and 10 are a direct result of the early attempts to develop the relationships between the various elements in the system, as shown in figure 1. An outline of the method used to develop these figures is given in the appendix to this report. These figures show that the greatest utilization of force measurements is in the primary metals, metal products, machinery, communication and transportation industries (SIC codes 33, 34, 35, 36, 37). In addition, impacts are felt in the chemical and measurement equipment industries and at government and other testing and research laboratories. Of the industries identified during this survey as users of force measurements, over half were represented in SIC two digit codes 35, 36, and 37. Most force measurements are made as part of quality control procedures.

An understanding of the importance of the measurement to these industries can be gathered from an analysis of the Direct Measurements Transactions Matrix for Force (table 8). Significant correlation of information can be made between the structure of the measurement system, (fig. 1) and the transactions in the system. The principal suppliers of force measurements have a very loose connection to the end user. Similarly, the principal suppliers of commercial goods supply few measurements to the industries outside their own. In most cases, they do not supply force measurements outside their own corporation. The force measurements which are supplied by these groups are generally strength of materials measurements and are required by the purchase contract. Progression left to right and top to bottom across the Input-Output chart is tending toward lower levels of accuracy and less dependency on parallel parts of the measurement system. The matrix shows adequacy and

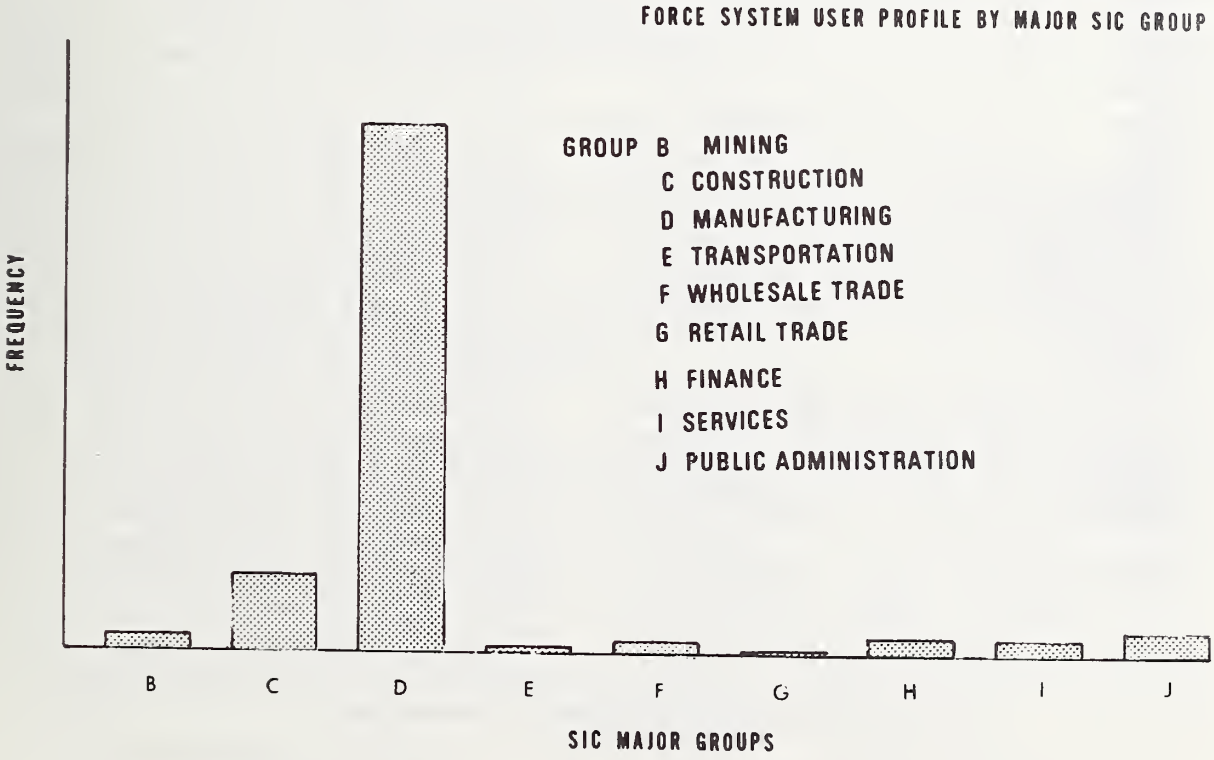

Figure 9 - Impact of force measurements in the standard industrial classification major groups

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR FORCE — USERS / SUPPLIERS	1 PROFESSIONAL SCIENTIFIC & ACADEMIC COMMUNITY	2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	3 DOCUMENTARY SPECIFICATION AND STANDARDS ORG	4 TRANSDUCER MANUFACTURERS	5 TESTING MACHINE MANUFACTURERS	6 SCALE AND WEIGHT MANUFACTURERS	7 NBS	8 STATE OFFICE OF WEIGHTS AND MEASURES	9 STANDARDS LABS	10 GOVERNMENT REGULATORY AGENCIES	11 DEPARTMENT OF DEFENSE (EXCL. STDS. LABS.)	12 OTHER FEDERAL GOVERNMENT	13 CITY, COUNTY, STATE GOVERNMENT	14 INDUSTRIAL TRADE ASSOCIATIONS	15 MINING AND CONSTRUCTION IND.	16 TEXTILE, LUMBER & PLASTICS INDUSTRIES	17 PRIMARY AND FABRICATED METAL PRODUCTS	18 MECHANICAL AND ELECTRICAL MACHINERY	19 TRANSPORTATION EQUIPMENT	20 WHOLESALE TRADE	21 RESEARCH AND DEVELOPMENT LABS	22 MISCELLANEOUS INDUSTRY AND COMMERCE	23 GENERAL PUBLIC
1 PROFESSIONAL SCIENTIFIC & ACADEMIC COMMUNITY	X	X	X	X	X	X	2 3	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	X	4 4	X	?			4 4	4 4	4 3	?													
3 DOCUMENTARY SPECIFICATION AND STANDARDS ORG	X	2 3	2 3 3 2	3 3	3 3 3	X	3 3 2	X	3 3	3 3	2 3	2 3	3 2 3 2	3 4 2	3 4 2	3 3 4 2	3 3 4 2	3 3 4 2	3 3 4 2	3 4 2	1 3 2	3 4 2	4 2 2
4 TRANSDUCER MANUFACTURERS	?		2 3	2 4	2 4	2 4 2	1 3 2	1 2	1 2	2 3	1 3	1 3	1 3	?	?	2 3	2 3	2 3	2 3	2 4 2	1 3	2 3	
5 TESTING MACHINE MANUFACTURERS	?		2 3		?	?	2 3	?		1 1	1 2	1 3	?	?	3 3	2 3	2 3	2 3	2 3	?	2 3	1 2	
6 SCALE AND WEIGHT MANUFACTURERS	X	X	X	2 3	2 3	2 4	X	2 3	X	X	X	X	X	X	3 ? 3 2	2 3	2 3 3 ?	1 1	2 3 3 ?	2 3 4 ?	1 2	2 3	2 3
7 NBS	2 3 2	2 4	2 3 2	3 3	3 3 4 2	4 3 4 2	2 3	4 4	3 3	3 3 3 2	1 4 N	2 4 2	2 3	1 2	2 3	2 3 3 ?	2 3 3 ?	2 3 3 ?	2 3 3 ?	?	2 3 3 ?	2 3	1 1
8 STATE OFFICE OF WEIGHTS AND MEASURES	X	X	X	3 4	3 2	3 3 4		X	4 4	2 3	?	?	3 4	1 2	2 3	1 3 3	1 2	1 3 3	1 3 3	3 4	1 3 3	1 3	1 3
9 STANDARDS LABS	2 3	2 3	2 3 2	2 3	3 4	X	1 2	?	2 3	2 3 2	3 4	3 4	2 2	1 2	3 4	2 3	2 3	2 3	2 3	3 4	2 3	3 4	
10 GOVERNMENT REGULATORY AGENCIES	X	X	3 2 4 2	2 ? 4 ?	2 ? 3 ?	X	2 2 4 2	X	3 2 4 2	?	3 3	3 3	?	3 2 4 2	3 4 2	3 3 2	3 3 2	2 3	3 4 2	3 4 2	1 1	2 3	3 4 2
11 DEPARTMENT OF DEFENSE (EXCL. STDS. LABS.)	2 3 2		2 3 2	3 3	3 3	X	2 4	X	2 3	?	3 4	2 3			2 3	2 3	2 3	2 3	2 3	?	2 4	2 4	
12 OTHER FEDERAL GOVERNMENT	2 3 2	?	2 4 2	3	3	X	2 4	X	2 3	2 4 2	2 3	2 3	2 4			See Documentary Standardization Organizations							
13 CITY, COUNTY, STATE GOVERNMENT	?		?	?	?	X	2 2	X	3 3	?			3 ? 3 ?	3 ? 3 2		See Documentary Standardization Organizations							
14 INDUSTRIAL TRADE ASSOCIATIONS	X		2 2 4 2			X	2 2	X	3 4 2	2 ? 3 2			2 ? 3 2	2 3		See Documentary Standardization Organizations							
15 MINING AND CONSTRUCTION IND. (SIC GROUP B & C)			2 3			X	2 2	X	2 2	2 2	1 ? 1 ?	2 ? 1 ?	?	2 3	2 3				2 3				3 3 2
16 TEXTILE, LUMBER & PLASTICS INDUSTRIES (SIC CODES 23 TO 28)	2 3		2 3			X	1 2	X	2 3	2 2	2 3	2 3	?	2 3	2 3	2 3			2 3	2 3		1 2	2 3 2
17 PRIMARY & FABRICATED METAL PRODUCTS (SIC CODE 33 & 34)	2 3		2 3			X	1 2	X	2 3	2 2	2 3	3 3	?	2 3	2 3		2 3	2 3	2 3	2 2	2 2	2 2	2 3 2
18 MECHANICAL AND ELECTRICAL MACHINERY (SIC CODE 35 & 36)	1 2		2 3			X	2 3	X	2 3	2 2	2 3	2 3	?	2 3	2 3			2 3	2 3	2 2		2 2	2 2
19 TRANSPORTATION EQUIPMENT (SIC GROUP 37)	2 3		2 3			X	2 3	X	2 3	2 2 2	2 3	2 3	2 4	2 3			1 1	1 2	2 3	2 3	2 2	1 2	2 2
20 WHOLESALE TRADE (SIC GROUP F)			?			X		X												X			
21 RESEARCH AND DEVELOPMENT LABS (SIC CODE 7391)	2 3 2		2 3	2 3	2 2	X	2 3	X	2 2	2 3	2 3 2	2 3	?	1	1 2	2 3 2	3 3	2 2	2 3		1 3	2 2	
22 MISCELLANEOUS INDUSTRY AND COMMERCE	?		2 3			2 3 2	1 1	X	2 1	2 2	2 3	2 3	2 3	2 3	1	?	?	2 2	2 2	2 2		2 2	2 2
23 GENERAL PUBLIC	2 1		3 1 2			X	1 1																2 3

Table 8 - Direct Measurements Transactions Matrix for Force

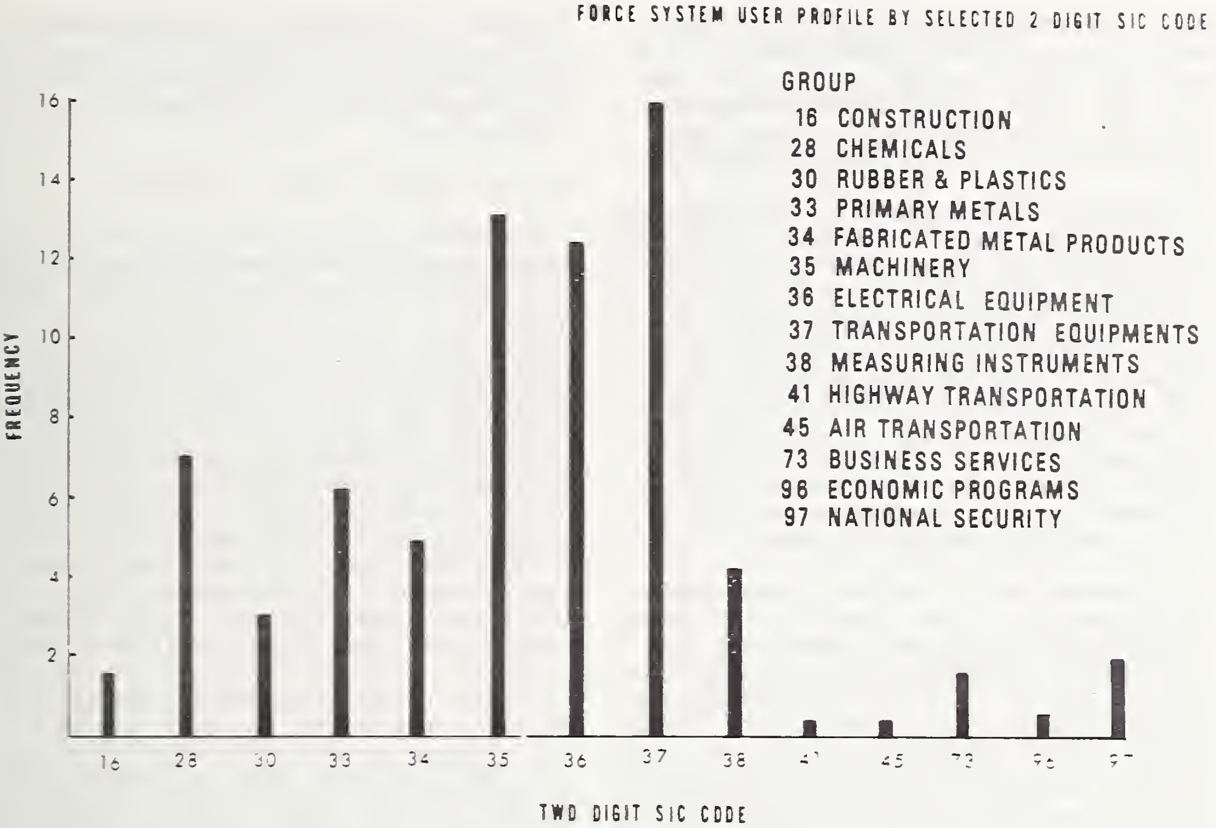

Figure 10 - Impact of force measurements in the standard industrial classification 2 digit codes

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stability. The basic relationships among the parts of the system are well established, are generally not changing or growing, and in the area of static force measurement are adequate from the users point of view. The only change in the system which appears here is the type of measurement being made. Current growth is in the measurement of dynamic properties of materials. In many cases, although static force measurements are completely adequate, an increasing number of materials and goods are now being tested and used under dynamic conditions. The test methods needed to test these materials, the standards against which the dynamic forces can be verified and in many cases, the basic understanding of the motions of the dynamic systems themselves are not available. These inadequacies show up heavily, for example, in the Documentary Standards and NBS portions of the matrix.

2.5.2 Highlights of Major Users

The force measurement industry, an outgrowth of the need to measure large weights and the properties of materials, has direct measurable sales of less than $70 million per year. This includes the direct costs of transducers ($40 million) and the fees collected for calibration of standards to be used for verification of production line testing machines.

Several of the major uses of force measurements have been discussed in earlier sections of this report. These include the impact of the testing machine industry, government and industrial R and D laboratories and commerical testing laboratories.

In addition to these direct measurements of force, other areas of measurement such as liquid and cryogenic gas flow rate, flow totalizer calibration, wind tunnel balance, and the measurement of electric current are derived from force measurement. These areas will not be discussed here.

2.5.2.1 Primary Metals Production

The objective of this section is not to describe the size of the total primary metals industry ($44.5 billion) [7], nor to detail the use of force measurements in the industry. It is, rather, to give some feel as to the number of measurements made and to provide a typical example of the traceability of force in an important industry.

Of the total primary metals industry, steel is the single largest fraction. In 1973, steel production in this country was about 136 million tons, valued at $22.3 billion. Each of the almost 100 companies producing steel perform tests for strength and ductility of the product as part of quality control. In 1973 about 3.8 million such measurements were made, just by the primary steel manufacturers. Several million additional tests are performed each year by finished product producers such as automobile and appliance manufacturers.

One manufacturing plant of a major aluminum company sends 7 load cells to NBS for recalibration every 2 years. These are used to calibrate 100 materials testing machines for compliance with ASTM E 4 specifications. These testing machines are used in the corporate quality assurance program to insure accurate measurements of mechanical properties. In addition, the testing machines are used to calibrate other force devices such as dynamometers used in fatigue machines and load cells for use in cranes used for material handling. Load cells used in the rolling mill to control plate thickness are calibrated directly against the laboratory standard. Uncertainties not exceeding 0.25 percent are required for calibrating testing machines; 5 percent can be tolerated in rolling mills. A staff of 3 people is employed at each of the seven corporation plants making such calibrations.

2.5.2.2 Torque

A complete, almost self-contained sub-system of the Force Measurement System which is concerned with torque measurement has been identified. This part of the system is only indirectly served by the remainder of the measurement system through the transducer manufacturers and the Office of Weights and Measures. The greatest percentage of measurements are made with torque wrenches. Most machinery manufacturers specify torque levels for the fasteners which join parts together. Applications range from spark plug installation in automobiles to chemical reactor vessel seals, steam generators, etc. Specified torque levels for these fasteners span a range of at least a million to one.

Primary torque standards use the application of known forces to a lever arm of a precisely measured length. The forces are traceable to primary standards through the paths mentioned above. Typical accuracies for primary torque standards range from 0.25 to 1 percent. Accuracies of torque measurements range up to 10 percent for fasteners tightened with impact wrench equipment.

Table 9 - Torque Instrument Manufacturers

Acurex Corp.
  Mountain View, Cal. 94042
Ametek, Inc.
  East Moline, Ill. 61244
BLH Electronics, Inc.
  Waltham, Mass. 02154
Camis Corp.
  Meadowbrook, Pa. 19046
Carlson Co.
  Oceanside, N.Y. 11572
John Chatillon & Son
  Kew Gardens, N.Y. 11415
Daytronic Corp.
  Dayton, Ohio 45429
W. C. Dillon & Co., Inc.
  Van Nuys, Cal. 91407
Dynamic Precision Controls Corp.
  S. Windsor, Conn. 06074
Falk Corp.
  Milwaukee, Wisc. 53201
General Thermodynamic Corp.
  Wilmington, Mass. 01887
Gentran, Inc.
  Santa Clara, Cal. 95051
S. Himmelstein & Co.
  Elk Grove Village, Ill. 60007
Howell Instruments
  Fort Worth, Tex. 76107
Kahn Industries, Inc.
  Wethersfield, Conn. 06109
Kavlico Electronics, Inc.
  Chatsworth, Cal. 91311
Lebow Associates, Inc.
  Troy, Mich. 48084
Link Engineering
  Detroit, Mich. 48227
McFauden Electronics Co.
  South Gate, Cal. 90280
McNab, Inc.
  New York, N.Y. 10012
Meridian Laboratory, Inc.
  Middleton, Wisc. 53362
Moxon, Inc.
  Irvine, Cal. 92664
Owatonna Tool Co.
  Owatonna, Minn. 55060
Power Instru., Inc.
  Skokie, Ill. 60076
Sensotec, Inc.
  Columbus, Ohio 43212
Snap-on Tools Corp.
  Kenosha, Wisc. 53140
Sturtevant/Richmont-Dresser
  Industries, Inc.
  Newtown, Conn. 06470
Sunshine Scientific Instru.
  Philadelphia, Pa. 19115
B. K. Sweeney Mfg., Co.
  Denver, Col. 80216
Transducers, Inc.
  Whittier, Cal. 90606
Tyco Instruments
  Waltham, Mass. 02154
Utica Tool Co., Inc.
  Orangeburg, S.C. 29115
Vibrac Corp.
  Chelmsford, Mass. 01824
Waters Manufacturing, Inc.
  Wayland, Mass. 01778
West Coast Research Corp.
  Los Angeles, Cal. 90025

An approximate value for torque instrument sales and calibration is not presently available. As shown in Table 9, torque measuring equipment is supplied by about 35 manufacturers.

2.5.2.3 Airfreight Industry

This final study report is introduced to show the dependence of a fairly compact industry on load cell weighing systems.

When an eastern United States camera maker recently needed to increase stocks of a new camera on the West Coast rapidly, he flew 70,000 cameras on Saturday for Monday delivery. This is typical of the use of air freight. This year such use will result in freight revenues of about $1 billion. More than 5.5 billion ton-miles of freight, mail and express packages will be air freighted on domestic airlines this year. An additional 2 billion pounds of goods worth $12 billion will be shipped in the international import-export trade. This industry is growing by 20 percent per year.

Load cell weighing systems are used at many different levels in this industry. Of primary importance, the aircraft are weighed and the maximum weight capacity and center of gravity of the aircraft are determined. These are important to the pilot for control purposes and determining the range of the aircraft. Of less critical importance is determining the weight of the cargo being loaded to aid in planning the proper location in the aircraft. The cargo is first weighed by the air freight shipper, containerized for easier handling, and consigned to an aircraft. Cargo containers are then distributed in the aircraft according to the aircraft's predetermined plan for load distribution. 23,000 kg (50,000 lb) of containerized cargo, in addition to almost 400 passengers and baggage, can be loaded into a single jumbo jet.

2.5.2.4 General Public

As in most measurements, the ultimate beneficiary of force measurements is the general public. Most of the time, the measurements have occurred many times during an item's manufacture and the public is totally unaware of their existence. In some cases, however, the public makes the final measurement. The most common example of this occurs at the supermarket produce counter where apples or tomatoes are purchased by the pound and at home when the overweight dieter checks his weight on the bathroom scale.

3. IMPACT, STATUS AND TRENDS OF THE MEASUREMENT SYSTEM

3.1 Impact of Measurements

3.1.1 Economic Impact

In considering the economic impact of force measurements, it should be noted that the purpose of such measurements is generally either to determine the strength of a load carrying element or to weigh the amount of material in a commercial transaction. From these considerations we see that the principal economic impact could be classified as "equity in trade," with the measurements either entering directly into the transaction e.g. weighing operations, or more indirectly as in the quality control checks on a production process. In either case, the measurement is made to assure both parties that a product is delivered in accordance with a contractual agreement, explicit or implied. In many cases, these contractual agreements refer, directly or by implication, to one or more voluntary standards. A comprehensive study of the economic impact would therefore include the use of such standards and also the processes and organizations that are involved in their development. However, here it will suffice to note that such standards contribute heavily by providing widely accepted procedures for testing the product without the buyer and seller having to devise and agree upon test methods, which could frequently be an expensive and time-consuming effort. Although the diversity of use of these voluntary standards makes it difficult to assign a dollar value to their benefits, we noted above that over 40 organizations producing voluntary, consensus standards involving some form of force measurement operate within the United States with support from industry and general interest groups.

There is a second impact which force is only beginning to have on the economy. There has recently been a rapid growth in the number and scope of federal and state mandatory regulations on the strength and durability of consumer products. Such regulations are the result of government's decision to protect the people from certain specific hazards for the public good without the direct consent of those to be protected. Clearly the costs for testing required by the regulations are added to the price of the item, and the incremental cost is felt directly by the final consumer. As an example, let us look at the testing of eyeglass lenses. Federal regulations require that every eyeglass lens be proof tested before being used. The lens is mounted on a fixture and a steel ball weighing 16 g (0.04 lb) is dropped on the lens center from a height of 127 cm (50 in). The lens, of course, must not crack. The manufacturers estimate that this test cost them $1.00 per lens and this cost is passed directly on to the consumer. Americans buy about 200 million pairs of glasses and sunglasses each year [9], so the add on cost for this testing is about $400 million. Clearly in such cases, government must weigh the increased economic costs against the expected social benefits.

3.1.2 Technological Impact

Improved test methods and instrumentation results in better material utilization, better made products and improved product safety. Thus force measurements are a means to an end. The goals of advancing technologies are to produce better products at lower cost. Making better measurements and measuring quantities which have never required measurement before are vital to this effort. This does not result in dramatic breakthroughs in force measurement, but rather in a steady advance of the total testing techniques which results in improved test results.

3.1.3 Social Impact

The social impact of the Force Measurement System is felt largely in the area of increased safety. The system promotes safety through enforcement of engineering standards and better, more accurate measurements. These have been discussed before. The social implications of mandatory safety requirements, while real enough, are hard to assess in their present early stage of development. In the future, an increasing number of commonly used items may come under the control of a safety related regulatory body. Some of these have been cited above: tires, car door beams, bumpers, bicycles, glass doors, toys, etc.

3.2 Status and Trends of the System

Our assessment of the National Force Measurement System is that some parts of it are stable and adequately maintained while other parts scarcely exist. Static force measurement, the historical area of major effort, over the range from 0.5 N (0.1 lbf) to 5×10^7 N (10^7 lbf), is fully adequate with the level of accuracy now provided, and will remain so for the foreseeable future. There does not appear to be any requirement to improve the static force standards in this range by the factor of 2 presently possible with an air density correction when devices are calibrated.

However, in the areas of dynamic measurement of force, measurement of very small forces, and measurement of torque, the system is not in good shape.

The measurement system for dynamic force does not exist. The standards and test methods that are needed to assure the accuracy of measurements and safety, reliability and efficiency of load carrying systems are not available. This lack of standards is a deficiency which gives every appearance of becoming a major concern. The American Society for Testing and Materials in its recently published, "Standard Method for Verification of Fatigue Machines" (ASTM Designation E 467) states that current methods of measuring dynamic forces make untested assumptions about the cyclic behavior of materials under dynamic conditions. Virtually every industry surveyed had some interest in being able to improve the ability to make dynamic measurements. The metals industry needs to be able to characterize materials better for resistance to crack propagation, forming, and improvement of extrusion and rolling mill procedures. The ability to measure the high speed effects will become economically important as plant speeds increase in the attempt to increase productivity. Motion weighing is already speed limited. Several important structural factors including the dynamic response of the weighing cells are unknown. Railroad operations, track and aircraft weighing operations and batch process operations are all limited by the available equipment. Other examples of dynamic force measurements which have unknown uncertainties due to being made without knowledge of the dynamic behavior of the force device include:

(1) Impact Forces
- (a) Barrier crash tests of automobiles
- (b) Tests of automobile seat belts
- (c) Biomechanical failure studies of human bone under impact

(2) Miscellaneous High Speed Transient Forces
- (a) Dynamic penetration of tires
- (b) Rocket and jet engine thrust measurements
- (c) Weapons testing
- (d) Skid resistance of highway pavement

(3) Cyclic Forces
- (a) Fatigue testing of all types
- (b) Mechanical impedance measurements

The measurement of very small static and dynamic forces has also been identified as an area in which work is needed. This measurement directly impacts the biomedical field where a means is needed to measure the pulling strength of a single muscle fiber. It also impacts the acoustic measurement field which has need of a way to map the output of ultrasonic transducers. If forces of 5×10^{-8} Newtons (10^{-8} lbf) could be accurately measured a method would then be available to provide an absolute calibration of the radiated power of the transducer at every point in the transmitted field. This would improve quality control of the transducers when they are manufactured and of the measurements made with these systems. The problem of calibration of ultrasonic transducers is one of current urgency and considerable effort is being spent on development of an "interim" technique.

All the aspects of information transfer and preparation for metrication need strengthening. The information transfer sector of the measurement system is quite cumbersome. As was noted above, this results from the diversity of the groups performing force measurements. The system is now only beginning to establish the lines of information return from the end user to the source of the first measurement in the calibration chain. In conjunction with the adoption of the new ASTM Standard for Calibration of Force Measuring Devices, E74-74, about 30 government and corporate metrology laboratories are cooperating in a round-robin calibration program. This is being done to assess the new standard in field use, to improve communication among the parts of the measurement system and to evaluate the magnitudes of the random and systematic errors which result when force standards are transferred to field measurements. NBS has agreed to provide the instrumentation packages and perform the statistical evaluation of the data for the round-robin group. It is hoped that variations in the data resulting from nonuniformity of test procedure and nonuniform methods of data presentation can be controlled. A workshop session to discuss problems encountered in trying to implement the new calibration method E74-74 has been held and 34 government and corporate laboratories participated. This workshop preceded adoption by NBS of E74-74 as its usual method of standards calibration.

Any discussion of trends in the measurement system must include the conversion from U. S. Customary Units of Measurement to the SI System of Measurement. For the force measurement system, the problems range from confusion over which unit will finally be adopted for customary usage to how to overcome the problem of long term depreciation of capital equipment.

The SI unit of force is the newton. However, many European countries are using the kilogram-force (kgf) as the force unit in much the same way as the pound-force unit is used instead of the Poundal in the U. S. Customary System. This has, and will continue to confuse engineers in this country. The present trend in the U. S. is to use the newton, despite the references in the literature to European use of kilograms-force. This confusion is added to the problems of education of engineers and technicians cited in the U. S. Metric Study [10]. Engineering education at the university level will tend to follow the increased usage of the SI system. If the common practice is to change, the education must start at the first levels of formal education. It has been estimated that 10 to 20 years might be required for the change.

We have also noted that most force measurement and producing equipment currently existing in the U.S. is graduated in U.S. customary units. This equipment is long lived and its continued use may delay the conversion to SI units.

As a result of these two reinforcing trends, the newton may be one of the last SI units in common usage. Even then, confusion may continue if the problem of newton versus kilogram-force is not resolved.

4. SURVEY OF NBS SERVICES

4.1 The Past

As was discussed in Section 2 above, the history of force measurement in the United States is closely linked to the history of NBS. The development of high-grade instruments for the accurate measurement of large forces began shortly after the end of World War I with the invention of the Whittemore-Petrenko proving ring [1, 11]. The proving ring, because of its accuracy, constancy and convenience, was further developed commercially and is now the most widely used device for the calibration of testing machines. About 4400 of these devices are now in service in commercial and government laboratories.

After the development of a proving ring design suitable for the calibration of testing machine, it became appropriate for the NBS to provide means for applying the precisely known forces to these rings to determine their performance characteristics. A deadweight machine was accordingly designed and placed into service in 1928. The Bureau has continued to provide deadweight calibration services and has extended the deadweight accuracy and capability to cover the range of 50 to 5 x 10^7 newtons (10 to 10^6 lbf) with uncertainties of less than 20 ppm (fig. 11).

In the early 1940's the idea of measuring forces by measuring the elastic deformation of a steel column under load with the newly developed resistance strain gages occurred to several experimenters at about the same time [12, 13]. Soon, force measurement devices capable of measuring forces up to 13 million newtons (3 million pounds) became available. Although basic load cell design has changed little since the 1940's, improved strain gages, gaging techniques and refinements in mechanical design have provided improved transducers. In 1971, an NBS analytical study of load cell design provided load cells with improved response for secondary standards for force calibration [14]. A set of 4.5 MN (1 million lbf) and 13.3 MN (3 million lbf) standards was fabricated and is now in service at NBS.

Although the growth of the system seemed fairly orderly with the design and installation of the first 493,750 N (111,000 lbf) deadweight machine at NBS, forecasts of expected needs made by NBS, other Government Agencies and a load cell manufacturer in the mid 1950's predicted an urgent need for much larger capacity, high precision, for measuring devices. It was expected that these would be a primary requirement in the development of an ICBM missile system. Accordingly new deadweight machines to be used to calibrate these devices were designed and installed at the new NBS site in Gaithersburg, Maryland. Additional state-of-the-art and economic studies were made in 1967 and 1971. Both of these studies were conducted for internal use only and the results were never published. These studies indicated that, because of technical developments in other fields during the planning and construction of the new deadweight facilities at

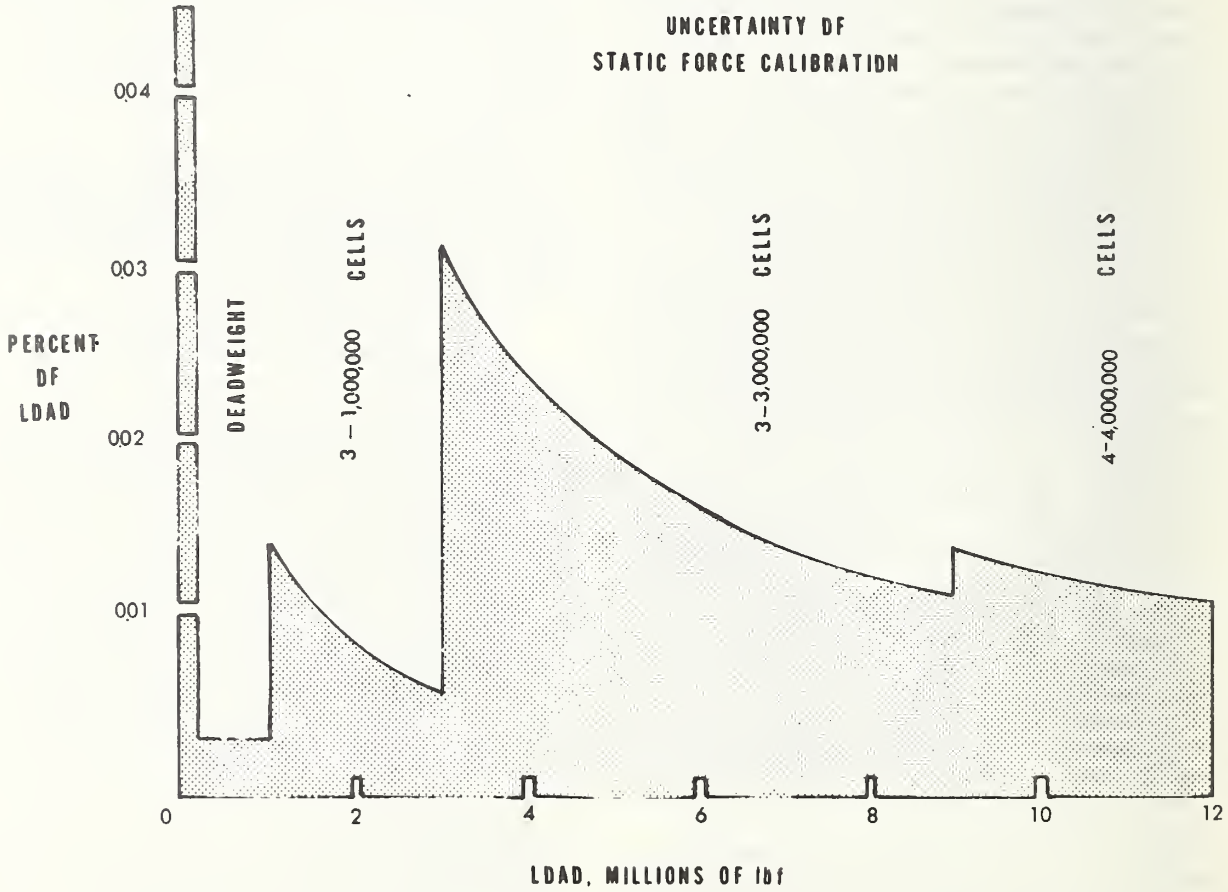

Figure 11 - Uncertainty of static force calibrations

Gaithersburg, the need was not nearly as large as had been predicted. The demand for force calibrations by NBS rose until it reached a peak of about 1000 devices per year in the early 1960's. It has since fallen to a current level of about 400 devices per year (fig. 12). This decline began at the time when deadweight machines were placed into service at DoD and NASA laboratories and by several transducer manufacturers.

4.2 The Present

4.2.1 Description of NBS Services for Force

NBS, because of its diverse program, affects, in some way, almost every sector of the measurement system. The NBS program, in addition to providing primary force calibrations to any client upon request includes the development of test methods for measurement of the physical properties of structures, metals, building materials, fabrics, glass, rubber, and many other materials. Tests performed on these materials attempt to establish their physical behavior under various environmental conditions. Materials are tested in hostile environments which include high vacuum and intense nuclear radiation. Test temperatures range from the near absolute zero of liquid helium to several thousand degrees. Much of this testing is related to the national problems of energy conservation and consumer safety. Only the research areas which relate to the force calibration and dissemination services of the National Bureau of Standards are within the scope of this study.

The services which NBS provides to the system are of three basic types. These are 1) maintenance and dissemination of force standards, 2) participation in voluntary standards activities, and 3) development of measurement methods and instruments.

Another way in which NBS interacts with the measurement system is through its development of innovative instrumentation. As was noted above, in 1971 a new set of transfer standards was designed for use at NBS to take advantage of the new force capabilities available with the installation

Figure 12 - Histogram of force calibrations at NBS

of the 54 MN (12 million lbf) testing machine. This new design was accomplished through the use of a finite element analysis of the response of the load cell body to the applied forces. The new design resulted in a transfer standard with improved and more uniform response characteristics. Currently, a new transducer for the measurement of dynamic loads is under development at NBS [15]. In this development, a fluorocarbon plastic film is mechanically loaded to straighten and polarize the polymer chains. When load is applied normal to the surface of the polarized film, a piezoelectric effect occurs and the output voltage is proportional to the dynamic load applied. This instrument is currently in use in several medical and defense related applications such as measuring the forces introduced into anthropomorphic dummies by seatbelt restraint systems used in automobiles and aircraft.

4.2.2 Users of NBS Services - Input - Output Analysis

The Engineering Mechanics Section, Mechanics Division, is responsible for maintaining the national standards of force, for providing a calibration service by which transfer force standards can be compared to the national standards, and for providing leadership in government and industry in the advancement of the science of force measurement. An analysis of the input-output flow chart (fig. 13) shows the influences which affect the directions of research and calibrations, and the directions in which the current output of the Section are directed.

4.2.2.1 Input

Inputs into the system are largely of three types. The single most important input is the use of the base units of length, mass and time which establish the force standards. Very careful mass measurements together with the best available value for g were used to produce a force standard with uncertainties of less than 0.002 percent.

The two secondary inputs are in the form of direct requests for calibration services and sponsorship of R and D in the areas of interest which coincide with the NBS mission. All of the types of organizations shown contribute to these inputs to some degree. However, most of the R and D support is funded by Congress or by other government agencies. Interaction with industry groups and standards organizations primarily takes place through calibration services.

4.2.2.2 Output

The output of the Engineering Mechanics Section is divided into three major parts: R & D publications, Standards and Test Methods, and Calibration Services.

R and D publications are the result of research supported by direct appropriation or supported by other government agencies. Research constitutes a major percentage of the total Section effort. Publications take the form of papers in archival journals, Technical Notes, and Technical Reports to the sponsoring government agencies.

The writing of standards and Test Methods results from the voluntary participation of 75 percent of the professional staff in organizations such as ASTM, ASME, etc. Staff members often perform a major percentage of the development of such documents.

The staff is occasionally requested by Government sponsors to write test methods or procurement specifications for items where research has shown that a new test method would be beneficial to the government.

Very often, the contact of the Section with the measurement system is through the calibration services. Devices are submitted for calibration by academic, industrial and government organizations. The direct calibration of force devices constitutes about 15 percent of the section's effort. About 400 force devices per year are calibrated using the deadweight force standards maintained in the section.

The numbers on the branches of the Output Section of figure 13 show the portion of the Section's effort in force measurement that is expended for the direct benefit of the organizations represented by the branch. This may not correlate well with the total benefit from such an activity. For example, the one percent effort that goes toward participation in voluntary standards organizations may have widely distributed benefits of significant magnitude to the users of these standards. Users of the standards are represented on other branches of this chart and the benefit to them is indicated there.

The percentage of direct benefit as shown on figure 13 should be compared with the percentage of calibration services provided as shown in figure 14. It is interesting to note the similarity between the two charts. Even though calibration constitutes only about 15 percent of the Section's output, it is distributed in about the same manner as

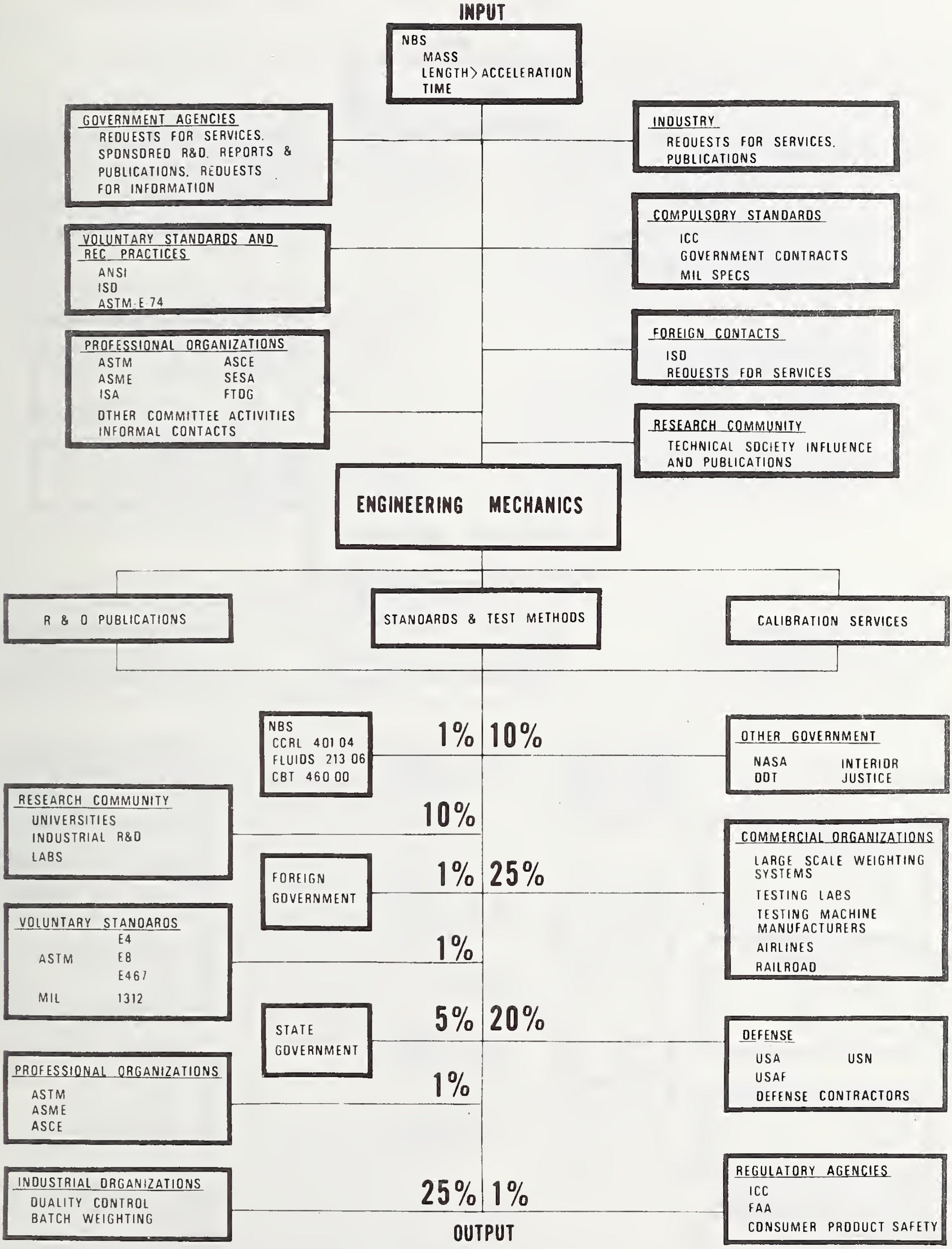

Figure 13 - Input-output flow chart showing distribution of section effort

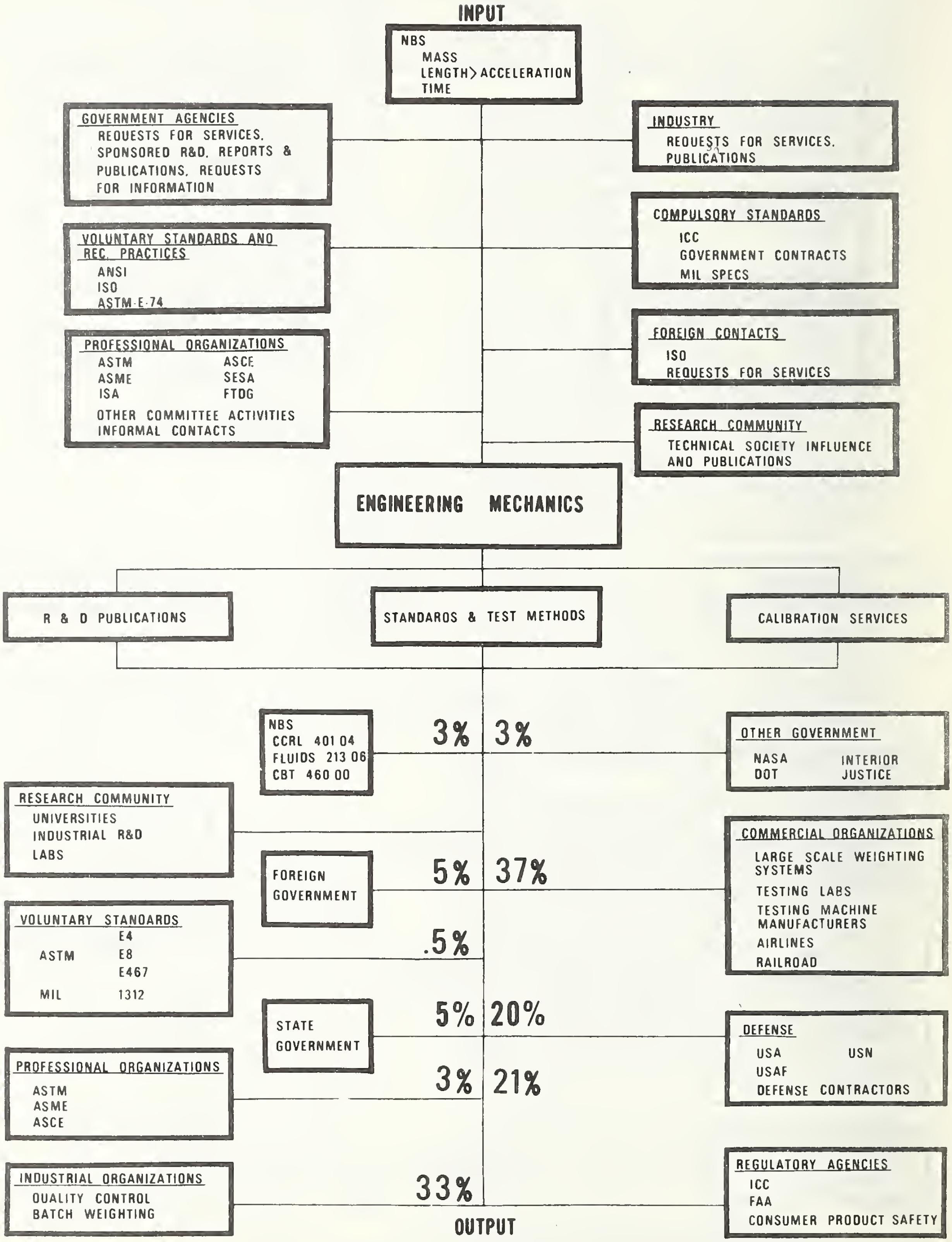

Figure 14 - Input-output flow chart for force calibration services

the total section benefit output is distributed.

4.2.2.3 Recalibration Rate Profile

A study of the recalibration histories of a statistical sample of all transducers which have been calibrated against the NBS deadweight force standards was made. The file of calibration records was sampled at random for each of the two principal types of transfer standard. The sampling procedure was as follows:

1) The calibration record for a single device was selected at random from the file. (The file for proving rings contains about 3500 entrees. The file for load cells contains about 2300 entrees.)

2) If the interval since the last calibration exceeded 5 years, the information was recorded but was not included in the computation of the recalibration interval.

3) If the interval since the last calibration was less than 5 years, the last two calibration intervals were averaged and recorded.

4) No device was included which had not been calibrated three times.

The study revealed that approximately 30 percent of proving rings and 40 percent of load cells do not have a recent NBS calibration, i.e., have not been calibrated within the last 5 years. Of the devices on which the calibration is current, figure 15, over half of the proving rings and almost 80 percent of the load cells have been calibrated within the interval recommended by ASTM E 74-74 (2 years). Approximately half of the current NBS clientele submit devices annually for calibration. Many of these clients submit multiple sets of rings or cells on a rotating basis such that the interval on each ring reflects the results presented above.

4.2.3 Alternate Sources

The alternate sources for the primary calibration of static force standards have been discussed earlier in this report (table 1). No alternative source exists for the 4.5 million newton (1 million lbf) deadweight standard at NBS. With one exception, force standards available elsewhere are limited to about 450,000 N (100,000 lbf) and only a few of these exist. Force standards below 100,000 N (20,000 lbf) are more generally available.

As was noted above, the availability of deadweight force standards increased greatly in the early 1960's with the growth in military and space rocket research. These machines were installed where a quick-turnaround of force calibration was necessary for completion of a mission. It is important to note that almost no new facilities have been built since that time. The cost of such an installation today might well preclude any such new development in the foreseeable future. As a result, the existing facilities constitute a natural monopoly.

As noted in section 2.2, most force standards used at the working level are calibrated using a back-to-back technique against a set of standards which have been previously calibrated with a primary standard. NBS has encouraged this type of calibration chain. It provides accuracies at a level needed by

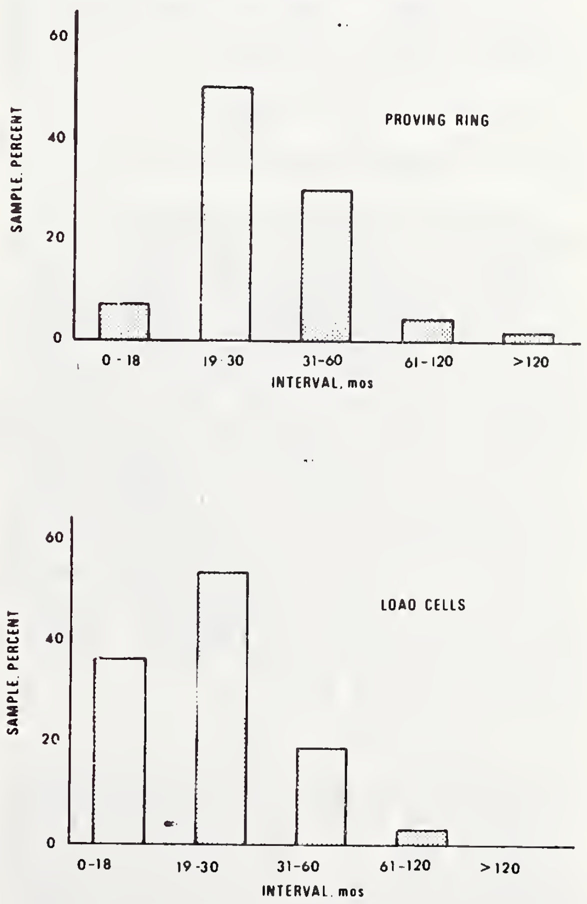

Figure 15 - Recalibration interval for force transducers at NBS

the users at a price which is reasonable, and keeps the workload on the primary standards at a manageable level.

In the field of dynamic force measurement, no standards exist at NBS or at any alternate source. The impact of this will be discussed in a later section.

4.2.4 Funding Sources for NBS Services

As was discussed earlier in this section, about 15 percent of NBS direct force measurement output is force calibrations for customers. These are paid for on a reimbursable fee basis. The remaining budget is supported by direct appropriation (about 35 percent) and other agency contract (about 50 percent). The only constraints associated with the funding are those imposed by restrictions in the NBS organic act and the functional statements of NBS and IBS.

4.2.5 Mechanism for Supplying Services

These mechanisms have all been discussed earlier in section 4.2.2.

4.3 Impact of NBS Services

4.3.1. Economic Impact

The users of force measurements in the measurement system have been identified in sections 2.4 and 2.5 of this report. Although, as can be seen from figure 1, NBS is not unique as a source of accurate primary force standards, support for all segments of the force measurement system is ultimately traced to NBS, much of it through the NBS force standards and some more directly through the basic units of mass, length and time. Therefore, it is important to note the general economic impact of force measurements as discussed above in section 3 and to realize that the greatest impact of NBS is not directly on the economics, but on the technology of the measurement system through the development of better measurement methods and tools.

4.3.2 Technological Impact

The technological impact of NBS services results from all the measurement services provided other than the direct calibration services (fig. 13). The historical role NBS has played and continues to have primarily through the development of force measuring instrumentation, voluntary participation in standards writing committees, and cooperation with government laboratories in the promotion of better measurement techniques has been mentioned above. In recent years, this latter area of participation has expanded to include influence in the preparation of mandatory standards by several federal regulatory agencies. Examples of recent work where the NBS effort has been to encourage or develop new test techniques include: 1) conducting tests in support of new voluntary standards for the testing of gypsum wall board for home construction; (2) developing standardized tests for pultruded plastic products; (3) developing testing techniques in support of new mandatory standards for architectural glass, bicycles, and lawnmowers; and (4) developing testing techniques in support of new government specifications such as those for threaded fasteners, airport runway marker lights, and automobile ignition locks. Typically our greatest impact has been on the technologies which require new tests or measurement techniques where experience has shown that strength or force measurements are now needed.

4.3.3 Pay-Off from Changes in NBS Services

As was noted briefly above, NBS has recently changed its calibration procedure to conform to ASTM Method E74. As a result, the same procedures are now used at NBS for the calibration of all forms of force measurement devices. This is a radical departure from the methods used historically where each type of device was calibrated differently, often using procedures defined by the customer. Many of these procedures were not representative of the manner in which the device was used in service and, as a result, were capable of masking errors which were inherent in the instrument design. The new procedures search out many of these systematic errors and are able to detect deterioration in performance which may occur as a result of normal use. In this way, at almost no increase in cost to the user, marked improvements in measurement accuracies were achieved at the user level. The benefits of these are directly traceable to the economic impact of force measurements on the economy. NBS, through its recognized leadership role in the field, is encouraging the other measurement laboratories to adopt the new procedure with the hope of establishing a nationwide uniform procedure.

The adverse consequences of the adoption of these procedures will be felt by those organizations who use secondary standards in the field to calibrate testing machines, loading frames, etc. These companies and labs will almost certainly be forced to use more devices to verify the total range of the testing machines being calibrated. Certainly there will be a small increase in the cost of the service from these companies, but this is outweighed by the benefits of the improved measurement accuracy.

NBS's role in establishing, changing, and improving calibration standards and measurement procedures is derived from the role of NBS and its statutory responsibility. It would be difficult to find another organization without a vested interest in force measurement to which this role could be entrusted.

4.4 Evaluation of NBS Program

NBS has, and disseminates to anyone who needs them, the most complete set of deadweight force standards in the world. These standards are closely coupled to a well-equipped laboratory staffed by diversified people interested in development of test methods for mechanical properties of materials and structures. The role of NBS is widely accepted by the technological and commercial community as the authority in force measurement. Through this role NBS provides the necessary stability to the static force measurement system. As a result, the needs of this historically important area appear to be adequately served and will probably remain so in the future.

As noted several times already, the weaknesses in the measurement system, and therefore, in the NBS program are in the areas of standards and procedures for the measurement of dynamic force and very small forces, in preparation for metrication, and improvement of communication between the various segments of the force measurement system. The plans in these areas will be discussed next, but it is important to note here that NBS, because of its historic leadership in the measurement field, must take the lead again in these areas.

4.5 The Future

The anticipated needs of the measurement system have been discussed at length in earlier sections of this report, and reasons for NBS involvement have been presented. These needs include: maintenance of existing static force standards along historic lines, establishment of dynamic force standards, basic research into techniques for measurement of very small forces, and improved communication and uniformity throughout the measurement system.

Because of its size and importance, the program for establishment of dynamic force standards has been subdivided into four parts and a standards and test method program has been outlined in each of these areas. The program has been divided as follows:

- closed frame testing such as in measuring the fatigue properties of materials.

- motion weighing such as on railroad track scales.

- forces in flexible couplings such as cables.

- open testing such as impact in automobile bumper testing.

Recently, the program for studying motion weighing was presented to a meeting of the National Scale Men's Association. The economic benefits of such a set of standards and test methods were immediately appreciated by the group and their cooperation was enlisted for the program. Similar economic benefits are expected from other phases of the program. In fatigue testing, for example, lower costs of testing, improved measurements and better material utilization are among the anticipated benefits.

Since the formal assessment of the trends in the National Force Measurement System began, the potential benefits of a switch in calibration procedures was appreciated and the change to E74 was made. In addition a workshop has been held and a round-robin calibration of transducers has been initiated to promote the use of E74. Current response to the workshop and round-robin has been favorable and some thought is being given to the development of a training workshop for calibration technicians. Several laboratories have indicated that this would be a useful education tool. Even at this early stage of the round-robin calibration program, significant differences in indicated load were observed from at least two participants when the calibration data were compared with data taken at NBS both before and after the devices were sent to their laboratories. It is expected that several such discrepancies in measurement will be observed during this set of round-robin tests. In each case, efforts to determine the reason for them will be made. In the future, the program may be expanded in depth, to include the secondary and tertiary levels of calibration.

5. SUMMARY AND CONCLUSIONS

The static force measurement system is stable in size. The accuracies presently available appear to be adequate for the foreseeable future. There does not appear to be any requirement to improve the accuracy of static force standards by the factor of two possible by correcting for the actual air density.

The measurement system is only beginning to include the positive feedback of information from the users of the measurement to the suppliers. A round-robin calibration of force standards is underway among about 30 government and corporate metrology laboratories. This will encourage the communication needed in the system and will allow an evaluation of the magnitude of the random and systematic errors which exist in transferring force standards to field measurements. This study will continue into 1977.

Through its basically contractual nature, the force measurement system impacts a major fraction of the technological, economic and social sectors of our society. An analysis, via the SIC codes of the users of calibration services, shows the greatest impact in the manufacturing and transportation industries. Secondary level impact can be shown in textiles and chemicals. Examples of this impact have been cited.

The measurement system for dynamic force does not have the standards and methods that are needed to assure the accuracy of measurements and the safety, reliability, and efficiency of load carrying systems. Uncertainties introduced by the rapid application of forces have large economic and safety ramifications where they affect such diverse things as eyeglass lenses, seat belt restraint systems, crane overload indicators and in-transit weighing systems. A few of these problems are under study but more research on the overall effects is needed.

Torque has been identified as an element of the force measurement system which is probably inadequately served. Traceability of the measurements back to the basic standards of force and length is tenuous at best. In some cases the path is not presently visible.

The measurement of very small static and dynamic forces has also been identified as an area in which research is needed. The technologies which require this measurement capability are growing rapidly. The greatest future impact might be felt in biomedical research and in nondestructive testing of manufactured parts.

The National Bureau of Standards, through its calibration of force standards, has a significant impact on a substantial fraction of the force measurement system. Through the combination of its calibration and research programs, NBS's impact is widespread and deep. Almost every material used in the manufacturing, construction, and transportation sectors of the economy is influenced by research programs or standardization activities at NBS.

This study has served to verify many of the current concepts of the condition of the measurement system. Several strengths and weaknesses have been pointed out. The research program at NBS will continue to be influenced by the effects of the study. It is expected that the Measurement System Study will be a continuing activity, contributed to be the NBS staff as it is continuously aware of the relationship of NBS to the National Force Measurement System.

APPENDIX A. METHODOLOGY OF THE STUDY

The study of a complex structure such as the National Force Measurement System revolves around defining the major structural elements, detecting the paths of interaction among them and filling out the detailed information about interaction rates and magnitude of impact.

For the force study, the major elements of the structure were generally well known through our long history in the field of physical measurements. The first step was to sort the NBS calibration service and research contact clientele into these major groups. A sample of each group in the structure was contacted by telephone, a visit to their location or personal discussion at NBS. The sampling was continued in each group until the interaction of that structural element with other structural elements could be defined, and a picture of its measurement needs and impacts on society could be solidified.

At the same time, non-client members of each group were identified from several sources ranging from the literature file to formal introduction by other contacts. The basic interaction impacts and needs of these contacts with the system were compared with those of NBS clients, and the differences, if any, were investigated for cause and effect. A list of many of the contacts made during this study is given in Table A1.

Economic data were gathered from open literature or public information sources such as the Census Bureau and several trade associations.

Table A1 - Listing of Organizations Contacted During National Force Measurement System Study

Airlines & Aircraft Companies
- Allegheny Airlines Inc.
- Boeing Corp.
- Butler Aviation
- Dulles International Air Freight Corp.
- McDonnell - Douglas Aircraft Corp.
- Pan American Airlines - Air Cargo
  - Load Master
  - Operation Engineering
  - Weight & Ledger Control
  - Instrumentation
- TWA

Calibration Services
- American Calibration and Testing Inc.
- Labquip
- RW Hunt Co.
- Service Physical Testers
- 5 Star Calibration Service
- Twin Cities Testing and Engineering Lab
- United Calibration Corp.

Government
- Census Bureau
- Consumer Product Safety Commission
- Dept. of Agriculture - Forest Products Lab
- Dept. of Labor - Bureau of Labor Statistics
- Interstate Commerce Commission
- Maryland State Highway Dept., Soils Lab
- National Bureau of Standards -
  - Cement and Concrete Reference Lab
  - Office of Weights and Measures
- U.S. Army - Corps of Engineers
- U.S. Army - Metrology & Calibration Center
- U.S. Army - Picatiny Arsenal
- USAF - Aerospace Guidance & Metrology Center
- USAF - Ogden AFB
- USN - Eastern Standards Lab
- USN - Mare Island Naval Ship Yard
- USN - Metrology Engineering Center
- USN - Western Standards Lab

Industrial Users
- ABL, Cumberland, Maryland
- ASEA Electric Inc.
- Brunswick Corp.
- Burndy Corp.
- Ford Motor Company
- General Dynamics (Pomona)
- Goodyear Tire and Rubber Company
- Hamilton Std. Div., United Aircraft Corp.
- Martin Marietta Corp., Denver, Orlando
- Rocketdyne Corp.
- Sandia Laboratories
- Schwinn Bicycle Co.
- Tektronics Corp.
- Westinghouse Corp., Research Lab, Steam Div.

Metals Industry
- Alcoa Research Laboratories
- Armco Steel Co. - Research Labs
  - Metrology Lab
- Bethlehem Steel Co.
- Kaiser Aluminum Co.
- Lukins Steel Co.
- Reynolds Metals Company
- U. S. Steel Research Laboratories

Testing Labs
- ATI, Advance Technology, Inc.
- Central Testing Labs
- Franklin Institute Research Laboratories
- Lawrence Calibration Lab
- National Standards Testing Lab
- Pittsburg Testing Labs
- Time National Laboratories
- U. S. Steel Research Labs
- U. S. Testing Co.

Testing Machine Manufacturers
- Ametec
- GCA Precision Scientific Co.
- Gilmore Industries
- Instron Corp.
- MTS Systems Corporation
- Satec Systems
- Testing Machine, Inc.
- Thwing Albert Instrument Co.
- Tinius Olsen Testing Machine Co.
- W. C. Dillon Co.

Torsion Industry
- Camis Corporation
- S. Himmelstein and Company
- Utica Tool Co., Inc.

Trade Associations
- American Council of Independent Labs
- National Concrete Masonry Association
- National Association of Home Builders
- National Scale Manufacturers Association
- National Scale Men's Association

Transducer MFR
- AH Emery Co.
- BLH Electronics
- Daytronics, Inc.
- Interface, Inc.
- Lebow Associates, Inc.
- Martin Decker Co.
- Morehouse Instrument Co.
- Revere Corp. of America
- Soiltest, Inc.
- Toroid Corp.
- Transducers, Inc.

Universities
- Catholic University of America
- Virginia Polytechnic and State University

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A study of the National Force Measurement System has been conducted. The overall structure of the system has been defined, and the size of several of its component elements has been measured. The interactions of many of these components within the system have been assessed. The position which NBS has and the role it plays in the system are better understood as a result of this study.

The best assessment of the condition of the National Force Measurement System is that areas such as static force measurement are fully adequate with the levels of accuracy now provided while other areas such as dynamic force measurements and information transfer, are very inadequate to serve even our present needs.

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Dynamic force; economics; force; national measurement system; metrication; standards

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