ED STATES
MENT OF
MERCE
CATION

NBS SPECIAL PUBLICATION 335

Innovative Metrology— Key to Progress

Proceedings of the 1970 Standards Laboratory Conference

U.S.
TMENT
OF
MERCE
National
Bureau
of
Standards

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, chemistry, and engineering. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts.

Published in three sections, available separately:

● Physics and Chemistry

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $9.50; foreign, $11.75*.

● Mathematical Sciences

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $5.00; foreign, $6.25*.

● Engineering and Instrumentation

Reporting results of interest chiefly to the engineer and the applied scientist. This section includes many of the new developments in instrumentation resulting from the Bureau's work in physical measurement, data processing, and development of test methods. It will also cover some of the work in acoustics, applied mechanics, building research, and cryogenic engineering. Issued quarterly. Annual subscription: Domestic, $5.00; foreign, $6.25*.

TECHNICAL NEWS BULLETIN

The best single source of information concerning the Bureau's research, developmental, cooperative and publication activities, this monthly publication is designed for the industry-oriented individual whose daily work involves intimate contact with science and technology—*for engineers, chemists, physicists, research managers, product-development managers, and company executives.* Annual subscription: Domestic, $3.00; foreign, $4.00*.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitive data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

---

* Difference in price is due to extra cost of foreign mailing.

Order NBS publications from:

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

UNITED STATES DEPARTMENT OF COMMERCE • Maurice H. Stans, *Secretary*
NATIONAL BUREAU OF STANDARDS • Lewis M. Branscomb, *Director*

Innovative Metrology—Key to Progress

Proceedings of the 1970
Standards Laboratory Conference

H. L. Mason, *Editor*

Presented by the National Conference of Standards Laboratories

June 15-17, 1970
National Bureau of Standards
Washington, D.C. 20234

t,
U. S, National Bureau of Standards. Special Publication 335

Nat. Bur. Stand. (U.S.), Spec. Publ. 335, 132 pages (Mar. 1971)
CODEN: XNBSA

Issued March 1971

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.10:335), Price $1.50

Abstract

The biennial Standards Laboratory Conference of the National Conference of Standards Laboratories convened at the Gaithersburg facilities of the National Bureau of Standards June 15–17, 1970. The theme of the meeting, Innovative Metrology—Key to Progress, was amplified by 23 papers presented at technical sessions devoted to new technologies and applications, laboratory management and operations, new methods of optimizing calibration intervals, new ways of managing, and new international developments.

Key words: Metrology management; National Conference of Standards Laboratories; physical measurement; Proceedings NCSL.

Library of Congress Catalog Card No. 70–608384

NCSL 70

CONTENTS

Session 1. New Technologies and Applications

Session 2. Laboratory Management and Operations Reports

Session 3. New Methods of Optimizing Intervals

Session 4. New Ways of Managing

Session 5. New International Developments

NCSL BOARD OF DIRECTORS—1970

Jerry L. Hayes, *Chairman*
U.S. Navy Metrology Engineering Center
Pomona, Calif. 91766

Herbert S. Ingraham, *First Vice Chairman*
Radio Corporation of America, Defense
Electronic Products Division
Moorestown, N.J. 08057

Frank J. Dyce, *Vicc Chairman*
Martin Marietta Corporation
Orlando, Fla. 32805

James F. Hadley, *Vice Chairman*
Bendix Corporation, Kansas City Division
Kansas City, Mo. 64141

William L. Vandal, Jr., *Vice Chairman*
McDonnel Aircraft Company
St. Louis, Mo. 63166

Paul H. Hunter, *Secretary*
Western Electric Company, Inc.
Winston-Salem, N.C. 27102

Don I. Hervig, *Treasurer*
U.S. Army SAFEGUARD System
Huntsville, Ala. 35807

Joseph M. Cameron, *Sponsor's Delegate*
National Bureau of Standards
Washington, D.C. 20234

Edward J. Arsenault, *Delegate Member*
General Electric Company, DVICS
Cherry Hill, N.J. 08034

William E. Boyes, *Delegate Member*
Sandia Corporation
Albuquerque, N. Mex. 87115

Paul D. Long, *Delegate Member*
Western Electric Company, Inc.
Reading, Pa. 19603

Thomas N. Marshall, Jr., *Delegate Member*
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Ala. 35812

Wesley H. McPhee, *Delegate Member*
Massachusetts Institute of Technology
Instrumentation Laboratory Division
Cambridge, Mass. 02139

Harvey W. Lance, *Past Chairman*
National Bureau of Standards
Boulder, Colo. 80302

1970 STANDARDS LABORATORY CONFERENCE COMMITTEE

CONFERENCE CHAIRMAN, W. L. Vandal, Jr.

TECHNICAL PROGRAM, E. J. Arsenault, R. J. Barra, C. Boyer, C. E. White

EDITOR, PROCEEDINGS, Dr. H. L. Mason

FINANCE CHAIRMAN, R. T. Cook

ARRANGEMENTS CHAIRMAN, W. R. Tilley

FOREWORD

The growth, effective application, and wise regulation of technology depend upon the ability to make valid measurements. Such measurements in turn depend upon the existence of sound and evolving physical standards and the effective functioning of a complex national measurement system, important elements of which are the standards laboratories that comprise the National Conference of Standards Laboratories.

The dramatic increase in the importance of measurement in areas of great public concern points to future NBS-NCSL interactions on a broader scale in keeping with the theme of the 1970 Conference—innovative metrology. In addition to the traditional ties to NBS through involvement with the basic measurement standards, NCSL's strengthened contacts with the measurement methodology in NBS areas of materials research and applied technology will contribute materially to technological progress that will benefit NBS, NCSL, and the technological community they serve.

Because of this mutual concern for measurement, NBS is pleased to sponsor NCSL, to host its 1970 Conference, and to publish these Proceedings. Primary responsibility for the technical content of the papers rests, of course, with the individual authors and their organizations.

LEWIS M. BRANSCOMB, *Director*

NCSL 70

ON THE CONFERENCE THEME

J. L. Hayes, NCSL Chairman
U.S. Navy Metrology Engineering Center, Pomona, Calif. 91766

As noted in your program, the theme of the 1970 Standards Laboratory Conference is "Innovative Metrology—Key to Progress." For those of you who are in a financial squeeze this year (and who isn't?), perhaps the theme would be better stated as Innovative Metrology—Key to Survival! Either way you put it, the application of innovations and fresh new ideas into the management and operation of the calibration and metrology business is essential if we are to survive in today's economic climate. We can't survive unless we progress into more effective ways of managing the calibration resources that are at our disposal.

Innovation is a catchword that many of us accept as being full of hope and excitement; however, it is also full of emotional impact and heavily burdened with responsibility. To innovate is to do more than come up with a bright idea. Innovations are impotent actions unless they precipitate valid change. Progress inevitably means change. Change begets fear of change; resistance to change is often the result. In addition, natural inertia must be overcome. If a sufficient will does not exist to execute the innovation, little or no gain results.

As managers of metrology operations, we all need the will to win, to persevere and doggedly to pursue innovations to fruitful conclusions. We also need the courage to try, and in trying, the courage to fail, if need be, to make significant contributions. I feel that our present responsibilities and the theme of the Conference bring us face to face with a dual problem of considerable magnitude. We first must have the energy and willingness to precipitate innovation. We can accomplish this by brainstorming and establishing a working environment that is conducive to the generation of new ideas which are directed towards improving our operations both in quality as well as in quantity. Secondly, we then must have even greater amounts of determination to test that environment by actually bringing about the changes that must be made in spite of the natural bureaucracy of our surroundings and the need for security that both our personnel and ourselves feel. This is bound to take all the wits we can muster, the sensitivity to the effect this has on the people involved in the change, and the absolute determination to succeed. You've all seen it, so have I—the situation where someone has a great idea but it never gets hatched into useful reality because no one was willing to suffer the real agonies of implementation. Perhaps there's a human simile that fits here: the joys and heady delights of innovation or conception must be followed by the pain and agony of project completion or childbirth, the only difference being that on the one hand we must force it to happen; on the other, it occurs naturally.

There is no question in my mind that we *can* innovate, nor is there any question that we *must* innovate. No matter what the fiscal climate of our nation is, it is our responsibility to do our jobs in the most cost-effective manner. That means that we should first challenge the very jobs we're doing and confirm that they are meaningful. Once having established that, we then must seek the most cost-effective means of executing those jobs and of maintaining appropriate quality levels in doing so. Specifically, operating cost reductions must be achieved without a loss in product quality. In our case, we must calibrate instruments faster and better and at the same time provide our customers with test equipment which is even more reliable during its period of use than it is now. Is this a wild idea? Maybe. An impossible dream? No, sir! I contend it can be done and is being done. It can be done by each of you if you have the desire. It must be done by each of you if you wish to survive in your present job environment and if you wish to make a meaningful contribution to your company or organization.

I firmly believe we can together develop ways and means to achieve significant improvements and to save our organizations significant financial resources if we put our minds and our hearts into it. Individually, we may have certain ideas that have not only been thought of but have been tried and proven to work. If we can but share these together, the mutual benefit to all of us within NCSL could be incredible. NCSL intends to initiate regional meetings in the fall of this year that will give each of you a chance to meet with your counterparts from the surrounding area to share ideas and innovations. Hopefully, from each of these sessions a composite listing of ideas, both tried and untried, can be collected and disseminated for possible application within your own organization. I've done some of this in my own organization and the results have been exciting and full of cost-reduction potential. But, during the next three days you'll hear of numerous innovations that you can employ. To achieve progress through innovation, you've got to want to change, you've got to instill in your people the desire to change, and you've got to make the change. It's up to you!

NCSL 70

MEASUREMENT IN A CHANGING WORLD—KEYNOTE ADDRESS

Lewis M. Branscomb

Director, National Bureau of Standards, Washington, D.C. 20234

It is a pleasure for me to open this Conference, a meeting that I believe will be both fruitful and effective.

I think it significant that the group here today is not quite so large as it sometimes has been. The field of metrology, along with every other field of technical endeavor in this country, seems to find itself on the defensive now. But I think it would be a mistake for us to misconstrue that situation: I do not believe that there is any significant diminution in the basic public faith in science or in the importance of the fruits of technology to the national life.

It is true that in the metrology field some people feel that the challenge of reliable quantitative measurements may not be quite as glamorous as space travel or some other dramatic new application of science. And sometimes we complain that measurement standards work cannot get management attention or that it is too low on the priority totem pole. Many people end up feeling that running a standards lab is rather like running a stock room, and you'll have to admit that there are many standards labs that do operate rather like a stock room—providing instruments that are calibrated with tender loving care to people who use them in some manner that may not be well known to the man who calibrated the instrument. And the standards lab that runs like a stock room is not usually in a good position to know whether or not the user made effective use of the effort that went into the original calibration.

But like everything else, the measurement standards field is feeling the winds of change, change that will dramatically elevate the importance and the professional standing of standards work. Public awareness of measurement is also, I believe, going to increase. I will speak in a few moments of the importance of measurement in environmental and technological management. But let me parenthetically call your attention to the fact that after 100 years of debate and 11 years of consideration of a specific measure, the Congress did, a year and a half ago, pass a Bill authorizing a study by the Department of Commerce of the consequences to the United States of increasing use of metric measures. We have one year left of the three given to make the study, and in August 1971 the Secretary of Commerce must report to Congress the results of our considerations.

I believe that this study, if done properly, will shed light on the significance of measurement in the national life. The role of measurement is badly misunderstood in most quarters, and only if we understand it properly can we assess the consequences to the United States of changing our measurement language. That, of course, is what going to the metric system really means—substitution of the international system of measurement for the present mixed system of customary units and various versions of the metric system used in different disciplines.

As we examine the consequences of metrication we will be able to sort out those parts of the measurement system that concern the language we use from those parts that actually influence the technology and will require changes in hardware in order to adapt to a change in the measurement system.

We are carrying out this study through different methods for gathering information. One of these methods is a set of national conferences opening in August 1970 with a meeting in Deerfield, Mass., at which we will have heard the views of the engineering professional societies and several large segments of manufacturing industry. Other conferences will deal with such sectors of the economy as education, consumer problems, labor, and others. It is my personal hope that the metrological community will make an effort to provide us with input on the advantages and disadvantages of increasing use of metric measure. But whatever the conclusions of the study, I believe that as of a year from this summer we will see major attention being given to the significance of our measurement language in the national life.

We are also now seeing a dramatic increase in the importance of effective standardization, for quantitative, compatible measurement is essential to the wise regulation of technology for the public benefit. The last 15 years have seen the United States science policy focus on the exploitation of our scientific capability through technological application. We have done some fantastic things in that period to enhance our military security, to increase our sources of power production, and perhaps most dramatically, to make possible man's first voyage to the moon.

But the next 10 years will be increasingly characterized by the Government's effort to see that science is used for the benefit of man and that technology is mastered by mankind rather than becoming his master. As a Nation we must learn how to live in harmony not only with nature but also with man's own works, the processes and the products of his technology.

It is obvious that regulation of technology for environmental improvement requires measurements to find out what is happening to the environment, to establish technological alternatives for its management, to determine the levels of pollution which will be acceptable under various circumstances, to trace pollution to its sources, and finally to be the tool for regulating environmental pollution. For it is clear that we cannot eliminate pollution of the environment. The only alternative we have, if we are to expend energy and not violate the second law of thermodynamics, is to determine the level and the character of that pollution in reurn for the benefits that the polluting technology will provide to us.

The challenge is to find those kinds of pollution, whether they be thermal or otherwise, that are relatively acceptable in relation to the benefits to be gained. This will require an elaborate process of setting a standard and of regulating the performance of every polluting organization or individual in the society in terms of that standard. If the standard is set on a steep part of the cost curve, then the financial incentive to come close to the edge of that standard without dropping below it will be very great. And that will put great stress on measurements of not only the environment, but of the technological process that produces the pollution. Finally, when conflicts over the management of the environment reach the courts, the validity, the credibility of the measurement system will come under judicial review. And I have said to many of my colleagues who have been debating in recent days about whether or not there really is an important future for measurement science, if you want to make yourself a bundle, quit your job and set up a small consulting company to provide expert testifiers to challenge in court the quantitative creditability of our measurement system. I believe that in the environmental area the measurement capability leaves very, very much to be desired, and that under a very severe court challenge many of the measurements we make could be shown to a jury to lack the credibility that is required.

Concern over the regulation of technology clearly goes far beyond environmental concerns. Public attitudes are fast changing concerning safety and, beyond safety, the consumer's pocketbook. Variations in quality control that were once accepted as the natural consequence of the vagaries of mechanical systems are no longer acceptable. Society is now asking that we extract on a routine production basis the quality of technology that we know is in principle possible at a reasonable price.

Each new area of concern (environmental pollution, consumer safety and protection, etc.) will reflect itself back through the chain of engineering events. That is, it will not only concern the measurement of the properties of the product or the amount of pollution injected into the environment, but will go right back through production, production engineering, design, research, to conception of the basic ideas.

Thus the measurement system will be called upon to establish not only credibility, but assurance of accuracy and control. Regulatory teeth and major issues will stand behind the requirement for assurance of accuracy and control. This will force us to face up to a credibility gap in measurement standards work—in metrology, to use that shorthand label for all of the quantitative measurement assurance services in which we are engaged. This gap is created by a widespread impression that the processes for assuring measurement coherence too often obscure the purposes, and as a result fail to achieve those purposes. So in the interest of conserving our resources, those of us who are in the measurement business need to ask ourselves several questions: What is the purpose of a given measurement? What is the intended user's need? What is his measurement capability? To answer these questions, we need a more effective information feedback system. We must get out into the field and find out just what is going on so that we can adapt what we are supplying to what is actually needed and used.

We at NBS must give attention to several different phases of our responsibilities. First, we are responsible for establishing the central basis for physical measurements in the United States—establishing, improving, and maintaining these basic measurement standards in our laboratories. These measurements realize the SI quantities—the quantities defined in the international system of measurement. Second, we must work down the measurement chain from these fundamental quantities—mass, length, time, temperature, luminosity—to the hundreds or perhaps even thousands of practical measurement processes that are needed in today's science and industry, such as cryogenic flow, microwave impedance, plasma thermometry, and so on. Third, we must work on the problem of transferring into the secondary laboratories throughout the United States the basic measurement capability that we generate here. Fourth, we must assure adequate verification that the transfer is sufficiently effective for the user's requirement. This requires an active, outward-looking role on our part.

There is no reason for NBS not being able to transfer its accuracy under all the conditions required into the laboratories of users in such a way that the user knows that he is tied back to the Bureau in an operationally effective way. Every other standards laboratory has a precisely parallel responsibility with respect to its clients, and to that extent all of you share with us the same nature of responsibility. Let me give you a couple of recent examples to indicate some of the things we are doing in two of those four responsibilities I named—those having to do with the establishment of standards and their more effective dissemination.

In length measurement, technology, through development of the laser, has again come to revolutionize measurement science as measurement science in turn pulls and leads technology. The laser obviously has not only given the promise but the actuality of revolutionizing precision distance measurement because of its particularly attractive properties of coherent light of very high brightness. We have recently in our research program found a way to stabilize a laser to an accuracy of about one part in 10^{11}. We have in fact built two completely separate lasers each oscillating in the near infrared at a frequency of about 10^{14} Hz, independently stabilized them with completely separate apparatuses, beat them together, and found the beat frequency to be only about 100 Hz. This development can be carried a good bit further. We have the prospect of a wavelength standard whose reproducibility is nearly competitive with the reproducibility of the frequency standard itself. Close on the heels of that development is the real likelihood that in the next year or two our scientists will succeed in multiplying the frequency standard all the way up to the optical range, permitting direct comparison of the standard of wavelength with the standard of time interval. At that point we will have the opportunity, if we wish, to assign an arbitrary value to the speed of propagation of electromagnetic radiation, and discard either the standard length or the standard of time at our convenience. This is an example of how rapidly the scientific basis for measurement is proceeding.

Let me now mention a new contribution that we are making in time standards dissemination. Many people are under the assumption that the two most essential uses of time are the measurement of time interval or elapsed time, and the determination of absolute time in relation to the motions of the earth in its astronomical context. The former obviously is essential for any physical measurement in which time enters as a parameter because, except in the field of cosmology, time enters physical processes as a time interval. Absolute time, or epoch, is vital to navigation, since we navigate on the surface of the globe with respect to geographic coordinates. It is obviously convenient to do so in relation to the position of the surface of the earth in its external environment of the moon, planets, and stars. But it is increasingly important in technology to be able to achieve simultaneity, which means the absence of a time interval between two remote locations. Simultaneity is now of very great importance in many applications. Included among them are problems of space navigation, of collision avoidance for aircraft, and in telecommunications. Pulse code modulation communications are made possible if there is an independent time base at all points in the system so that the train of pulses can be decoded at the receiving end.

Two of the ways of achieving simultaneity around the country are to proliferate atomic clocks or to establish a satellite time signal system. You can proliferate atomic clocks, since every man's cesium is the same as the next man's, but the capital investment in clocks is rather prohibitive. The clocks must be carried from place to place to keep them synchronized. Carrying clocks from one place to another is of course used to establish a coordinated time base for independent laboratory clocks, but this process is also expensive. The satellite system is a perfectly practical means of establishing simultaneity technologically, but it is even more expensive.

Our laboratories in Boulder are now experimentally investigating the feasibility of another way of establishing simultaneity through color television. The idea is basically a very simple one. The three major networks in New York, in transmitting their color pictures, generate a very accurate 3½-megahertz subcarrier. It is possible to put a modulation on the subcarrier during the interval of time between pictures. There are several lines on the TV screen on which one can impress a code that will transmit a time signal throughout the television network. An encoder attached to the TV set displays numeric time information on the screen. It is then only necessary for a given laboratory to determine once what the phase delay is between its location and the source of this coded signal, in order for the television signal to establish the time difference between the absolute time reference maintained by NBS and the laboratory's local clock. This provides a running correction for the local clock as well as a basic time base in hours, minutes, seconds. This system is being evaluated experimentally over TV stations in Denver and Washington. It is also being used to provide the frequency comparison between the Naval Observatory clocks in Washington and those of our laboratories in Boulder. We have permission from the FCC, AT&T, and the major TV networks to proceed with the examination of this system with a view to implementation on a national basis. We hope to evolve a dissemination system which can provide synchronization accuracy of a microsecond or better in any laboratory which otherwise would have to accept the millisecond precision inherent in real-time use of the ionospherically propagated signal from WWV.

Beyond improving the basic standards and means for transferring those standards effectively into the laboratory of the user, we must study the whole process of measurement in order to ensure that it serves its intended purpose. Some people think of a measurement in terms of a measuring instrument. I think the word "calibration" tends to convey that image. But a measurement can be understood only in terms of a total man-device system. Heisenberg, in developing the uncertainty principle, taught us that there is really no meaningful measurement that does not affect the system being measured. We must also recognize that the human beings involved in the measurement system are an important influence on the measurement as well as being influenced by it. We must also incorporate the people making and interpreting a measurement in our understanding of a measurement.

A measurement results when we have a theory for the measurement, and know the system response in relation to a range of system circumstances—all those that might show up in the measurement, including a subset of special circumstances called calibration. This special subset of circumstances gives the restrictions needed when the system is configured to permit a theoretical tie back to the basic measurement standards. In the determination of physical properties carried out in many laboratories all over the country, this philosophy is too often ignored and as a result there is entirely inadequate attention given to systematic errors involved in absolute measurements of all kinds; errors that derive not only from the intrinsic properties of the device being used but also from the manner and skill with which it is used. It is important to determine when absolute accuracy is really needed. Then we must ensure that we really get what we require. In the past we have too often accepted a calibration system that failed to assure this accuracy in actual practice. Perhaps such failures have occurred in part because of realization that requested accuracies were not always required.

In the area of materials management we have an attractive method of transferring accuracy from a central standards laboratory into the field. This is the determination of certain properties of matter in absolute units with known precision and accuracy. We are establishing here at the Bureau a program on such "bench mark data" devoted to a properly documented determination of selected properties. And we will not use the traditional standards of excellence of the scientific literature for judging the quality of our work in this area. Instead we treat a bench mark data problem just as any systems engineering problem, in which you set up the necessary procedures for documenting that such accuracy has been achieved well enough to satisfy any group of skeptics. I mention this program because the scientific community accepts the idea that work may be done and published as correct and yet still not be believed by the peers of the scientist performing the work. In the laboratories of those concerned with the measurement system we cannot accept a system in which measurements are not accepted as credible. In the establishment of absolute data, it is essential that we learn how to document an experiment so that it can stand on its own.

A consistent national measurement system properly coordinated with the system of other nations depends on several things: the existence of a theory of measurement based on the relationships among physical quantities; the establishment of a set of units and reference standards; the development of a set of technical procedures for comparing a quantity to be measured with the measurement unit; and finally, the development of measurement equipment for carrying out such comparisons and for determining multiples and submultiples of basic units. Too often in the past the thinking of metrologists has been dominated by such matters as traceability, calibration certificates, accuracy charts, fee schedules, echelons, calibration intervals, accuracy ratios, and class tolerances. These are material requirements or, if you like, design requirements, as opposed to the performance requirements that we would like to apply to the measurement system.

To illustrate the inadequacy of merely requiring traceability, consider the following situation that could occur and indeed does occur in the area of mass measurements. Suppose a laboratory has its reference standards regularly calibrated by NBS, by shipping them here and having them measured here. And having the best conditions for storing its weights, so they are properly cared for, the laboratory finds that there is essentially no change in the values as measured by the NBS over an extended period of time. Surely this is traceability at its best. Yet the measurements made by such a laboratory may be subject to great error if environmental controls in the user laboratory are not adequate, or if procedures are not properly followed, or the measurement equipment is in some way faulty. Stated another way, we may know all about the laboratory's standards, but still know little about its ability to measure.

I was even told a few days ago of a standards laboratory which was making repeated traceability certification of the standards of a subordinate laboratory. This subordinate laboratory seemed to have an extraordinarily good record, as its standards showed little deviation from year to year. Then it was discovered that the subordinate laboratory had not even unpacked the standards it submitted to the central laboratory! Its staff just left them in the box and shipped them back for recalibration the next year. Well, that is perfection in traceability and zero in measurement assurance!

Concern over calibration interval, accuracy ratio, and traceability is quite popular in the maintenance of standards, and standards are a vital element in a consistent system of measurement. But standards alone are not enough to meet the demands of modern technology.

The interchangeability requirements of industrial processes, the compatibility and authenticity requirements of guidance and control systems, and the compatibility of measurement controls in commerce are all examples of a need for a coordinated measurement system. However it is the kind of measurements made by the system and not just the quality of the standards that is at issue. Measurements in a physically consistent system for which the requirements of compatibility and authenticity apply are incompletely and sometimes even incorrectly characterized by the properties of the standards used. Our focus then should be on the measurements that count and the process that generates those measurements.

Although NBS establishes measurement standards for some 50 basic physical quantities, the transfer from these standards to practical measurements is a responsibility resting primarily with users. However, the Bureau must know the user's measurement needs, so that it can be responsive to providing standards and methodology that are suited to those needs. The transfer of measurement capability can be achieved with the usual calibration approach, but for the highest accuracy work the laboratory may need to set up an independent realization of the basic units from their fundamental definitions. Or more economically, a laboratory may tie to the Bureau by comparative procedures so that that independent laboratory can be as good as if the Bureau had set up an alternative laboratory of its own on their site.

It is the answer to the following question that we seek as a new approach for the dissemination of measurement capability: What procedures, how much work, what kind of control, what performance criteria would be needed to constitute evidence as to the quality of measurements of a laboratory? Practical measurement can be easily described in terms of its elements, the concept of the quantity to be measured, the pertinent physical laws, the various instruments used, the physical standards, the operators and the appropriate procedures, the environment in which the measurement is to be carried out, the computations to be made, and finally the means of establishing parameters of performance.

The measurement process is essentially a production process, the product being numbers—that is, measured values. A well-known characteristic of a measurement process is that repeated measurements of the same thing result in non-identical numbers. To specify a measurement process involves ascertaining the limiting mean of the process, its variability or imprecision due to imperfections in the system, the possible extent of systematic errors or bias from identifiable sources, and the overall limits to the uncertainty of independent measurements.

When we have tolerances of ± 5 microinches on ball-bearing diameters, the uncertainty in our measurements may be a large part of the tolerance. We have to cope with the problem of stating in numbers the degree to which we have achieved the desired goal. In all cases, the metrologist must understand the real goal of measurement effort. For example, in the case of the ball bearing, the important element may be the need for a matched set of balls of identical diameter, and it may be possible to produce sets of balls that match to much better tolerances than one would assign to the value of an individual ball in an interlaboratory comparison study.

Another example is in the measurement of light output from fluorescent tubes—the product of a 1 billion dollar industry. Here it appears that the marketplace hinges on 1 percent differences in levels of performance claimed by manufacturers—that's 30 lumens out of 3,000. On the other hand, we do not have sufficient confidence in our basic standards here at the Bureau to assure us that it is possible to measure the light emitted by a fluorescent tube to sufficient accuracy to ensure a one percent transfer of accuracy into the industry.

And it may be that in this industry not only the accuracy but even the precision with which fluorescent tube output can be measured is not as good as 1 percent. But the question that we must ask is "Is it necessary to try to have every lamp manufacturer in a position to measure fluorescent tube output in absolute units—that is, in lumens to better than 1 percent? Or is it sufficient to ensure harmony in the industry with respect to luminosity precision, allowing normal market forces to determine the adequacy of the level of light output?" These questions are not easy to answer because they hinge not only on direct cost studies, but on questions of confidence in the market process to which measurement has an important contribution.

The key element in evaluating cases of this kind is that of obtaining a sequence of measurements of the same quantity. In standards laboratories this is fairly easy to achieve simply by remeasuring one of the laboratory standards as if it were an unknown, or using one or more items typical of the test items for the same purpose. The routine calibration of the same object used as a check standard tells us what the measurement process can do. It is not just a simulation of the calibration process—it is the real thing, without the need for any assumptions. Continued measurement of the check standard provides the basis for the precision statement and correlating its behavior with environmental procedures or other factors enables us to measure or set bounds for possible systematic error. For control of the measurement process, this check standard need not have the stability one would require of members of the standard group. Predictability of its performance is the basic requirement.

Having established control in one's own laboratory one then asks—what is the most effective way of coordinating my measurement process with others in the national measurement system? The problem is that of transfer of measurement capability and again one has to study this transfer mechanism as a process and determine its operating characteristics just as was done for measurements in his own laboratory.

The Bureau is considering new approaches for the transfer of measurement capability in selected areas to avoid the wasteful duplication implied by having each user develop his own procedures for assuring the adequacy of the transfer. For example, in voltage standards the Bureau is engaged in a program of developing procedures using shippable standards for transferring the value from the national reference group to other primary laboratories. The old practice of moving the customer's reference group to NBS for calibration left unanswered the question of whether the group survived the return trip unchanged, and placed on the user the burden for the study of the transfer mechanism.

The first or pilot program of this type was in the calibration of mass where the question of transportability of the standard does not arise. We first established that a state of statistical control existed in our own laboratory. Participating laboratories were required to evaluate their own performance parameters, and with the aid of a pair of kilogram standards borrowed from the Bureau could know to what degree their work would be compatible with others in the system. A fundamental difference from their usual procedures is the emphasis on the continued verification of control within the laboratory and between it and other parts of the measurement system. This tells the laboratory how well it performs—and is more meaningful than a certificate that says how well some other standards laboratories performed. The amount of effort is dictated by the measurement needs of the user and not by tradition. Similar efforts, which we call Measurement Analysis Programs, are under way for voltage, resistance, capacitance, temperature, length, and several other quantities.

To optimize our efforts in serving the national measurement system, we must look at such objectives of our calibrations as achieving compatibility among a number of laboratories. Even if an individual in a laboratory sends a device to the Bureau, and we make the assignment of its value with the smallest possible error, his job is not done. For example, if he sets up his balance in a breezy hallway, his measurements are not necessarily improved by having a super-accurate NBS mass calibration. He still has to evaluate, in his own laboratory, the component of error due to his breezy hallway. In cases where the device may be altered by the trip to the standards laboratory his knowledge will be no better than the evidence in his laboratory that it has survived the trip.

If there are problems in comparative measurements or in transporting the standards it may be better that we develop standards that we can ship to the other laboratories. Then they can calibrate their reference standards on their own site by using their own comparator and procedures, and all the associated systematic errors will affect this transfer to the same extent as it will their future measurements. This eliminates a source of bias that would be present if the reference standards were calibrated at the standards laboratory. The user then works only as hard as he needs to in order that the error in the local intercomparison be as small as required, while NBS concentrates on the maintenance of the absolute units and the problem of the transport of those units to his laboratory.

These examples are illustrative of our desire to make sure that our measurements are not only accurate but also optimally relevant to the actual end use of the measurements. The measurement process is a highly complicated one and needs to be evaluated constantly as to efficiency and effectiveness, so that the services that you and we provide will meet neither more nor less than is required to satisfy the needs of users.

My remarks have ranged from generalizations to technical details of the measurement process. I wanted to emphasize the fact that any standards laboratory has, I believe, the same responsibility that we now are increasingly feeling—namely, the assurance of the effective transfer of measurement into the hands of users. And I believe that this requires a relationship between the standards laboratory and the user in which the people and the system are coupled and the standards laboratory has the opportunity and the obligation to evaluate the effectiveness of the user's measurement. Once a standards laboratory is in a position to do that, then that laboratory becomes an effective and indeed an indispensable tool of management. We in the Bureau are finding in various areas of technology that the integrity of the measurement system is increasingly impacting the policy-making levels of government concerned with the regulation of technology. If a standards laboratory is in a position not only to calibrate instruments, but to assess the quality of the job being done by those who are making measurements of importance to the laboratory's sponsor or clients, then that standards laboratory becomes an important element of overall management and technological control in the client institution.

NCSL 70

INNOVATION IN MEASUREMENT

Myron Tribus

Assistant Secretary of Commerce for Science and Technology
U.S. Department of Commerce, Washington, D.C. 20230

This appearance marks a new experience for me. When I talk to engineering or educational groups I can always say, "I feel right at home here because I have been in this business." Tonight for the first time I can say to a group, "I feel right at home here because I run a standards laboratory too." The word "run" is a bit strong for in a real sense no one as far from the bench as I am can "run" a precision laboratory. But my pride in this association encourages exaggeration.

I am tempted to say, "My standards laboratory is better than your standards laboratory," but that would not be fair. It is, but by definition, not necessarily by any particular effort of mine.

I have often said that what you purchase from a standards laboratory is negentropy—the reduction of uncertainty. We tend to think of that quantity in relation to the standards laboratory in a rather restricted sense. But it has an extended sense, and that sense of negentropy has a good deal to do with the reasons for which we are gathered here this week.

It is accepted, certainly by this group at any rate, that civilization is built on measurement. Civilization is also built on negentropy. Our ability to plan and to build depends on our ability to know the limitations of things, of devices, of institutions, and of processes. So in this sense the standards laboratory does indeed, within its scope, provide the very stuff of civilization.

As a main prop of civilization, the standards laboratory is subject to the forces and currents of that civilization. One of the main currents of our civilization, and one of its tribal gods, is innovation. And so we are gathered here to perform a ritual soul-searching in quest of that elusive, magical power which resides in all of us and merely needs to be bidden to spring forth and grant its bounties.

Unfortunately, my experience as engineer, educator, and administrator has shown me that innovation, like most gods, is a capricious servant. Once summoned, it has a way of overpowering sense and reason, of demanding an allegiance beyond that which benefits the believer. It becomes an end in itself.

This aspect of the innovation problem is balanced by the fact that few people, even those who talk and promote innovation, really want it. Innovation disrupts our routines and our security. It challenges our competence, and there are few of us who will put up with that sort of thing.

So there are two conflicting currents here which the management of a standards laboratory, like any other modern enterprise, must keep in balance—the impulse to change, and the resistance to change. The key to that balance is being able to recognize what constitutes progress—not change or innovation, but progress. Change for change's sake must be avoided; but no change which promises improved operations and services should be lost.

These considerations are common to all management, not just to the standards business. But in the standards and calibration activity we have an added dimension which makes the decision-making process more difficult and makes desirable changes perhaps more difficult to introduce. That added dimension is the great degree of routine and established procedure which a standards laboratory must have to insure the accuracy and repeatability of its results. Obviously these routines must not be disturbed for light and transient causes.

Neither should the people in a standards operation be disturbed unnecessarily. They are a special breed with an orientation toward and a commitment to excellence. They will, rightly, resist any incursion into the quality of their work.

How does the manager of a standards and calibration operation keep it moving forward with all deliberate speed in full recognition of these realities? It seems to me the first necessity is a firm understanding of his operation and what it can and should do.

What do we expect of a first-rate standards laboratory? Two things stand out in my mind. First is the ability to give the customer an unambiguous statement of what the laboratory has done for him. Second is the provision of a range of services to meet the varying needs of various customers. Some customers want the utmost in accuracy in a calibration; some are willing and able to sacrifice a decimal place or two for a quicker turnaround time; many are not so interested in the extremes of accuracy as they are in extreme certainty of the limits of inaccuracy. A first-rate standards laboratory must be able to meet the needs of this range of customers and to be able to tell them exactly what they are getting for their money.

It is up to the manager to make sure that his laboratory can meet the demands made on it in a sound and economical framework—that is, in terms of the usual management decisions which must balance services against investment in floor space, hardware, personnel, and so on.

Even as the manager develops for himself a good idea of what his organization is about, he must communicate that idea to the people who work for him. If he has an obligation to provide his customers with an unambiguous statement of what the laboratory is about, he owes the same to his people. The more clearly the aims of the laboratory are stated and understood, the more surely the individual employee can relate himself to the mission and feel a part of it.

What I am advocating here is that a laboratory should have a clear set of performance criteria for itself and its employees. This is a necessity for knowing where you are and where you intend to go. More to the point, these performance criteria give you a basis for innovating. Like all performance criteria, they make it possible to evaluate new technology in objective terms to see if it advances the state of the art or is merely change for the sake of change. Performance criteria enable the laboratory to make desirable innovations without undue disruption in operations and service.

I think you can understand my insistence that you "know thyself." It is only to the extent that you understand your own operation that you can manage for innovation. But, how many of you really know the trade-off between cost and accuracy in your operation? Do you know the trade-off between cost and turnaround time? Do you know your customers' trade-offs on these items? An even better question: does your customer know his trade-offs on such items? If not, does your service include helping him to determine them? I can think of no greater waste of resources than giving your customers services they really do not need and should not have to pay for.

So the message is: measurement man does not live by precision alone, but by all the dimensions and interactions in the measurement and calibration process. If we are to talk of innovation, we must talk about innovation in all phases of that process. We must not fall into the trap of thinking that innovation is always aimed at one more decimal place. One can easily see how a standards laboratory could improve itself right out of business by pushing accuracy, and thereby costs, in an unreasonable way. Innovation may be aimed at one more decimal place, but it is equally possible and equally valuable, under the proper circumstances, for it to be aimed at cutting cost for a given accuracy, at increasing the knowledge of the uncertainty in a calibration, or at any one of a number of other factors.

To manage this process, you must know in a quantitative sense what the parameters of your operations are, and most especially the cost-benefit relationships in your operation, your customers' operations, and in the interactions between you and them. It is only with this sort of knowledge that you can tell progress from change and distinguish improvement from innovation.

In this connection I think that the recent development by the National Bureau of Standards of the Measurement Analysis Program is a significant step in the right direction. This MAP—the idea must be a good one since it already has an acronym—belongs to the next generation of calibration techniques. NBS is now offering MAP for mass calibrations and is investigating the possibilities for calibrations of voltage standards and of gage blocks.

MAP recognizes that the laboratory in possession of a nicely calibrated set of weights has indeed nothing else for certain. It is entirely possible to misuse dreadfully a well-calibrated set of weights and provide very poor calibration services. MAP is designed to calibrate, in effect, the laboratory's entire operation, to spot errors in handling, random or systematic environmental effects, and so on.

Even more important, over a period of time the MAP data give the standards laboratory a concise and quantitative history of its operation so that it can spot instantly any anomalies which might crop up.

Now, you see, we are beginning to develop a tool which will give the manager of a standards laboratory the kind of broad and continuing overview of his operations that I have been advocating here tonight. The very facts that MAP is brand new, that it is just being developed in a few areas, that it is being well received by the laboratories which have begun to use it, are all evidence of how little most laboratories really know about their own programs.

I am glad to say that NBS—one of my departments—is taking the lead in such an important effort. I know they will continue to develop and to expand MAP to the benefit of the entire measurement system. I think all of you here should be thinking in these terms and using such tools as this to develop the most complete picture possible of the operations in your own laboratory, your relationship to your customers, and your place in the measurement system. It is only with this kind of outlook that you can reliably tell culturally induced innovation from true progress in the measurement and calibration arts.

NCSL 70

SESSION 1: NEW TECHNOLOGIES AND APPLICATIONS

Chairman: O. L. Linebrink

Battelle Memorial Institute, Columbus, Ohio 43201

THE EVOLUTION OF A RADIOLOGICAL MENSURATION TECHNIQUE

Herbert Bardach and Stanley Wisnieff

Avco-Lycoming Division, Stratford, Conn. 06497

A radiological mensuration technique was devised to measure the minimum wall thickness anchoring from interior corner points of small castings invested with internal cavities. The factors involved in the development of the mensuration technique which culminated in the manufacture of a semi-automatic machine tooled with a strontium 90 gage were examined in detail. These factors included included the phenomenology of beta transmission through plural media, the subtleties of counting geometry, and the characteristics of the beta spectrum, all of which contributed in some measure to the efficacy and uniqueness of the beta emitter as a mensuration tool.

The technique involved the positioning of an encapsulated strontium 90 point source contiguous with the interior points at which the minimum wall thicknesses were to be measured and determining these thicknesses by referencing the observed beta transmission counting rates to a calibration curve.

Key words: Attenuation of betas; beta-transmission phenomenology; counting geometry; mass absorption coefficient derivation; strontium 90 wall-thickness measurement gage; thin-wall mensuration.

1. Introduction—The Mensuration Problem

The emphasis in gas turbine design for greater efficiencies and increased power/weight ratios has led to the use of higher operational pressure and rotational speeds. This has resulted in an increase in the stresses imposed on the power-stage turbine blades. Accordingly, in order to abate these stresses, it has been required to invest these turbine blades with internal passageways to facilitate air-cooling and improve their metal temperature profile. This has been accomplished by an investment casting process which can be used to cope with the complex curvilinear dimensional requirements of the blade's contoured surfaces. A typical air-cooled turbine blade casting is shown in figure 1.

As a consequence of the effort to reduce blade metal temperatures by the incorporation of air-cooling passageways, quality control inspection techniques had to be bolstered to insure the retention of the blade's structural soundness and dimensional accuracy. Such inspection mainstays as x ray and Zyglo which were well established for determining flaws had to be supplemented—for another structural characteristic had soared into prominence: wall thickness. What previously had been spot-checked by a destructive sectioning technique had now to be scrupulously determined, for if during the investment casting process an occasional miscast occurred in the form of an internal core shift, so that blade walls buttressing one side of the core were made too thin, blades with such unduly thin walls

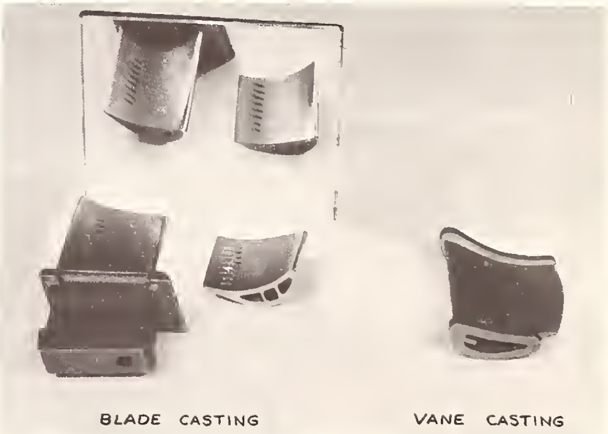


Figure 1. *Typical castings measured for wall thickness by radiological mensuration technique.*

might rupture under the imposed centrifugal forces. If one such blade were mounted in a power turbine wheel of 62 blades and should fail, the resultant weight imbalance might cause the entire wheel to fail with severe damage to the engine.

Several well-established mensuration techniques, including eddy currents and ultrasonics, were adapted to tackle the wall-thickness measurement problem, but all were confounded by an obvious difficulty: None of them could satisfactorily measure the wall thickness at the points of highest stress concentration—the linear distances (shown dashed in fig. 2) from the narrow ends of the covered space approaching tangency with the external blade surfaces. It became apparent that current mensuration techniques reliant upon macrodispersive or echo-sensing phenomena could not focus sufficiently on these wall thicknesses to provide accurate results. Subsequently, an innovative dial micrometer gage was tried, but the narrow (5/64 in.) access holes to the internal passageways, together with the steep thickness gradient in the region of the tangency points, especially when core shifting was pronounced, caused difficulties which could not be surmounted. The conditions for resolving the problem were now beginning to clarify. What was needed was a mensuration technique which had very high resolution capability—a technique which could virtually focus in on the thin-walled corner pockets caused by core shifting.

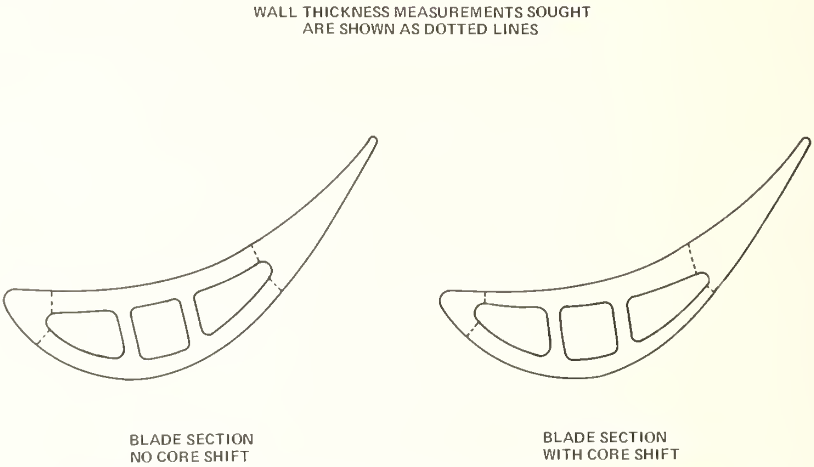


Figure 2. *Properly cast blade compared to core-shifted blade.*

2. Genesis of the Radiological Mensuration Technique

After some rumination, the idea of using beta transmission for wall-thickness measurement was lit upon. The phenomenology of beta transmission through thick foils was well established—electrons or positrons when given kinetic energy will issue in random orientations from the nuclei of radioactive atoms undergoing nuclear-energy transformations at random time intervals. The kinetic energies imparted to these charged particles are multivarious, ranging from zero to a fixed maximum energy which uniquely characterizes the particular species of beta-emitting radioisotope. The effect is the generation of a continuous beta energy distribution having two termina: zero energy and a maximum energy. The beta spectrum thus reflects a complex beta-emission probability distribution, to wit: Each radioactive atom has a probability that a beta particle will be emitted; and additionally, each radioactive atom has a probability distribution associated with the range of possible beta particle kinetic energies that can be emitted. (See fig. 10 in appendix for depiction of a typical beta spectrum.)

Thus, beta particles of multivarious energies and manifold orientations, many travelling close to the speed of light, stream pointillistically from the nuclei of origin into the ambient matter, sustaining energy absorption loss and scattering interactions with the atomic electrons and atomic nuclei. The interactions are profuse and the path of the beta particle is very tortuous—a path that is the compounding of four interaction phenomena:

(1) Scattering by atomic electrons without beta energy degradation (scattering);

(2) Scattering by atomic electrons with beta energy degradation (ionization);

(3) Backscattering by atomic nuclei without beta energy degradation (backscattering);

(4) Scattering by atomic nuclei with energy degradation resulting in transformation of beta energy to electromagnetic wave energy (Bremsstrahlung).

Indeed, a moderately energetic beta particle sustains such a multiplicity of energy absorption loss and scattering collisions while passing through a 0.020-in. thickness of stainless steel that it resembles a wavering, weakening drunk, who in trying to toe the long white line to its terminus reaches the terminus by virtue of the multiplicity of his random deviations. During his reeling walk, the drunk is not apt to sober up, nor is the beta particle likely to convert its kinetic energy to Bremsstrahlung despite the multiplicity of collisions it experiences. Actually a beta particle of 1 MeV energy, which sustains 10^3 to 10^4 collisions while passing through a 0.020-in. thickness of stainless steel, suffers a Bremsstrahlung generation of only a few percent of its total energy loss. This fortuity proves to be of cardinal importance relative to the efficacy of beta transmission as a wall thickness measurement technique, as will be seen later.

As a result of the multitudinous energy absorptions and diverse scatterings it experiences, the effective path length of the beta particle of kinetic energy E is proportional to the actual path length and is a simple linear function of E. Thus if 2-MeV monoenergetic electrons were used for thickness measurement, the attenuation characteristic would be described by noting the diminution, with increasing material thickness, of the conical solid angle formed by the pencil of rays representing the range of possible effective electron path lengths. Then the extent of the conical solid angle emanating from the point of electron entry would be constrained by the maximum effective path length of the 2-MeV electrons. If this were 0.050-inch in steel, then the loci of possible electron emission sites for an absorber thickness X would be circular areas πR^2 where $R^2 = (0.050)^2 - X^2$ which would plot approximately as a straight line on Cartesian coordinates for a middle range of X thickness values.

A formalization of the range of the electron path lengths is Feather's rule, an empirical formulation relating maximum electron energy to maximum thickness penetration for material of a given density. It states that for $E > 0.6$ MeV, the range of the electrons in the material is given by

$$R(\mathrm{g/cm^2}) = 0.542\,E - 0.133$$

where the range R is the maximum thickness penetration for the given material. Another empirical formulation is

$$R(\mathrm{mg/cm^2}) = 412\,E^{1.265\,-\,0.0954\,\ln E},$$

which is applicable to the range of $0.01 \leqq E \leqq 2.5$ MeV.

It is remarkable fact that both the identity and uniqueness of the beta spectrum are preserved even as beta particles issuing from the nuclei of origin are gradually attenuated by successive thicknesses of material. Thus, a beta spectrum having a maximum energy of $E_{\max}$ retains its characteristic form regardless of the fraction of its total energy that has been absorbed by matter. In other words, if an absorber is used to reduce the beta particle intensity to a fraction of its original intensity, the beta particles streaming out of the surface of the absorber have the same mass absorption coefficient[1] (cm²/g) as the betas streaming into the absorber. This implies that the average energy loss per incremental path distance $-\Delta E_t/\Delta X$ is independent of X and is solely a linear function of the total energy E_t; also, that the probability distribution of orientations induced by scattering and backscattering is independent of X. Thus, $dE_t/dX = -kE_t$ and $E_t = E_{t_o}\, e^{-kX}$; but as E_t is equal to the product of the average beta kinetic energy and number of beta emissions, or $E_t = N \cdot E_{\mathrm{avg}}$, and E_{avg} is invariant since the beta spectrum does not change its proportionality, we then have $N_x = N_o\, e^{-\mu X}$ where N_o is the initial number of beta emissions, N_x is the number of beta emissions transmitted through absorber thickness X, and μ is the linear attenuation coefficient.

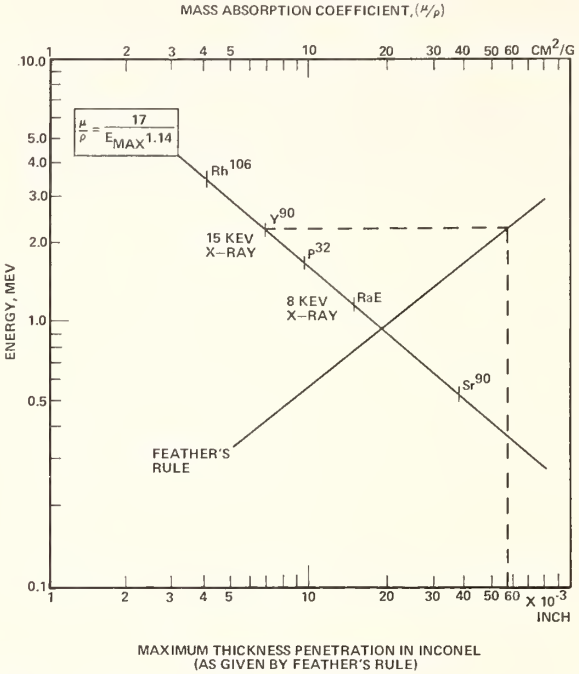


Figure 3. *The relationship of beta energy to mass absorption coefficient and Inconel plate thickness.*

A graphical display of mass absorption coefficients for a few pure beta emitters and their corresponding thickness penetration values for Inconel having a density of 7.9 g/cm³ are given in figure 3. Feather's rule is also delineated. The corresponding equivalent mass absorption coefficients for electromagnetic waveform radiation (gamma or x ray) are indicated adjunctly to the depicted beta emitter. However, since the authors, after a fairly thorough search, were unable to find a commercially available radioisotope of halflife greater than one year which was either a pure x ray emitter (electron capture made), a pure gamma emitter, an x ray and beta, or gamma-ray and beta emitter with a composite mass absorption coefficient comparable to that of any pure beta emitter, no identification of such alternates is included. In fact, the use of a beta-gamma emitter of disproportionate mass absorption coefficient would result in the gamma emission contributing a fairly constant background noise to the beta's attenuation slope. To illustrate: The only beta emitter of any consequential halflife which is more energetic than yttrium 90 is the daughter of ruthenium 106. Ruthenium 106, a pure beta emitter of 0.039 $E_{\max}$ with a halflife of one year, decays to rhodium 106, a 30-s halflife daughter which has a beta of 3.53 $E_{\max}$ with an emission probability of 0.68 per atomic disintegration and gamma emissions of 0.513

---

[1] The mass absorption coefficient for a given absorber is the linear attenuation coefficient or transmission constant of the absorber divided by its density.

MeV and 0.625 MeV with emission probabilities of 1.00 and 0.53, respectively. Since the mass absorption coefficients of the 0.513 MeV and 0.624 MeV gammas are less than 1/40 that of the 3.53 beta, the gammas would behave as a significant noise factor, and thus contaminate the beta attenuation curve. It appeared, therefore, that yttrium 90 loomed as the optimal choice for measuring wall thickness in the range of 0.015 to 0.040 in., which was the anticipated dimensional range of forthcoming mensuration problems.

Strontium 90, a pure beta emitter of 0.54 $E_{\max}$ with a halflife of 28 yrs, decays to yttrium 90, a 64-hr halflife virtually pure beta emitter of 2.27 $E_{\max}$ (1.734 gamma emission less than 0.0002 probability), which in turn decays to stable zirconium. Whereas the strontium betas are stopped by a 0.009-in. stainless steel foil thickness, the more energetic yttrium betas are merely attenuated by 0.015-in. to 0.040-in. thicknesses. Since the attenuation gradient for Inconel thickness in this range is steep and very nearly exponential, wall thickness differentiability was readily obtainable. The attenuation gradient may be expressed as the change in counting rate (customarily counts/minute) per unit change of material thickness, where counting rate is the number of discrete radiations entering a radiation detector and counted during a time interval. The attenuation of a pure beta emitter such as yttrium 90 with increasing material thickness over a significant fraction of the yttrium 90 beta penetration range is closely approximated by a straight line on semilogarithmic paper, where counting rate is the logarithmic scale and material thickness the linear scale.

From a macroscopic point of view, the principle of using beta transmission for measuring blade wall thickness at a particular site appears simple and straightforward. A radioactive point source is juxtaposed beneath the blade wall site, and a radiation detector positioned in proximity above. The number of beta particles issuing from the radioactive source and transmitted through the blade wall is then determined as a counting rate by the detector, and the wall thickness determined by referral to a calibration curve relating counting rate and wall thickness for the given counting geometry. See figure 4. However, the reader can appreciate the pitfalls which can befall the user who is unaware of the intricate phenomenological interactions which may be contributory to the calibration curve. The previous discussion concerned only the phenomenology of beta transmission through a single medium. If now the problem is complicated by the condition of plural media, as is the customary condition in counting configurations, whatever contributory factors may be present in the single medium will be magnified.

There are customarily seven media involved in the usual counting configuration. Beta particles issuing from the radioactive source transmit sequentially through the radioactive source itself, through the source containment, through air, through the wall thickness, through air, through the detector window, and finally into the detector sensitive volume.

If the radioactive source, source containment, detector window, and detector sensitive volume are maintained without material or spatial alteration throughout the series of counting periods, these media will merely represent collectively an absorber which reduces the effective range of wall thickness measurement. Clearly, if these media have collectively a high mass absorption coefficient, thickness measurement may be precluded over a significant fraction of the thickness range.

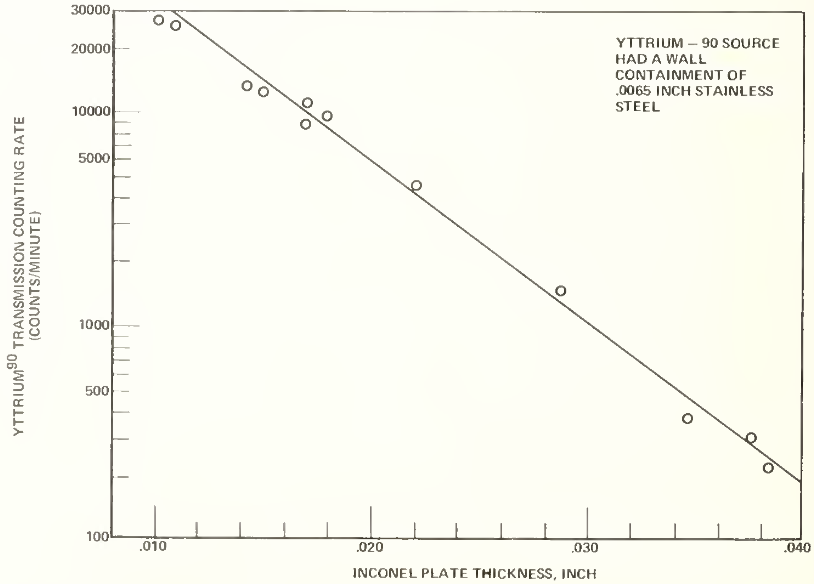


Figure 4. *Calibration curve, yttrium 90 transmission versus Inconel plate thickness.*

3. Counting Geometry Considerations

In the macro sense, the key to obtaining consistently accurate results is the maintenance of constant counting geometry during the measurement sequence. Several subleties are implicit in this statement, since the maintenance of constant counting geometry depends not only upon the spatial configuration of the three elements—radioactive probe (radioactive source and source containment), wall thickness to be measured, and radiation detector—but also upon the spatial configuration of the wall thickness itself. If the wall thicknesses to be measured have variable thickness gradient profiles or do not have the same ambient matter distribution, measurement errors may ensue.

A brief example will elucidate the factor of ambient matter distribution. If the reader refers to figure 1 and notes the numerous air-cooling cuts along the edge of the turbine blade, and imagines a point source of radioactivity moving along the interior corner of the core space in which these holes terminate, he may appreciate the periodically ascending and descending counting rate that would be observed as the point source traverses the path length, and further appreciate that blades with such cuts might give thickness variations from 0.002 to 0.015 in. in excess of the thickness readings for blades without such cuts. Indeed, this adventitious finding was used as a calibration check to ascertain the proper spacing and positioning of these cuts!

The turbine blade wall thickness measurement problem involves measurements of variable wall thickness profiles, since it is the exceptional case of core shift that produces excessively thin walls. If the reader refers to figure 2, he can visualize the possible core shifts that would create this condition.

The dimensional properties of the radioactive probe were of paramount importance to the wall thickness measurements to be undertaken. It was desirable to assure that the radioactive probe closely approximated a point source, for excessive spatial extension of the source or of the source containment would broaden the surface area impinged by the beta particles and thus lessen focusing ability. The two constraints on the diminution of spatial extension were construction capabilities and rigidity considerations.

4. Description of Radioactive Probe

The radioactive probe (see fig. 5) was a sealed source comprising essentially a stainless hypodermic tube within another stainless hypodermic tube, the inner tube encapsulating two 0.002-in. ceramic microspheres [2] perfused with a total of three microcuries of ionically bound strontium 90. The strontium 90 microspheres were situated at the sealed tip end of the inner tube, in a pocket formed by the insertion and securement of a 0.0094-in. piano-wire plunger in the inner hypodermic tube's 0.010-in. i.d. in a manner so as to snugly buttress the microspheres against the inner surface of the tube's sealed end. The outer hypodermic tube, with an i.d. of 0.020 in. and an o.d. of 0.032 in. tapering down to 0.025 in. at its tip, served as an overshoe to prevent wear of the 0.018-in. o.d. inner tube encapsulating the strontium 90 source. If and when 0.0005-in. wear of the overshoe occurred, a diurnal calibration check, involving the comparison of a one-minute test count with the calibration standard count of 3500 cpm, would be sufficient to discriminate 0.0005-in. wear from the wall thickness of 0.0065-in. thickness at the tapered radioactive end.

FIGURE 5. *Strontium 90 probe.*

After construction, the probe's beta emission profile along its length was determined. With the strontium 90 probe in a fixed position and a 1.4 mg/cm^2 end-window Geiger-Mueller detector viewing it from above, a 0.015-in. stainless steel foil was interposed between detector and used as a length interceptor coverlet. The foil was indexed in 0.01-in. increments to cover successively greater lengths of the probe, and the counting rate of beta emissions was noted for each position of the foil. For probe length interceptions of zero, and of 0.01 through 0.09 in. the counting rate was steady at 10,800 ±500 cpm; however, when the foil was indexed to 0.01 in., the counting rate dropped dramatically to 6450 cpm, indicating at least partial coverage of the strontium 90 source by the foil. Subsequent indexing to probe length interceptions of 0.11, 0.12, 0.13 in., etc., failed to alter significantly the counting rate, which was sustained at the level of 6500 ±300 cpm. Thus it could be concluded that the radioactive source was effectually contained with the 0.09 to 0.10-in. interval of the probe length. Iteration of the foregoing procedure for other rotational orientations of the probe established the near-radial isotropy of the probe's beta emission profile at the 0.09 to 0.10-in. interval, there being a maximum deviation of 7 percent in beta emission intensity attributable to the minute variation in hypodermic tube wall thickness girding the radioactive microspheres.

5. Phenomenology of Beta Transmission Through Plural Media

There are two principal factors involved in the mechanics of beta transmission through plural media:

---

[2] The microspheres were fabricated by 3-M Company, St. Paul, Minnesota.

geometric dispersion and attenuation. While the former concerns dispersion in space, or in-vacuo dispersion, the latter refers to the combined energy absorption loss and scattering interaction phenomena of betas with the atomic electrons and nuclei.

If the medium is air and the beta emitter is sufficiently energetic, attenuation will be negligible for brief transmission paths. Under such conditions, transmission through air may be deemed geometric dispersion. Consequently, if an yttrium 90 point source opposite a flat surface is separated by an air gap, the interception of the yttrium 90 betas by the surface will be represented by a probability density distribution which is a function of geometrical considerations alone. Referring to figure 6, wherein a planar representation of a symmetric counting geometry configuration is depicted, we note that if surface 1–5 were assumed as being flat, the probability distribution of betas along surfaces 1–3 and 3–5 would be precisely the distribution of cos θ where θ is the angular displacement of the geometric ray from axis 0–3. In extending this analysis to the actual three-dimensional counting geometry configuration, the planar representation is revolved about the axis of symmetry generating circumferences which have probability values corresponding to a cos θ (A tan θ) distribution.

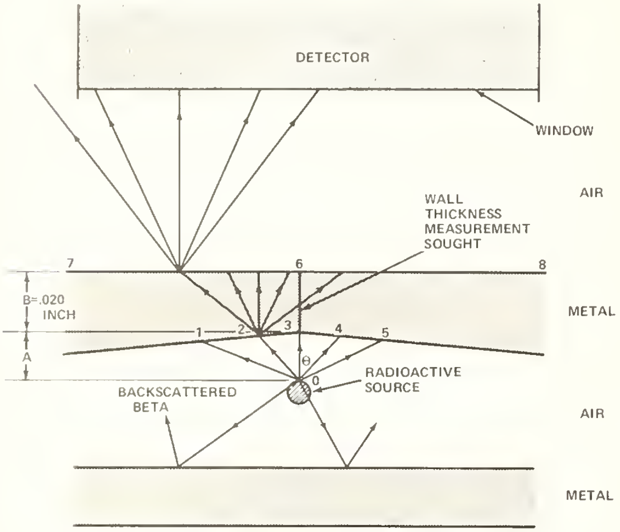


FIGURE 6. *Chart guide for "Phenomenology of beta transmission in plural media" discussion.*

If the constant A is disregarded, this distribution reduces to sin θ. Since there is symmetry, the position of the beta in the circumference is immaterial and the sin θ distribution can be properly depicted as being distributed along lines 1–3 and 3–5. Thus, the probability of a beta entering circumference 5 would be greater than that of beta entering circumference 4, and the probability of a beta entering a circumference more remote from the origin that circumference 5 would be greater than that of a beta entering circumference 5, and so forth. This consideration instructively emphasizes the importance of minimizing the source size, source containment, and source distance from the thickness to be measured, if it is anticipated that the wall thickness profile may vary. Ideally, the radioactive source should be a point source contiguous to the point at which the wall thickness is to be measured. If this is nearly accomplished, then the procession of beta transmission through the wall thickness will resemble the conical dispersion of rays shown issuing from point 2.

Beta transmission through matter combines the factors of geometric dispersion and attenuation. Beta particles entering at point 2 undergo so many diffuse deflections and collisions in a 0.020-in. metal thickness that the probability distribution relating to attenuation is merely a function of the effective path lengths travelled by the betas.

The factor of beta attenuation, however, is complicated by an ancillary factor: Bremsstrahlung. Bremsstrahlung is electromagnetic wave radiation which is generated by the interaction of the beta's wavefront with the coulomb field of an atomic nucleus. During this interaction any possible fraction of the beta's energy can be converted to electromagnetic wave radiation. Thus, when the beta intensity is sufficiently high, the multiplicity of interactions results in the generation of a Bremsstrahlung spectrum characterized by the diminution of photon intensity with increasing photon energy; i.e. photon intensity is maximized as the photon energy approaches zero, and is minimized as the photon energy approaches $E_{\max}$. Since the probability of producing Bremsstrahlung is a function of the number and intensity of the nuclear coulomb fields confronting the beta particles, the intensity of Bremstrahlung generated will increase to a maximum value for a material thickness corresponding to the beta range. Thereafter, for greater material thicknesses, Bremsstrahlung attenuation will occur, albeit at a much lesser rate than that of beta attenuation since the medial Bremsstrahlung photon energy of 0.2 MeV has a mass absorption coefficient about 1/30 that of its parent beta. However, the Bremsstrahlung photon contribution to the beta attenuation curve will be inconsequential except for thicknesses approaching the range since the percentage of total beta energy converted to Bremsstrahlung is $ZE_{\max}/3000$ where Z is the absorber's atomic number, or about 2.5 percent for strontium 90–yttrium 90.

Since the Bremsstrahlung contribution to the yttrium 90 beta attenuation curve is insignificant for Inconel thickness less than 0.040 in, we shall now resume the analysis with the imposed constraint of this thickness limitation.

Referring to figure 6, one notes the typical effective path lengths depicted as originating from point 2. As before the geometric dispersion probability distribution is sin θ, but with the complication that θ now has a limiting value fixed by the range of the $E_{\max}$ betas through the medium. If we calculate the relative probabilities of beta transmission along these path lengths, as effectuated by the attenuation factor using $e^{-136.5(0.020/\cos\theta)}$ where 136.5 is the approximate linear

TABLE 1. *Calculated thickness penetration probability values versus experimentally derived probability values*

Wall thickness		Relative probability values	
		Combined geometric dispersion and attenuation factors	Calibration curve (*cpm*)
(*inch*)			
0.020	$\sum_{\theta=0^\circ}^{67^\circ} e^{-136.5\,(.020/\cos\theta)}\sin\theta =$	0.08795	5400
0.030	$\sum_{\theta=0^\circ}^{53^\circ} e^{-136.5\,(.030/\cos\theta)}\sin\theta =$	0.01564	980
0.040	$\sum_{\theta=0^\circ}^{37^\circ} e^{-136.5\,(.040/\cos\theta)}\sin\theta =$	0.00312	175

attenuation coefficient [3] per inch of yttrium 90 in a medium of 7.9 g/cm^3 density, the proportion of these attenuation factor probability values will correspond fairly well with the counts per minute (cpm) values given by the calibration curve for the thinner wall sections, but suffer progressively poorer correspondence as the thickness increases, by dint of the fact that the geometric dispersion conical solid angle is diminishing with increasing thickness.

It should be noted that these attenuation factor probability values would correspond to the calibration curve cpm values if a pinhole collimation window had been interposed between the measured wall thicknesses and the detector during the generation of the calibration curve.

Recalculating the relative probability values for yttrium 90 transmission through Inconel thicknesses of 0.020, 0.030, 0.040 in., but now considering both the geometric and the dispersion factors, and using an effective maximum penetration path of 0.0505 in. (the 0.057 in. range of yttrium 90 betas in Inconel diminished by the source containment thickness of 0.0065 in.), we obtain the summations given in table 1. The calibration curve cpm values abstracted from figure 4 are juxtaposed to facilitate comparison.

A collation of complete results is given graphically in figure 7. The results are normalized. As anticipated, the beta particle attenuation values calculated from the derived analytical expression of the combined geometric dispersion and attenuation factors of an uncollimated counting geometry corresponded much more closely to the calibration curve values which were determined from uncollimated counting geometry measurements than do those values calculated from the derived analytical expression for a collimated counting geometry.

If these calculations are performed for other selected points on lines 1–3 and 3–5 and repeated at these points for varying gradients, it becomes clear that varying wall thickness gradients can produce serious measurement errors when the radioactive source is not contiguous to the point at which the wall thickness is to be measured, but this implies precise positioning, for if the point source had been placed at point 5 rather than at point 3, the wall thickness measured would be somewhat greater than thickness 3–6.

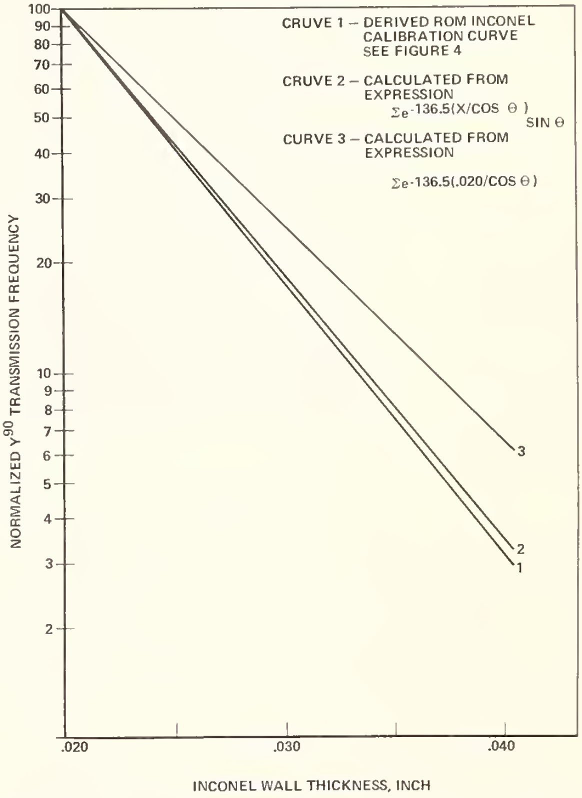


FIGURE 7. *Comparison of calibration curve of figure 4 with analytically derived calibration curves.*

Once the probability distribution of betas issuing from surface 7–8 has been determined, the geometric dispersion considerations are once more undertaken for the air path to the detector window. Here again important parameters loom, namely: the size of the

---

[3] Linear attenuation coefficients are experimentally derived; however, it is possible from a consideration of first principles to derive not only the analytical expression of the beta spectrum but also to use that beta spectrum in coordination with interaction-phenomena factors and count-geometry factors to derive the calibration curve analytically. An attempt to do this in a simplified manner is presented in the Appendix.

detector window, its distance from the surface of the wall thickness facing the detector, and its orientation with respect to the wall thickness.

The window should be oriented to favor the line wall thickness measurement sought. Collimation of the window or reduction in window size may be used to minimize "thickness summing" in the region of the line wall thickness; however, this is contraindicated if sample positioning is not precise since serious positioning errors may ensue.

Some mention should be made at this point of backscattering since it is often a significant source of error. As the probability of hackscatter (deflection greater than 90 degrees, of a beta by an atomic nucleus) is steeply ascending with diminishing energy of nonrelativistic betas, and inconsequential for relativistic betas, the following discussion will concern only the former.

The probability of backscatter relative to the possible modes of interaction can be given as $0.25\, Z^2/\beta^4$ where β is the ratio of beta velocity to the speed of light in the medium considered, while the probability of ionizing collision, the principal attenuation mode, is given as $(2\, Z/\beta^4)\ \ln\, (E\sqrt{2}/I)$ where I is the average ionization energy lost by the beta per collision and E is in eV units. For Inconel the value of I is about 330 eV ($I \cong 12\, Z$). Hence, the ratio of ionizing collision probability to backscatter probability for beta energies less than 100,000 eV is $8/Z\ \ln\, (E\sqrt{2}/330)$ or about 1.7:1 for 0.1 MeV betas. Thus, if there are surfaces in proximity of the radioactive probe which function as beta backscatter reflectors, and the counting geometry configuration has the detector viewing these surfaces, a significant alteration of the calibration curve values may occur.

6. Test Results

A rigorous performance test was used to determine the feasibility and precision of the pullulating radiological mensuration technique: Each of 24 vanes was to be measured at 24 sites—these sites comprising four interior corners at three cross-sections at both sides of the vane—with the time allowance for measurement limited to 15 seconds.

The measurements were made by manual insertion of a strontium 90 radioactive probe, similar to the one described in the text, which was flagged and graduated to cue the operator as to the proper probe orientation and probe insertion depth. An unshielded low-level beta background counter (background less than 5 counts/minute) was used to determine the heta transmission rates. A typical vane is depicted in figure 1.

It was necessary, of course, to establish calibration curves. All 24 vanes were first counted at each of their 24 sites. A 6-s counting rate was deemed sufficient to ensure good counting statistics, since the average counting rate was about 600 counts/6 s and the anticipated count differential per 0.002-in. thickness differential was 180 counts/6 s at a thickness of 0.026 in., the anticipated wall thickness median. Thus, if the precision criterion was a 0.002-in error at a two-sigma deviation (where for the appertaining Poisson distribution, sigma equals the equare root of the total number of amassed counts, the background being negligible) a two-sigma deviation would be $\pm 2\sqrt{600}$ or ± 48, a value comfortably within the 180 count differential per 0.002 in. Eight vanes, those which to a first approximation collectively provided an optimal range of counting rates for establishing calibration curves over an anticipated span of 0.015 to 0.040-in. thicknesses, were recounted for 1 min, and then sacrificed for the calibration curves. It was possible by virtue of the flatness of the vancs, and through careful positioning of the detector, to resolve the 24 formative calibration curves, one for each wall measurement site, to a single master calibration curve.

The eight vanes culled for sacrifice were sectioned in four parts, and optical measurements taken of the minimum line wall thicknesses at the tangency points at the confluence of the interior corners and internal surfaces. The precision of these optical measurements had a probable error of 0.0005 in. The sets of data relating counts per minute to wall thickness for each of the formative 24 calibration curves were then fed to a computer which was programmed to determine the value of the slope which best fitted each set of data. The criterion used was the method of least squares. The slopes of each of these curves deviated from the slope of the Inconel attenuation curve by less than 10 percent, the average being 5 percent.

Subsequently, a second computer program was run using as data input the slope value of the Inconel attenuation curve and again the method of least squares was used, this time to determine the best-fitting slope-intercept value at a 0.015-in. thickness. Having established the constants of the equation:

log counts at thickness $X = -($slope $\cdot$ thickness X + counts at thickness 0.015 in.),

a master calibration curve had now been resolved from the 24 formative calibration curves, and this curve was used for determining the wall thickness of the remaining 16 blades from the 6-s counts which had already been taken.

Table 2. *Error distribution*

Strontium 90 Gage Thickness Measurements

	Error Frequency		
Error* ($\times 10^{-3}$ in.)	Thin Wall 0.017-0.025 in.	Medium Wall 0.026-0.030 in.	Thick Wall 0.031-0.040 in.
0–1	97	93	23
1½–2	35	52	20
2½–3	8	25	12
3½–4	3	7	6
4½**	0	0	3
5	0	0	0
5½**	0	0	1

*Deviation of strontium 90 gage measurement from 10× reticuled optical measurement.

**Measurements were taken to nearest 0.0005 in.

All 16 blades were then sectioned in four parts and optical measurements taken of each of the 24 sites. A comparison was made between optical measurements and radiological measurements. The results are given in table 2.

7. The Machine

On the basis of the celerity and efficiency with which the test measurements were dispatched, interest was stimulated for the design of a prototype semi-automatic machine version of the strontium 90 radiological mensuration technique. Such a machine was built for Avco Lycoming Division by the Accurate Machine Tool Company, Cleveland, Ohio. An overall view of its moving elements is given in figure 8. The machine can be described briefly as follows:

A turntable outrigged with four mounting fixtures is indexed sequentially to four stations: sample loading, measurement, accept-reject stamping, and accept-reject discharge. The machine has both manual and automatic functions. The manual function merely involves loading the blades and indexing the turntable to the measurement station. Then the machine takes over.

In rapid sequence the probe, guided by servo motors regulating orientation in five coordinates (X, Y, Z, orbital, and azimuthal), is advanced to and retracted from four preset positions in the blade's interior passageways, each time advancing into and pulling out of a 5/64-in. diam port at the blade tip. At each position a 6-s count is taken by the end-window Geiger-Mueller detectors viewing the convex and concave walls of the blade. These counts are displayed on two Baird-Atomic 530 readouts and electronically compared with the preset counts dialed into the limit switch for each of the eight counting positions.

If the displayed counts exceed the preset counts, indicating an overly thin wall, the reject lamp lights, the probe is withdrawn, the turntable automatically indexed, the part stamped reject, the turntable re-indexed, and the part discharged into the reject bin. The turntable then indexes the next blade into measurement position and the cycle is repeated. Accepted blades which finish the cycle are simply discharged into the accepted bin.

The machine has proven to be fast, highly accurate, and reliable. In a 1-hr period, the machine can dimensionally check out a hundred blades at eight measurement sites while maintaining an accuracy within 0.002 in. over 95 percent of the time, for the thin-walled blades it is seeking to discriminate.

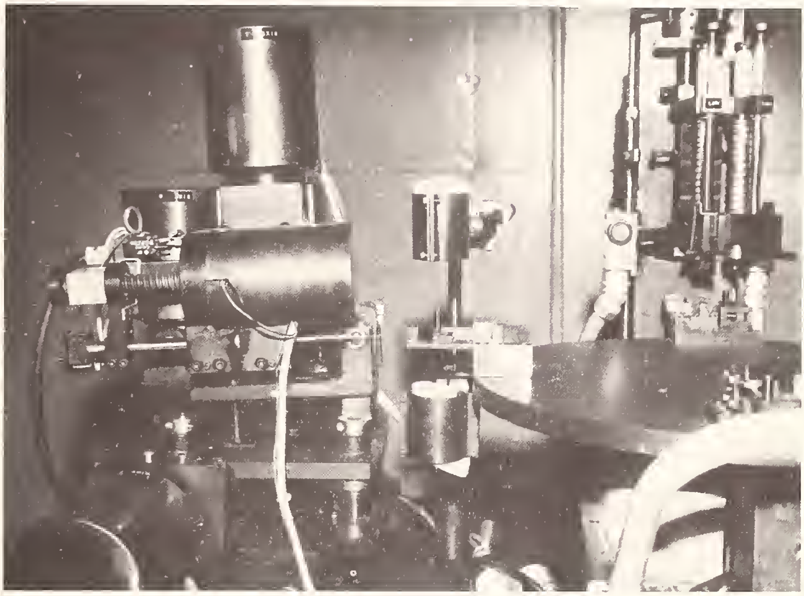


FIGURE 8. *Closeup of turntable, probe positioning mechanism, and detector mounts of radiological mensuration machine.*

8. Appendix. A Non-Rigorous Analytical Method for Determining the Beta Transmission Calibration Curve

The beta transmission calibration curve which relates beta count-rate intensity to absorber thickness is derivable from the beta spectrum. If the beta spectrum has been experimentally determined as by a magnetic focusing β-ray spectrometer, or analytically derived as from Fermi's theory of beta decay (Ref. 1), an empirical formulation such as Feather's rule can be used in conjunction with the previously discussed characteristics of beta transmission through plural media to perform successive integrations over the portion of the beta spectrum which can transmit through the absorber thickness span of interest. In other words, if it were desired to determine the beta transmission calibration curve of yttrium 90 for Inconel absorber thicknesses of 0.015 through 0.040 in., one would first determine the beta energy having a 0.015-in. range. This would then constitute the minimal beta energy required for penetration through the 0.015-in. thickness. Thereupon, using sin θ to generate the circumferentially symmetric probability density distribution of betas emitted from the surface, one calculates the sin θ distribution for each beta energy of the beta spectrum capable of transmitting through 0.015-in. Inconel, and appends thereto the corresponding beta emission probabilities as weight factors. Having obtained a column of numerics which are summed up to give a probability intensity value, one repeats this process for other thicknesses in the span 0.015 to 0.040 in. In this manner one generates the probability intensity values of the beta transmission curve. The justification of this method lies in the fact that the beta spectrum proportionation is virtually invariant even as the beta energies are being diminished by successive absorptions. Thus one can reconstruct the beta spectrum with monoenergetic electrons and apply Feather's rule and the sin θ distribution to the continuum.

Table 3. *Calculated beta transmission probability intensity values*

Beta Energy (MeV)	Beta emission frequency	Range	Generated sin θ beta emission probability values* per absorber thickness (inch)						
			0.020	0.028	0.036	0.044	0.052	0.060	0.0675
		(inch)							
0.5	4.5	0.020	0	0	0	0	0	0	0
0.6	3.3	.028	0.792						
0.7	2.4	.036	.833	0.702					
0.8	1.5	.044	.879	.772	0.574				
0.9	0.7	.052	.923	.842	.722	0.533			
1.0	0.25	.060	.940	.885	.802	.685	0.500		
1.1	0.05	.0675	.953	.910	.845	.758	.838	0.456	
1.17	0	.0722	0	0	0	0	0	0	0
Beta transmission probability intensity value			6.86	3.70	1.61	0.582	0.166	0.023	
Feather's absorption data (relative intensity values)			240	112	48	19	6.60	1.75	

*Numerics are weighted sin θ values representing approximate relative probability intensity values for variously energied RaE betas being transmitted through and emitted from the surface of different thicknesses of aluminum absorber. Each sin θ value is the complement of the cos θ value representing the ratio of absorber thickness to beta penetration range.

In the absorption experiments of RaE betas through aluminum foils, Feather used a thin mica-windowed Geiger-Mueller detector. The RaE source was thinly spread over a 3-cm area closely matched to the area of the detector window. The source was mounted in a slight cavity in a wooden block and positioned at a distance of 2 cm from the window.

In order to give credence to the this proposed method, the authors used the original data of the RaE (bismuth 210) beta transmission curve through aluminum absorbers as experimentally determined by Feather (ref. 2), in conjunction with the RaE beta spectrum experimentally derived by Neary (ref. 3). See figure 9. For the sake of simplicity and elucidation, a histogramic area summing technique was used instead of integration to determine the sin θ distributions. These approximations were sufficiently accurate as will be borne out later.

Since the maximum beta energy of RaE is 1.7 MeV, the maximum penetration depth of RaE betas in aluminum was 0.0722 in., and this thickness was adopted as the constraining effective path-length side of the conical solid angles formed by the beta transmission paths in the considered span of thicknesses from 0.020 to 0.060 in. A summary tabulation of calculations is given in table 3. To facilitate comparison, some datum point values from Feather's RaE beta transmission curve are presented in the same table.

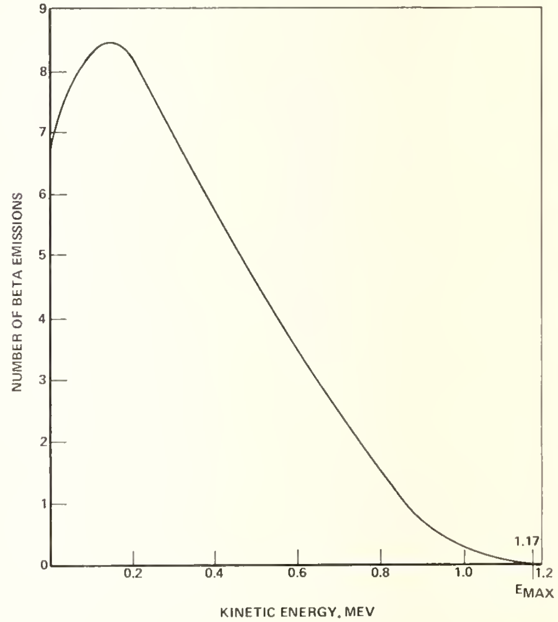


Figure 9. *The beta spectrum of radium E (bismuth 210) from Neary (ref. 3).*

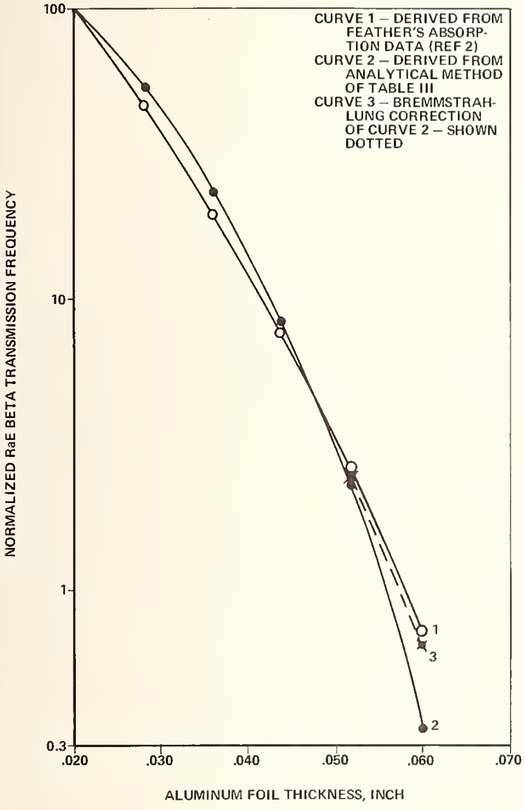
Normalizations of the beta transmission curve derived in table 3 and Feather's beta transmission curve are compared in figure 10. The reader will note the close correspondence for the thinner aluminum foils and the lesser correspondence for the thicker foils. This is attributable to the absence of a Bremsstrahlung correction factor in the analytical method exemplified by table 3. Since the fraction of total beta energy which is converted to Bremstrahlung is approximately $ZE/3000$ or 0.005 for aluminum foils shielding RaE betas, and the beta intensity for an unshielded RaE source is about four times the intensity for a source shielded by 0.020-in. aluminum foil, then we have as the maximum possible Bremsstrahlung count contribution $0.005 \times 6.86 \times 4 = 0.14$ count, assuming that only one Bremsstrahlung photon is produced per beta particle. Since the source was about 2 cm from the 1-cm diameter window, and the preponderance of the Bremsstrahlung photon spectrum may be assumed as penetrating the aluminum foil thicknesses, the fraction of Bremstrahlung entering the detector had effectually two origins: Either the Bremstrahlung photon was generated at a point in the aluminum foil medium which was sufficiently close to the point of beta entry into the medium to constitute a possible intermediate path position of a beta which could pass through the aluminum foil, or the photon was generated at a point in the aluminum foil medium or ambient matter too far removed from the point of beta entry to constitute such an intermediate path position. Clearly the conical solid angle of the beta particles intercepted by the detector was approximately the same as that for the Bremsstrahlung because of the limited 0.0722-in maximum penetration distance of the beta. Thus since the fraction of the total conical solid angle intercepted by the detector was

$$\frac{\text{detector window area}}{\text{spherical surface area}} \approx 1/12$$

then the Bremsstrahlung contribution derived from beta particles not at possible intermediate path positions was approximately 1/12 of 0.14 or 0.012 count. This value was relatively constant for all absorber thicknesses. In addition the Bremstrahlung contribution derived from beta particles at possible intermediate path positions had a variable value of

$$0.012 \times \frac{\text{absorber thickness}}{0.0722}$$

Thus, although there would be produced for a 0.020-in. aluminum absorber a total Bremsstrahlung contribution amounting to $0.012 + (0.020/0.0722 \times 0.012) = 0.015$ count, which is negligible compared to 6.86 counts, the Bremstrahlung correction for 0.052 and 0.060 thicknesses was significantly 0.02 and 0.022 counts, thus raising the calculated count values of 0.166 and 0.023 to 0.186 and 0.045, respectively. Accordingly, the adjusted normalized values would be 2.71 and 0.66. These Bremsstrahlung corrected values are shown in figure 10 as a dotted line.



FIGUTE 10. *Comparison of Feather's curve depicting radium E beta transmission through aluminum foils with analytically derived curve.*

If the reader proceeds to determine the beta transmission calibration curve by this *a priori* method he will observe that the transmission curve is only approximately a straight line on semi-logarithmic paper. Clearly this preliminary determination will provide him with a good guide for performing accurate curve fitting of the experimentally derived data in establishing the calibration curve. Of course the user must take into consideration the effective cumulative absorber thickness due to the source containment and the detector window, and adjust the abscissal values accordingly. Furthermore, he must devise his counting geometry configuration so as to minimize backscatter.

9. References

[1] Evans, Robley D., The Atomic Nucleus, (McGraw-Hill Book Company, Inc., New York, 1933). An excellent simplified treatment of Fermi's Theory of Beta Decay is given in Chapter 17.

[2] Feather, N., Proc. Cambridge Phil. Soc. **34**, 599 (1938).

[3] Neary, G. J., Proc. Roy. Soc. (London) **A175**, 71 (1940).

NCSL 70

AN AUTOMATED TIME DOMAIN INSTRUMENT TEST CONSOLE

L. S. Kreyer

EG & G, Inc., P.O. Box 98, Goleta, Calif. 93017

This paper describes a computer-controlled system which automatically tests the performance of oscilloscopes and other time domain instruments. The system utilizes advances in pulse technology to speed up the calibration process by replacing frequency domain test methods with time domain test methods. Cost effectiveness of this system in terms of reduced man hours to calibrate an instrument, reduction of systematic errors due to operator bias, and consistent reporting of test results are described.

Key words: Automatic measuring devices; automatic performance test; computer control systems; instrument calibration procedures; instrument performance testing; pulse technology; time domain testing.

1. Introduction

The growth of sophistication of electronic systems has been proceeding at a rapid rate, due largely to inventions in electronic components and in the science of cybernetics. These systems require a high degree of expertise on the part of the technical community to maintain and to calibrate at a level which will assure measurement reliability.

Both the quantity and complexity of the testing and measuring equipment used by a calibration facility to maintain these systems are growing in direct proportion to the systems themselves.

The metrology and calibration program of every organization is directly affected by this increase in the measurement requirement within its jurisdiction. Exact quantities from which to judge are not available, but one may reasonably estimate that the burden placed upon a calibration facility is growing at an exponential rate.

The calibration laboratories are not only faced with moving through the shop the apparatus requiring calibration or repair, but they must also acquire and evaluate variables data on each piece of equipment handled. The calibration process, beginning with writing instrument calibration procedures, then measuring parameters, recording the measurements, making adjustments if necessary, etc., must be streamlined and made more cost effective.

In addition, the enormous bookkeeping problems associated with the proper recording and processing of calibration data and their statistics have never been adequately solved. Metrologists have long been aware of the necessity of analyzing variables data on all individual equipments requiring routine calibration. The potential gains resulting from such an analysis have not been realized because of the difficulty and cost of acquiring and storing reliable data on all the equipment involved. Solutions must be found for the problem of the growing calibration backlog and the associated bookkeeping.

2. Computer-Controlled Test Systems

Introduction of the minicomputer has made the use of dedicated computers in areas of test and measurement economically feasible. Combinations of these machines with programmable test equipments have resulted in the introduction of automatic test systems which have applications in calibration laboratories. Implementation of these computer-controlled test systems in the calibration laboratories would automate many of the steps in the calibration process. For example, instrument calibration procedures could be written in the form of program test tapes, which are more easily revised and distributed than the present manuals; instrument performance parameters could be tested more easily using automatic test machinery; variables data could be recorded more reliably and cheaply using automatic data logging. Any well designed automatic test system will provide sufficient input/output equipment to automatically load instrument test procedures and record variables data; and will contain a computer which is easily interfaced with programmable equipments and has sufficient memory capacity to allow programming in one of the higher level languages.

A factor which has not generally been considered, however, is the reduction of complexity in automatic test systems made possible by the use of time domain test methods.

3. Performance Testing Using Pulse Techniques

Time domain test methods are much more readily incorporated into a computer-controlled system than frequency domain methods because the elements needed for stimulus generation and response measurement in time domain are pulse generators and digital-to-analog converters (stimulus); sample and hold amplifiers and analog-to-digital converters (response). These elements are natural computer peripherals and are quite easily interfaced to a computer and packaged in computer architecture. Further, they naturally fit into reflexive control modes (self test). Frequency domain test methods require oscillators (or sweep generators) which are programmable to many discrete frequencies, power amplifiers programmable to many output levels (stimulus), AC/DC converters, digital voltmeters, frequency counters, power meters, VSWR meters, etc. (response). These elements represent highly complex instruments which are costly and difficult to interface into an automatic test system. Their complexity, in turn, requires additional system downtime to assure that the system is in calibration.

The choice between time domain and frequency domain test methods is dictated by the instrument being tested. There is a natural tendency to reduce instrument bandwidth as higher accuracies are achieved, resulting in two classes of test instruments: high-accuracy narrow bandwidth, and low-accuracy wide bandwidth.

The time domain testing approach is divided into two test categories:

1. Transient response test—determination of instrument frequency bandpass.
2. Steady state test—determination of instrument sensitivity, balance and gain.

The former technique utilizes a fast pulse generator to generate a stimulus and a sample and hold amplifier/ADC to measure a response. The latter method uses a DAC to generate a stimulus and an ADC to measure a response. Dividing the test into these two categories provides two benefits in system design:

1. It is not necessary to know the absolute amplitude of the fast pulse generator in order to perform the transient response test. This is true because the computer normalizes all measurements (rise time, overshoot, topline aberrations), with respect to measured pulse amplitude.
2. Steady-state tests can be performed at DC using the more accurate DAC/ADC.

4. Comparison of Pulse and Frequency Response Measurements

The performance of electron voltmeters (EVM's) is usually checked by applying a known sinusoidal voltage at a number of discrete frequencies and measuring the output with a calibrated meter. An alternate to this technique is to apply a fast pulse to the instrument under test and measure its response. Since this fast pulse is composed of a flat frequency spectrum ranging from zero cycles (DC) to beyond cutoff of the instrument, the shape of the output pulse describes the instrument's frequency response. This section describes tests in which frequency and pulse responses of an HP-400H EVM were measured and compared at several settings of the frequency compensating networks.

Figure 1 shows a block diagram of the HP-400H EVM. This instrument is composed of an attenuator, wide-band video amplifier, full-wave rectifier, and milliammeter. A large amount of negative feedback is used around the rectifier-amplifier loop to correct for nonlinearities introduced by the amplifier and rectifier. The output milliammeter indicates the average value of the waveform, and its scale is calibrated in terms of the rms value of a sine wave.

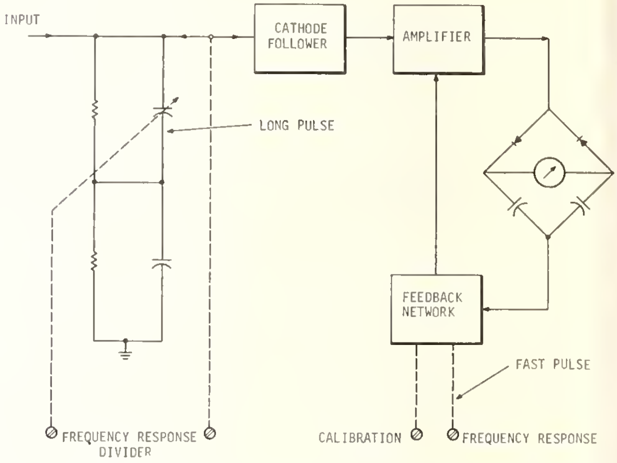


FIGURE 1. *Amplifier-rectifier voltmeter block diagram.*

The input attenuator is divided into two sections. The first is a 1000:1 capacitive-resistive divider with a conventional frequency adjust (C4). This adjustment is one of the most critical of all in the instrument, and any maintenance or frequency "tweaking" should not be made unless its performance is checked. The first test, then, was to check C4.

Frequency response of the instrument in its properly calibrated condition is shown in curve 1F of figure 2. We can see that the response is flat from 10 Hz to 4 MHz, per specification. The time response, shown in curve 1T of figure 2, shows a standard step function. By purposely misadjusting C4, the frequency response showed a break point at 1 kHz, with the output stabilizing at 80 percent (at 6 kHz) of the low-frequency value out to 4 MHz. The time domain response corresponding to this condition is shown in curve 2T of figure 2.

Examination of curve 2T shows that the pulse has a rising characteristic with time. Proper setting of C4 would produce a square pulse. The departure of the curve from a step function is found to be 20 percent, the same as that produced by frequency response methods. It is interesting to note that, experimentally, proper setting could be made in the time domain much more easily and accurately than in the frequency do-

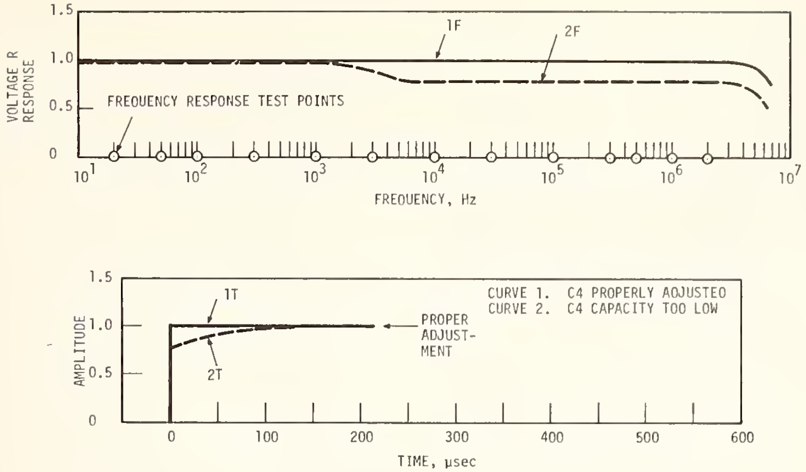


Figure 2. *Effect of misadjusting C4 on HP–400H.*

main. Note that this effect occurs at long pulse lengths, and has a time constant of approximately 100 μs. From this we would expect the "break point" in the frequency domain to be

$$\frac{0.3}{10^{-4}} = 3\text{kHz}.$$

The measured break point was very close to this value.

The second test was to misadjust C21, the main high-frequency compensator in the feedback loop. As can be seen in figure 3, too little capacity resulted in the frequency domain curve 3F and its time transform curve 3T. Note that 30 percent peaking occurred in frequency response. This is vividly shown by the ex-

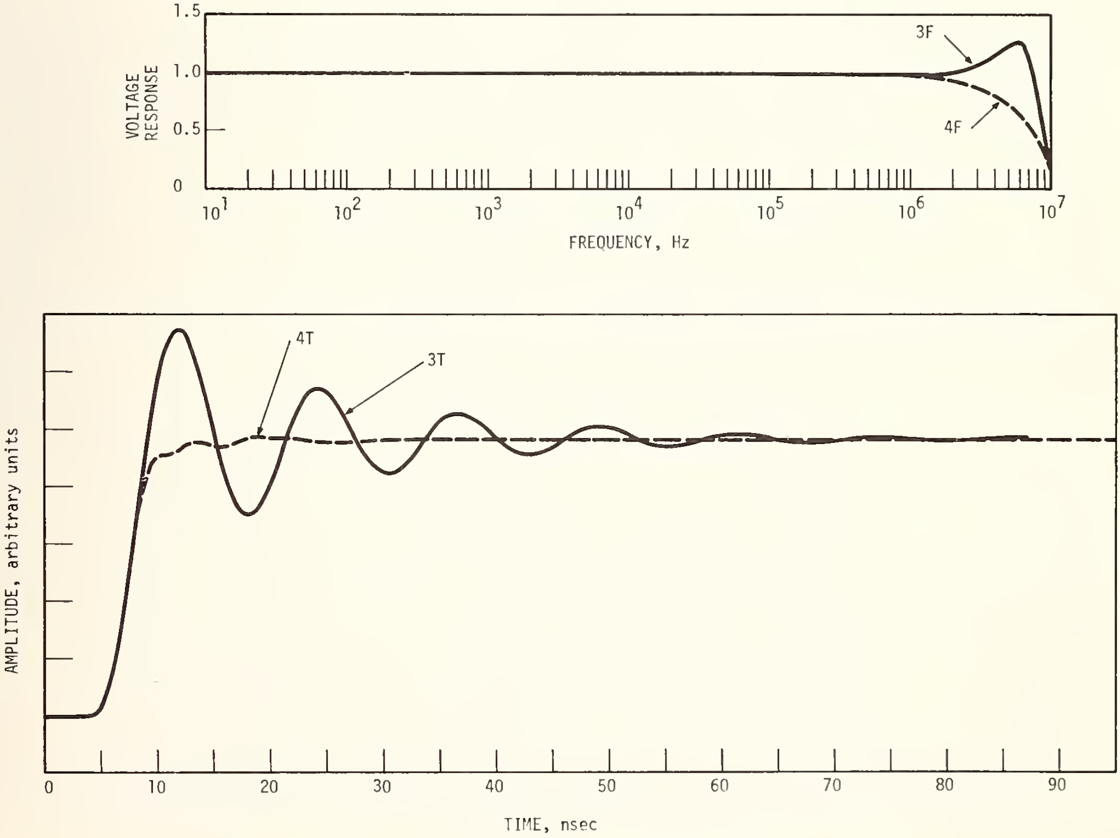


Figure 3. *Effect of misadjusting of C24 on HP–400H.*

ponential ringing in the time domain (about 2 cycles to $1/\varepsilon$). When C21 was adjusted too high, a value rolloff occurred beginning at 1 MHz (curve 4F of fig. 3). Feedback amplifiers of this type are usually compensated for maximum frequency response and, as such, will produce a small amount of peaking near the unity gain crossover frequency. The peaking is related to pulse response, phase margin, and damping ratio. In general, for maximum flat-amplitude response the quadratic damping factor will be about 0.7. This produces no peaking in the frequency domain, but will produce about 5 percent overshoot when the EVM is subjected to the step input. Thus, optimum frequency response will be achieved if the time domain check is for 5 percent overshoot.

Several other frequency compensation adjustments can be made for individual voltage ranges of the test instrument. Tests using frequency and time methods produced curves 5 and 6 of figure 4 for C14. These curves are similar to those produced by C21 (fig. 3).

Discrete frequencies normally used to test this instrument are shown by the circles on figure 2. The main amplifier has not been tested because weak tubes will cause a minor change at the very low frequencies (10 Hz) and at the very high frequencies (>1 MHz) due to a change in gain-phase margin of the feedback system. These parameters are usually checked by extensive frequency testing at the extremes of the frequency range, the very place where pulse testing is most sensitive.

Therefore, we must conclude that pulse testing is as sensitive as frequency testing in detecting misadjustment, and that pulse response measurements are much faster and better adapted to automated systems than discrete frequency measurements.

5. Applications

The EG&G model 3003 time domain test system is an interesting application of pulse test methods in a computer controlled test system.

Referring to figure 5, the system consists of ten major assemblies. A description of the function of each follows:

1. Operator Input/Output Console—Accepts program tapes and/or test console operator keyboard entries and converts these data to serial format for servicing by the stored program controller. It also converts program status messages and operator instruction to English Language statements which are typed on the operator console. Further, it logs instrument performance test results on punched paper tape for machine processing.

2. Stored Program Controller—Stores instrument test program, transmits program status messages to the test console operator, interprets and executes test pro-

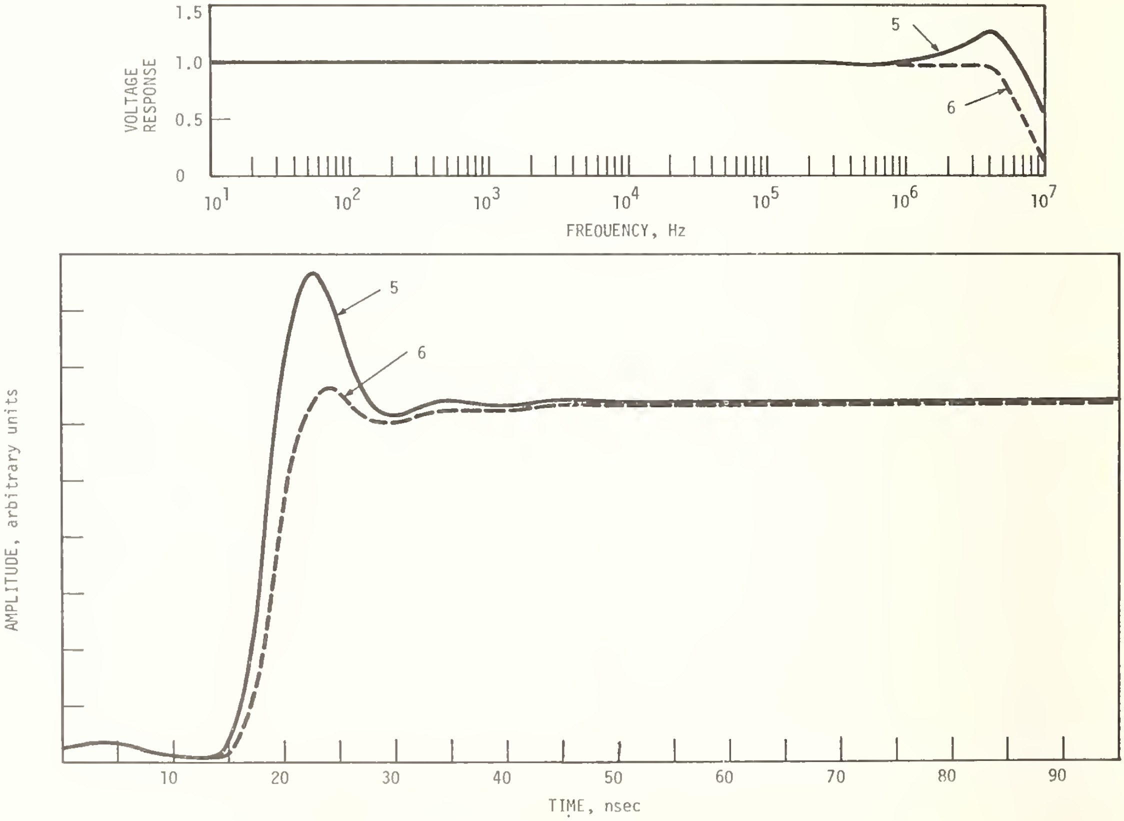


FIGURE 4. *Effect of misadjusting of C14 on HP–400H.*

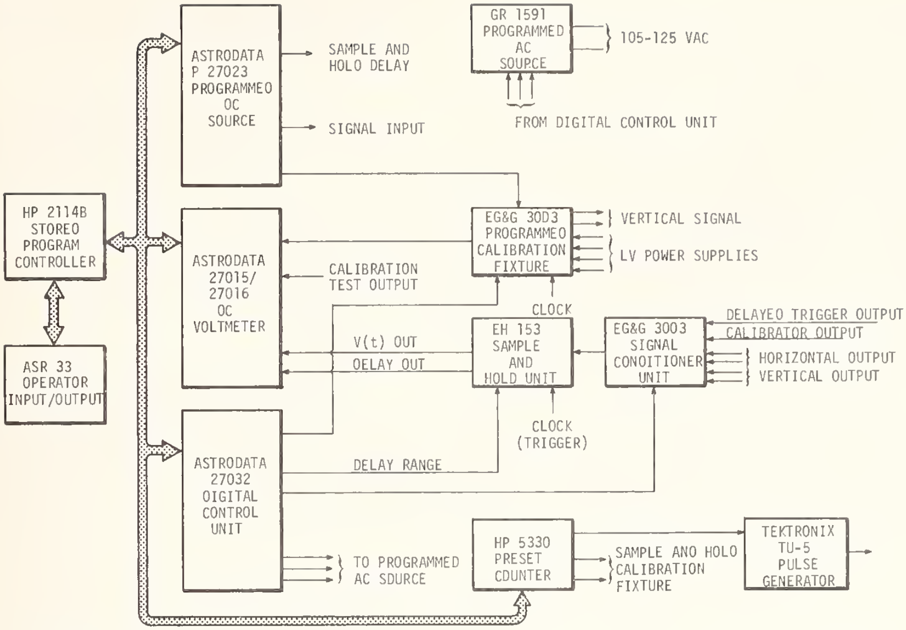


FIGURE 5. *EG&G Model 3003 time domain instrument test system; functional block diagram.*

cedure instructions. Transmits programming commands to the digital control unit, and compares test results with test procedure tolerance limits.

3. *Digital Control Unit*—Decodes programming commands from the stored program controller and routes them to the proper interface unit. Accepts digital data from measurement units and routes them to the stored program controller.

4. *Analog-to-Digital Converter*—Converts analog voltages from the programmed calibration fixture and the strobing voltmeter to digital numbers which are then fed to the digital control unit for processing by the stored program controller.

5. *Digital-to-Analog Converter*—Converts digital control unit to six analog output voltages. These voltages perform the role of stimulus to the instrument function generators and amplifiers, and of control inputs to analog interface units.

6. *Strobing Voltmeter*—Converts wide bandwidth input signals to narrow band output signals for digitization by the analog to digital converter. Under program control, it strobes signals from the programmed calibration fixture at precise times for measurements of voltage as a function of time.

7. *Programmed Calibration Fixture*—Under program control, it (1) conditions power supply voltages to proper voltage and impedance levels for measurement by the analog-to-converter unit, (2) delivers precision pulse waveforms to the instrument amplifiers for transient response tests, and (3) conditions analog voltages from the D/D converters for amplifier gain tests.

8. *Programmed Line Voltage Source*—Supplies ac power to the instrument under test, and varies the line voltage from 105 to 125 V under program control, for instrument power supply line regulation tests.

9. *Preset Counter*—Synchronizes the instrument under test with the strobing voltmeter, and services those program interrupts which signal functional completion. The counter unit provides a time base for real time sampling for the 100 μs/cm and slower oscilloscope sweep rates, and serves as an electronic frequency counter for measurement of time mark interval, pulse generator, repetition rate, etc.

These equipments, in conjunction with programmed test routines (software) developed by EG&G for instrument calibration, constitute a test system which automatically sequences the test necessary to validate performance of an instrument and which indicates accept/reject for each parameter in the performance test sequence.

6. Operational Procedures

Introduction of automated test systems into workload areas requiring skilled people can lead to job dissatisfaction, particularly if the system denies the technician the feeling of accomplishment which he derives from making a significant contribution toward some goal. The engineer who reduces the worker to the role of feeding a machine errs in his systems design; he should recognize that:

1. Computer-controlled systems are capable of high-speed data logging, automatic equipment set up, and computation (including comparison to tolerances), but are not capable of making qualitative judgements.

2. Human beings have slow responses and cannot rapidly make computations, but are capable of qualitative judgements.

Systems designed for use in calibration laboratories should delegate to the computer the functions of measurement. computation and control, but should make the operator an integral part of the system. The operator is relieved of the rather mundane tasks of equipment setup, data recording, repetitive measurement comparisons and computations, but is the sole judge of instrument overall quality, and is responsible for basic parameter determinations.

For example, in oscilloscope testing, the operator must judge CRT display quality, trigger amplifier hysteresis characteristics, amplifier unbalances, etc. The computer queries the operator on these measurements and proceeds as directed. Having stored measurement tolerances from the operator acceptances, the computer can go on to repetitive tests.

An important distinction is made herein. The oscilloscope cathode ray tube is a useful indicator, but was never intended to be a precision measurement device. Having established that the CRT is working properly, the system can extract all other parameters directly from amplifier outputs (in fact, more accurately, since the CRT reading accuracy is proportional to beam writing rate, focus, pattern distortion, flicker, etc.).

Perhaps the most unique feature of the time domain system is the interface unit, which among other things, transforms the electrical signals extracted at the CRT plates to levels suitable for processing by the strobing voltmeter without sacrificing measurement system frequency bandwidth.

7. Conclusion

Criteria which make automatic test systems suitable in calibration laboratories have been reviewed. These are:

1. Input/output compatibility with the data reporting system;
2. Computer architecture and programmability;
3. Interfaceability of programmable test equipments;
4. System complexity required to provide total calibration workload capability.

The first three criteria are met by any well-designed automatic test system. The fourth criterion can be effectively met by systems which utilize time domain test methods.

The author wishes to thank Mr. Jerry L. Hayes for valuable assistance in estimating the performance requirements for oscilloscope testing; Mr. Arthur Garafolos for assistance in defining the need for automation in calibration laboratories, and Phil Painchaud for valuable insights in metrology practices.

This work was supported by the U.S. Navy Metrology Engineering Center, Pomona, Calif.

NCSL 70

STANDARDS LABORATORY APPLICATIONS OF A COMPUTER-AUTOMATED SYSTEM

Frederick B. Seeley

U.S. Army Metrology and Calibration Center, Redstone Arsenal, Huntsville, Ala. 35481

A computer-automated calibration system whose accuracy and precision make it suitable for standards laboratory applications is described. The system has been applied to electrical, radio-frequency, electro-optical, and electro-mechanical measurements. Results are summarized that include saturated standard cell, standard resistor, resistance thermometer, micropotentiometer, and attenuator calibrations. Additional topics include the experience in computer programming, reliability, and systems operation.

Key words: Computer automation; resistance thermometers; resistor intercomparison; standard cell surveillance.

1. Introduction

The purpose of this paper is to describe how a computer-automated system is being used to perform many precision measurements typically required of a standards laboratory. The approach taken using this automatic system often has differed from classical techniques and apparatus normally used by standards laboratories. Several typical applications that will be discussed illustrate the use of an on-line instrumentation computer to perform real-time control of experiments, computer-corrected measurement and stimuli, unattended measurement processes, and the use of alternative techniques that would be impractical without the computational speed of the computer. Some applications to be discussed will also illustrate how rapidly precision measurements can be made and how statistical techniques can be used to increase further the confidence in the measurement results. It is not the intent of this paper to present the full details of each application, but rather to present an outline of the methods and apparatus used and the results that have

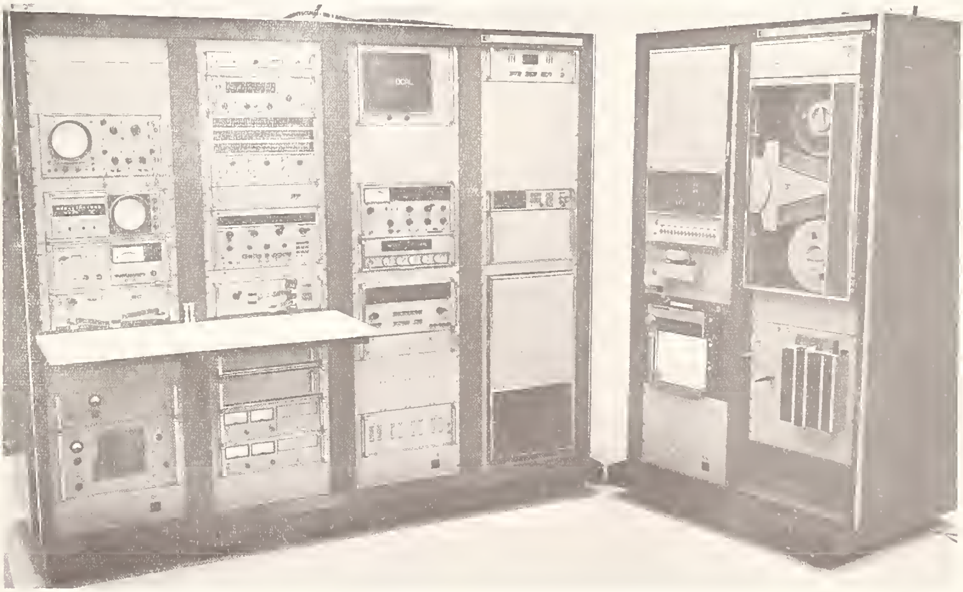


Figure 1. *Computer-automated calibration system.*

been obtained. The automatic system has been applied to intercomparison of saturated standard cells, to within ±0.2 μV, standard resistors to within 1 ppm, resistance thermometer calibration within 0.01 °C, and to the calibration of micropotentiometers and rf attenuators. The general methods used to obtain these results will be presented, as well as a brief system description, comments on the system software, operation, and general applications.

2. System Description

The computer-automated system shown in figure 1 is being evaluated for general metrology and calibration applications in the Army's calibration system. However, the system is available commercially and is representative of many typical computer controlled instrumentation systems. The extent of parameter coverage in a single system does make this one somewhat unusual, however. Measurement and stimuli instrumentation, all computer controlled, operate over the frequency range from dc to 12.4 GHz. The computer is a 16K-word memory, 16-bit-word machine with an input/output extender that houses the interface between the computer and the instrumentation. A magnetic tape recorder, photoelectric tape reader, teleprinter, and graphic terminal provide the primary peripheral equipment for handling programs and data. The instrumentation is extensive and includes two digital voltmeters, a dc voltage/current source, an ac voltage source, a ratio transformer, a wave analyzer, a frequency counter, and an *X–Y* recorder. An automatic network analyzer is included as a subsystem for making s parameter measurements of rf devices from 100 MHz to 12.4 GHz. Two switching units, a 200-channel crossbar scanner and a 4-channel 16-output distribution switch, are also included as a programmable portion of the system. The software supplied by the manufacturer of the system includes two high-level languages, BASIC and FORTRAN. The BASIC software package can be used to program the entire system, both microwave and nonmicrowave instruments. Assembly language capability also exists and has been used for some special applications.

Before discussing the measurement applications, it is appropriate to mention some of the reasons for the size of this particular automated system. First, the concept of using a single, automatic facility to make broad spectrum of measurements is being developed. In this sense, the system is multipurpose and is being used in a "job share" mode. Measurements and experiments are brought to the proximity of the machine, rather than using several different automatic systems at different locations. This operational concept relies upon the speed with which measurements may be made, upon its reliability, and also on certain automatic features which make possible 24-hr unattended operation. A second reason for developing a single multipurpose system is that Army doctrine requires that calibration service be brought to the user's site. This mobile calibration service is at lower echelon than what would normally be considered "standards laboratory" work. A development project is investigating the use of computer-automated equipment for mobile calibration operations in the Army. A mobile automatic calibration system is presently being envisaged as a multipurpose measurement and calibration system.

3. Applications

3.1. Saturated Standard Cell Intercomparisons

A group of four saturated standard cells in an air-bath has been used in our evaluations of the stability and precision of the d-c voltage measurement and source instrumentation. It was originally intended to have these four cells periodically remeasured at our standards laboratory and use in all subsequent calculations the individual cell emfs that had been assigned. However, it was noted in a simple cell intercomparison design that when the emf differences between these four cells were measured using the system's digital voltmeter and crossbar scanner, the measured results were in agreement with the differences calculated using the emfs determined in our standards laboratory to a fraction of a microvolt! These surprising results prompted a redesign of the cell intercomparison experiment based on NBS Technical Note 430.

Twelve channels of the crossbar scanner were connected to the four cells so that the 12 possible emf differences between the four cells could be measured by the system's digital voltmeter. A BASIC language program was prepared which measures each of these 12 differences and calculates the differences of each cell from the mean emf of the group, the new emf of each cell, the deviation of each observation, and the standard deviation of a single observation. Each observation is actually an average of 10 voltage measurements made by the DVM. In the cell intercomparison, the difference emfs, which are on the order of 1 to 20 μV, are measured by the DVM on its 100-mV range, whose resolution in the last window is one microvolt. However, the average of 10 or more single observations has been found by direct test to be correct to 0.2 μV plus any zero offset. The design of the cell intercomparisons does use a left-right balance technique and corrects for the zero offset in the system. The entire cell intercomparison process is very rapidly executed, taking about 12 s to perform. This time includes the 120 voltmeter readings, crossbar switching, and the calculations mentioned above.

The process has been statistically studied over two time intervals, one 16 hours long, the other 6 months long. The primary intent of the shorter term experiment was to study the precision of the instrumentation in the 16-hr period. The cell surveillance was performed, along with other DVM tests, every 30 min beginning at the close of the normal workday. The system's software clock was used to time and initiate the total experiment which lasted approximately 5 min. The process was automatically repeated every 30 min until interrupted by personnel the next morning. The results of one such overnight cell intercomparison are shown in figure 2. As can be seen from the control charts, the standard deviations for the standard cell intercomparisons are approximately 0.3 μV. Similarly, the upper and lower control limits are 0.3 μV.

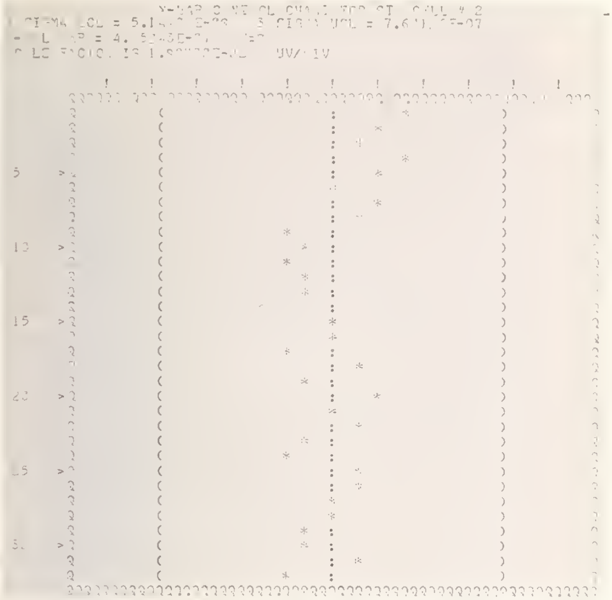


FIGURE 2a. *Typical 16–hour standard cell emf.*

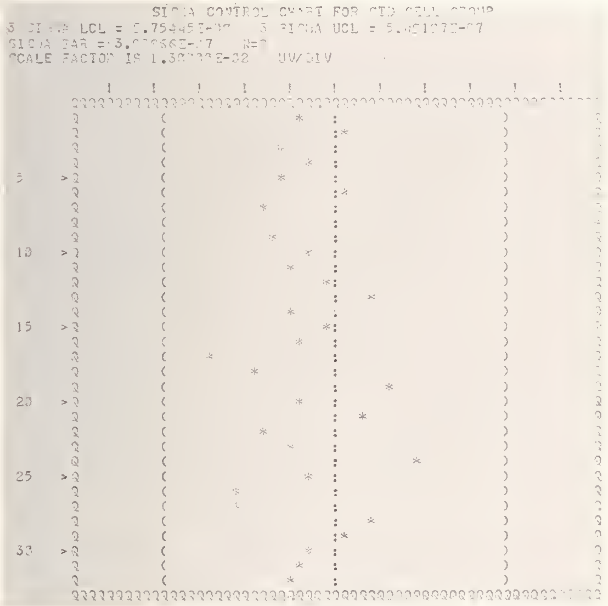


FIGURE 2b. *16–hour standard deviation of standard cell group.*

The study of the same measurement process over a 6-months period was conducted by running the standard cell surveillance program once a day. Each day on which the program was run, the data were stored on magnetic tape. A separate analysis program was written for accessing the data from tape and calculating the average standard deviation, the average emf of each cell in the period, upper and lower control limits, etc. The program also plots the above information on control charts. The results of the longer term process are consistent with those of the short-term experiment, i.e., within 0.3 microvolts.

3.2. Standard Resistor Intercomparisons

The results obtained by using the digital voltmeter to measure emf differences of 1 to 20 μV suggested that the same measuring system could be used in lieu of a galvanometer at the output of a Wheatstone bridge for measuring two terminal resistors. In this method, no attempt is made to balance the bridge. Rather, the input and output voltages of an unbalanced bridge are measured by the DVM and crossbar scanner system. For precision resistor intercomparison on the order of 1 ppm, a substitution technique is used. Four resistors are placed in mercury-wetted stands wired in a bridge arrangement. The resistance value of only one of these resistors must be known precisely and enters the program as the value of the "standard." The precise values of the remaining three resistors are not critical in the calculations. The preliminary steps of the program include asking the operator "how many unknown resistors" does he intend to measure? The operator is asked to enter (via the keyboard) the fractional or ppm value of the resistor being used as a standard.

After these preliminary manual steps, the measurement sequence is initiated by the computer after a programmed wait period. A programmable supply applies voltage to the bridge network, the digital voltmeter is switched via the crossbar across the bridge input, which is measured ten times and averaged. Then the crossbar switches the digital voltmeter to the bridge output and an average of ten measurements is obtained. Next, the polarity of the power supply is reversed and the process is repeated. These two sets of measurements are subtracted to correct for small thermal emfs and zero offset in the system. The process halts and a message is displayed that instructs the operator to "remove the standard and place the first unknown resistor in the stand." An empirically determined wait of 10 s was found to be necessary to allow for decay of transient emfs that arise when resistors are placed on the stand. The computer then initiates the same measurement process described above, to measure the bridge input and output voltages with the unknown resistor in the bridge. In less than 1 s, the ppm fractional deviation from nominal is printed out. The program continues instructing the operator to place unknown resistors in the mercury stand until all are measured and the corresponding answers are displayed.

Two mathematical models have been used to calculate the value of the unknown. The first of these can be used when the standard and unknown are nominally equal. The input impedance of the digital voltmeter is approximated as being infinite and the simple expression,

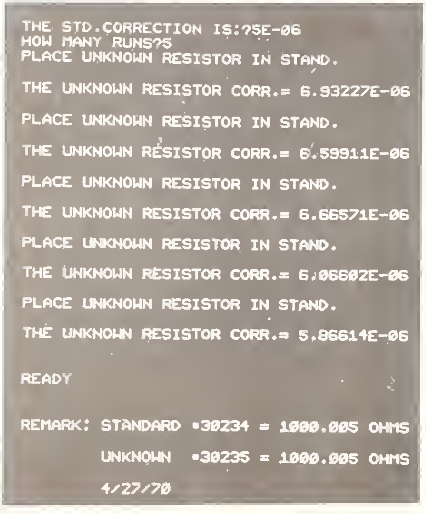
$$Cx = Cs + 4\,\frac{(Vx - Vs)}{V_{in}}$$

is used to calculate the fractional or ppm deviation, *Cx*, of the unkonwn from the nominal value. *Cs* is the ppm deviation from nominal of the standard. The measured bridge output voltages for the unknown and standard are Vx and Vs, respectively. V_{in} is the bridge input voltage. A general solution has also been used. Essentially, it consists of solving a system of five simultaneous equations that describe the bridge network. The five unknown quantities are the four currents that flow through the four resistors in the network and the product of the current times the standard (or unknown) resistor. By solving the system of equations, no assumptions are made about impedance of the digital voltmeter and the measurements can be made over a wider range of validity. Using either method, there is no delay that the operator can perceive, other than the 10-s delay mentioned above.

Some typical results of standard resistor comparisons are illustrated in figure 3. Tests have been conducted to determine the precision and resolution of the method using resistors in air at 23 °C ±0.1 °C. The precision or repeatability of the unbalanced bridge technique has not been studied statistically over a long time period. However, the range of results is generally less than 0.5 ppm when measuring 100 to 10000 Ω resistors. The accuracy of the difference measurement has been established by shunting a standard resistor with 1 MΩ (±0.01% tolerance). In summary, it has been found that the combined effect of systematic and random uncertainties is less than 1 ppm for resistor intercomparisons.

3.3. Resistance Thermometer Calibrations

The redetermination of the constants for a platinum resistance thermometer is a tedious time-consuming task in most laboratories. An approach for automating this task was selected which was intended to yield results adequate for most applications. The goal was to automatically redetermine the thermometer constants and calculate a new table of temperature and resistance ratios so that the thermometer could be used to make measurements of temperatures with uncertainties not exceeding 0.01 degrees Celsius. The approach which was selected is to use a standard and test thermometer in thermal equilibrium with a liquid bath or other gradient-free environment. The resistance of these two thermometers is measured at three or more temperatures, and each temperature calculated. From these data, it is a comparatively simple matter to calculate the least squares coefficients of a second degree polynomial. In turn, these coefficients can be used to generate a new table of resistance or resistance ratio as a function of temperature.



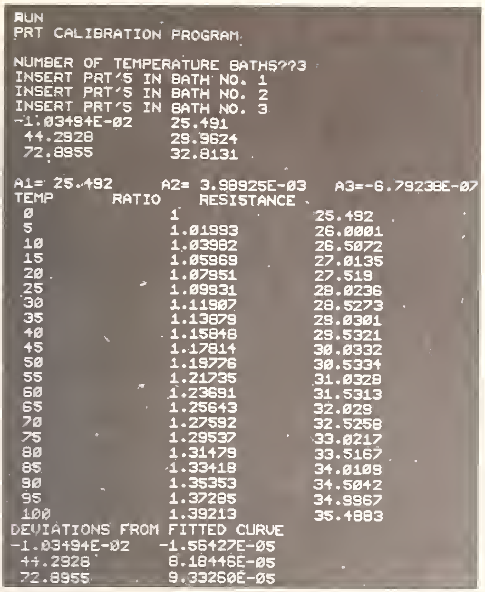
```
THE STD.CORRECTION IS:?5E-06
HOW MANY RUNS?5
PLACE UNKNOWN RESISTOR IN STAND.

THE UNKNOWN RESISTOR CORR.= 6.93227E-06

PLACE UNKNOWN RESISTOR IN STAND.

THE UNKNOWN RESISTOR CORR.= 6.59911E-06

PLACE UNKNOWN RESISTOR IN STAND.

THE UNKNOWN RESISTOR CORR.= 6.66571E-06

PLACE UNKNOWN RESISTOR IN STAND.

THE UNKNOWN RESISTOR CORR.= 6.06602E-06

PLACE UNKNOWN RESISTOR IN STAND.

THE UNKNOWN RESISTOR CORR.= 5.86614E-06


READY


REMARK: STANDARD •30234 = 1000.005 OHMS

        UNKNOWN  •30235 = 1000.005 OHMS

        4/27/70
```

Figure 3. *Resistor intercomparison output.*

The system's digital voltmeter and crossbar scanner are used to measure the voltages across the standard and unknown or test thermometer, and also the voltage across a standard resistor. The resistor and two thermometers are connected in series and 2 mA thermometer current is provided by a programmable constant current source which is stable to 10 ppm per day. The resolution and linearity of the digital voltmeter are adequate for determining the resistance ratios of the two thermometers with respect to the standard resistor. For example, the linearity of the digital voltmeter has been found by direct test to be better than 10 ppm. This amounts to an equivalent temperature error of less than 0.0005 °C. The resolution of the digital voltmeter on its 100 mV range is limited to 1 μV for a single observation which corresponds to a temperature resolution of 0.005 °C. By averaging ten or more digital voltmeter observations, a resolution approaching 0.001 °C has been achieved.

A BASIC language program has been prepared which accomplishes the calibration of one platinum resistance thermometer with reference to a standard thermometer. Figure 4 illustrates the instructions, data, and results as displayed on the system's graphic display terminal. In this example, calibration is performed at the ice point, room temperature, and 70 degrees. The software clock is used to program a 5-min wait period to allow each thermometer to reach thermal equilibrium with the bath. After this 5-min wait, the resistor and two thermometer voltages are automatically measured and stored in memory. The operator is instructed to place thermometers in the next bath. The process is repeated until the third set of data is obtained. The temperature is then calculated from the measurement data for the standard resistance thermometer and its constants which have been previously included in the program. The measurement data, temperature, and resistance of the unknown thermometer are listed. A solution for three thermometer constants, the zero resistance, the coefficient for a linear temperature term, and a coefficient for a quadratic temperature term, is found. These constants are used to generate a table of resistance ratio and resistance as a function of temperature for the unknown thermometer. In the example shown in figure 4, the table has been generated in 5-deg increments, which of course is an arbitrary choice. Any temperature interval may be chosen.

The accuracy of the results has been verified by intercomparing thermometers each of which have manufacturer's or NBS calibration reports. In general, the goal of ±0.01 degrees uncertainty appears to have



```
RUN
PRT CALIBRATION PROGRAM

NUMBER OF TEMPERATURE BATHS??3
INSERT PRT'S IN BATH NO. 1
INSERT PRT'S IN BATH NO. 2
INSERT PRT'S IN BATH NO. 3
-1.03494E-02    25.491
 44.2928        29.9624
 72.8955        32.8131

A1= 25.492     A2= 3.98925E-03   A3=-6.79238E-07
TEMP      RATIO    RESISTANCE
 0               1               25.492
 5               1.01993         26.0001
 10              1.03982         26.5072
 15              1.05969         27.0135
 20              1.07951         27.519
 25              1.09931         28.0236
 30              1.11907         28.5273
 35              1.13879         29.0301
 40              1.15848         29.5321
 45              1.17814         30.0332
 50              1.19776         30.5334
 55              1.21735         31.0328
 60              1.23691         31.5313
 65              1.25643         32.029
 70              1.27592         32.5258
 75              1.29537         33.0217
 80              1.31479         33.5167
 85              1.33418         34.0109
 90              1.35353         34.5042
 95              1.37285         34.9967
 100             1.39213         35.4883
DEVIATIONS FROM FITTED CURVE
-1.03494E-02   -1.56427E-05
 44.2928        8.18446E-05
 72.8955        9.33260E-05
```

FIGURE 4. *Resistance thermometer output.*

been attained in the range of 0 to 100 degrees Celsius, though the process is still under study to determine its actual limit. There is no reason that the program and apparatus cannot be expanded to calibrate more than one test or unknown thermometer at a time. Core storage, analog switching, and the constant current source are adequate to handle 10 or more thermometers. The practical limit of the number of thermometers that could be tested in one 15-min period is felt to be the size of the gradient-free temperature baths that would be suitable.

3.4. Rf Applications

Other applications of this computer-automated system have included rf measurements from 100 MHz to 12.4 GHz using the Network Analyzer subsystem. The Network Analyzer has been described in the literature [1, 2][1] and will not be repeated here. The Network Analyzer has been experimentally evaluated by measuring rf devices that had been previously measured by NBS or our own standards laboratory. Results of such measurements have more than substantiated the accuracy claims of the manufacturer. A combination of the rf and dc system instrumentation is being used to determine the ac–dc differences of rf micropotentiometers to better than 1 percent relative to a standard micropotentiometer.

4. System Software

The BASIC language compiler supplied with this system is similar to the BASIC language used in commercial time-sharing computer services. It provides conversational-style, on-line program modification in the same way. This is commonly referred to as an interpretive compiler. The BASIC compiler for this system allows external subroutines to be accessed by a CALL statement. Such subroutines or instrument drivers were provided by the manufacturer to supply data to, control, and read data from the measurement and control instruments in the system.

This interpretive or on-line mode, while expensive in terms of computer core (requiring approximately 6K of core), has been found to be convenient and satisfactory. The measurement application programs discussed in this paper all were prepared in the BASIC language by personnel with no previous programming experience. No BASIC language application programs were provided by the system manufacturer. The time required to prepare and debug a measurement program varies, of course, with its complexity. The program using the simple model for the unbalanced Wheatstone bridge was prepared in approximately 5 hr. The standard cell surveillance measurements program was prepared in less than one day. However, the refinements and experimentation with a working program before it can be regarded as finished have taken several weeks to a month.

5. Conclusion

The measurement of emf, resistance, and temperature are common problems of most standards laboratories. The automated apparatus and methods described above do not necessarily yield results that represent the ultimate with respect to precision and total measurement uncertainty. However, the measurement results are satisfactory for the majority of calibrations performed by industrial and Department of Defense standards laboratories. The applications discussed in this paper were chosen to illustrate how little or no measurement uncertainty need be sacrificed when automating a measurement process to increase productivity and reduce skill levels.

The author wishes to acknowledge the special efforts of Mr. William J. Barron for his direct assistance in both the supporting experimental work and in the preparation of this paper. Many other staff members of the U.S. Army Metrology and Calibration Center have also contributed to this work. Among those whose efforts should be acknowledged are M. Shelton, George Marshall, and R. Free.

6. References

[1] Hackborn, R. A., An automatic network analyzer system, Microwave J. 11, No· 5, May 1968.

[2] Hand, B. P., Developing accuracy specifications for automatic network analyzer systems, Hewlett-Packard J. (Feb. 1970).

---

[1] Figures in brackets indicate the literature references at the end of this paper.

NCSL 70

COST REDUCTION IN CALIBRATING BOLOMETER MOUNTS

William F. Dentinger and Louis dePian

Weinschel Engineering Co., Inc., Gaithersburg, Md. 20760

Ordinarily a great deal of time is spent in calibrating bolometer mounts. Manual bridges require considerable care for proper balances, bias adjustments, and calibration procedures. New instruments have been designed to automate many of the manual operations. These instruments are self-balancing and maintain precise power levels with minimum adjustments. Due to the fact that in previous setups a series of measurements had to be made in order to average out errors caused by temperature changes, the new automated system described in this paper can save about 90 percent in measurement time. In addition, a less skilled operator can perform the measurement with the same accuracy.

Key words: Automated dc substitution; bolometer calibration; radiofrequency power measurement; self-balancing Wheatstone bridge.

1. Introduction

This paper presents a new technique in making rf (radiofrequency) power measurements which results in an overall cost reduction in the calibration of bolometer mounts. Employing this technique permits a calibration accuracy of better than 99 percent. The range of power involved is from 0.5 to 10 mW over the frequency range 100 MHz to 12.4 GHz for coaxial systems and 2.6 to 12.4 GHz for waveguide systems.

Power measurements of this type are currently needed in (1) primary standards laboratories, (2) secondary standards laboratories, (3) inspection stations, and (4) production testing facilities.

The measurement approach is known as dc substitution. It uses a sensitive element (a bolometer) whose electrical resistance varies with temperature. This element is placed in a Wheatstone bridge circuit as shown in figure 1. When the proper amount of dc power is supplied to the bridge, the bolometer element heats to the proper temperature to make its resistance equal to that of the other three resistors, and the indicator will show a null. If we now supply an additional rf power to the bolometer element, it will heat up to a higher temperature, thus changing its resistance and unbalancing the bridge. However, if we also decrease the dc power to the bridge by an amount equal to the applied rf power, the temperature of the bolometer element will remain the same. This keeps the bridge in balance, and the indicator nulled. The amount of applied rf power is assumed equal to the difference of the dc power before and after applying the rf power:

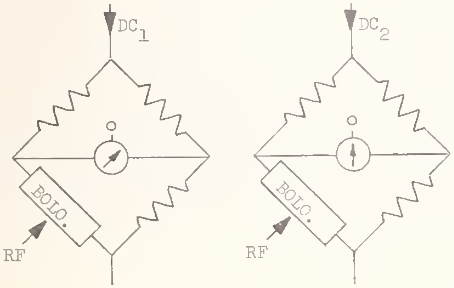


FIGURE 1. *Dc substitution method, assuming unity calibration factor for bolometer.*

$$\mathrm{rf} = \mathrm{dc}_1 - \mathrm{dc}_2 = \mathrm{dc\ substituted}.$$

This method of measurement by using dc substitution has proven to be one of the most accurate and is the basis of most of the existing measurement setups. However, there is one important consideration: not all of the rf power incident on the bolometer mount reaches the bolometer element. Therefore the actually applied rf power is not exactly equal to the dc substituted power. A small correction factor, called the "calibration factor," is needed:

$$\text{Calibration factor } K = \frac{\text{dc substituted power}}{\text{rf incident power}} = \frac{P_{\mathrm{dc}}}{P_{\mathrm{rf}}}.$$

In order to determine the calibration factor of an unknown test bolometer mount (i.e., to calibrate a test bolometer mount), we must compare it with a standard bolometer mount. The procedure is as follows (see fig. 2). Since we can accurately measure the dc substituted power (P''_{dc}) of a test bolometer mount, its calibration factor (K_{T}) can be determined if we can also accurately determine the rf power incident upon the bolometer mount. This rf power (P'_{rf}) is calculated by measuring the dc substituted power (P'_{dc}) in a standard bolometer mount and knowing its calibration factor (K_S) with an accuracy traceable to the National Bureau of Standards: $P'_{rf} = P'_{dc}/K_S$.

The essence of the calibration is therefore to calculate accurately and conveniently the rf power incident upon the test bolometer mount.

2. Previous Method

The method previously used to calculate this rf power required a laborious procedure to determine first the dc substituted power (P'_{dc}) to the standard bolometer mount. The essential steps employed in this procedure were as follows:

1. Supply d-c voltage to the standard and manually adjust the voltage until the bridge is nulled. This is accomplished by adjusting a variable potentiometer.
2. Compare the dc voltage applied to the bridge with an accurate dc voltage calibrated with a precision potentiometer.
3. Read the dc voltage volue E_o.
4. Apply rf power to the standard and repeat step 1.
5. With an external potentiometer, measure the change in dc voltage to the bridge by comparison with the voltage E_o.
6. Read the change in d-c voltage $\triangle E$.

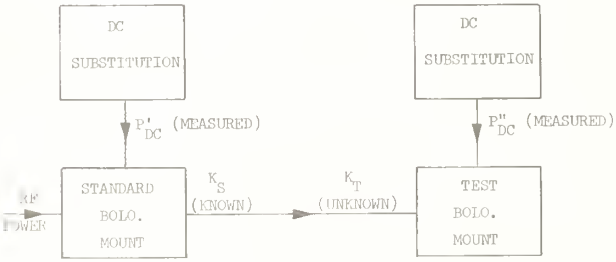


FIGURE 2. *Determination of calibration factor* K_T: *Calculate*

$$P'_{rf} = P'_{dc}/K_S,\ K_T = P''_{dc}/P'_{rf}\ .$$

7. Calculate the dc power using the formula

$$P'_{dc} = 0.025R_o\ (2E_o - \triangle E)\ \triangle E \text{ mW}$$

(where R_o is the bridge resistance)

8. Calculate the unknown rf power by using the formula

$$P'_{rf} = \frac{P'_{dc}}{\text{calibration factor of standard bolometer mount}}$$

The total time required for an experienced operator to make the measurement by following these steps is about 10 min. However, during the relatively long time required to perform these steps, the room temperature is unlikely to remain constant, and this will introduce an error in the measurement. Additional errors will also be involved if during the measurement time the rf power source varies in magnitude and frequency. In order to reduce the effect of these errors, the measurements must be repeated from three to five times. Thus the total time required to make an accurate (better than 99%) measurement is usually about 30 min at best.

3. New Method[1]

A new instrument developed by Weinschel Engineering, called the *precision rf power level controller*, greatly simplifies and automates the dc substituted power measurement we previously described. The salient features of its design are as follows:

(a) provision for about 30 mW of dc power to the standard bolometer mount;

(b) decrease of dc substituted power by accurate fixed amounts, 0.5, 1.0, 5.0, or 10.0 mW.

(c) through an automatic leveling loop, the rf power supplied to the bolometer mount is forced to remain equal to the preselected dc substituted power, i.e., 0.5, 1.0, 5.0, or 10.0 mW.

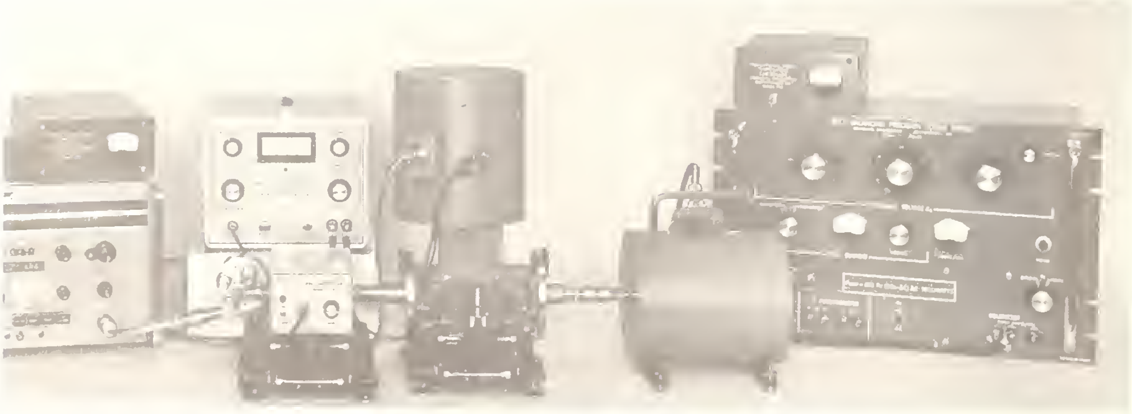


FIGURE 3. *Measurement setup using new method.*

---

[1] Weinschel Engineering Application Note 12, Calibration of bolometer mounts with leveled power, Form 867–3/70.

Because of these design features, the measurement is now simplified, and involves only the following steps:

1. Supply d-c voltage and manually adjust it until the bridge is nulled. This step of the procedure has been greatly simplified.

2. Select desired decrease of power level (0.5, 1.0, 5.0, or 10.0 mW, to within ± 0.1% + 1 μW) by setting a switch.

3. Apply rf power, which will automatically be equal to the selected power of step 2.

4. Calculate the unknown rf power using the formula

$$P'_{\mathrm{rf}} = \frac{\text{selected dc substituted power}}{\text{calibration factor of standard bolometer mount}}$$

The total time required for this new method is about 3 min, providing a saving of 90 percent of the time previously needed. To obtain other desired power levels for dc substitution, external resistors may be added to the precision rf power level controller. Figure 3 shows a complete measurement setup using the new method described in this paper.

4. Comparison of Methods

The previous method required about 30 min by an experienced operator. The new method requires only 3 min for the same measurement for the same accuracy, and its simplicity allows a less experienced operator to make the measurement. The savings in time and costs for the measurement are obvious.

NCSL 70

SESSION 2: LABORATORY MANAGEMENT AND OPERATIONS REPORTS

Chairman: F. J. Dyce

Martin Marietta Company, Orlando, Fla. 32805

MEASUREMENT COMPARISON PROGRAMS

Herbert S. Ingraham, Jr.

RCA Corporation, Defense Electronic Products, Moorestown, N.J. 08057

The measurement comparison program of 1965 circulated unknowns in pairs, allowing use of Youden diagrams to distinguish systematic from random error. In 1969, two pairs were sent out several months apart, allowing check of the correlation effect; a round robin was started on acceleration; a 24-inch end standard was included in the physical package.

Key words: Accelerometer round robin; computer program for Youden diagrams; correlation effect; end standard of length.

Innovation in metrology as a key to progress is the theme of our Conference. Certainly the establishment of a Measurement Comparison Program of national scope meets the criterion for innovation. The basic program is now a historical innovation. The current question, to paraphrase another, is, "What have you innovated for me lately?"

To determine the changes which constitute innovation in today's Measurement Comparison Program, we must compare the program as it stood at the 1968 Standards Laboratory Conference and what useful changes have taken place since that time.

The concept of circulating measurement unknowns in pairs was, in itself, a significant innovation (in 1965) in the Comparison Program. This allowed the use of the Youden diagram concept to separate, to a high degree, systematic error from random error in the calibration and measurement process. This was a first in the measurement comparison process and was an extremely valuable step.

It was felt, however, that measurement of a pair of unknowns at nearly the same point in time left something to be desired. Laboratories traditionally repeat the same type of measurement several times a year, and it was felt that, if both items of a pair were measured at the same time, random errors would tend to be masked by an undesirable "correlation effect."

To obviate this correlation effect, we are currently splitting our "pairs" so that they are measured at different times, separated by at least a month. When the results of this program are analyzed, we would expect to have a truer picture of a laboratory's measurement capability than was possible before, particularly if the correlation effect was significant.

One such split has already been completed in the mass comparison and will be reported by Lloyd B. Macurdy. These data, and data from other programs where the split pair technique can be applied, should provide a base for evaluation of the significance of correlation effect.

Other program changes since 1968 include the expansion of the Program to other areas of metrology than were previously included. These include the addition of a long (24-in) end standard in the physical package, the separate circulation of the mass packages, and, more recently, the start of the first round robin comparison in acceleration, currently circulating to 20 participants. (The acceleration comparison is the first in which the pairs of unknowns were deliberately separated to evaluate the correlation effect.)

In the last major round robin program, all data reduction and analysis were accomplished by the route supervisors. This was a lengthy and burdensome process, accomplished only through the dedication of the route supervisors. Now the task of data reduction and analysis has been assumed by the National Bureau of Standards, and they have added a certain amount of innovation.

Primary to this effort has been the development of a plotting program for the CalComp plotter to generate the Youden diagram directly from the data and to obviate the manual plotting done before. In addition to this, a handbook has been developed to assist in the analysis of the Youden plot, for use by participants in analysis of their results. This plotting program can be made available to those who are conducting measurement comparison programs, either as an intercompany program or as an area program, and who wish to use the Youden presentation for data analysis and have a CalComp plotter available.

The value of the Measurement Comparison Program can be improved through innovation in the future. Other comparison techniques, currently under consideration, will result in pilot comparisons of limited scope to aid in evaluation of the techniques. The most useful of these will be incorporated into the Program to provide the laboratories of the metrology community with the most effective method of assessing the contribution of their own innovations to their measurement capability.

NCSL 70

REPORT ON THE 1968–69 MASS MEASUREMENT AGREEMENT COMPARISON ROUND ROBIN

Lloyd B. Macurdy

Staff Metrologist, Mettler Instrument Corporation, Princeton, N.J. 08540

Seventeen laboratories took part in the round robin measurements of the NCSL Mass Comparison packages during 1968 and 1969. In order to speed up the measurements the laboratories were divided into two groups. The weights were calibrated by the NBS Mass Laboratory at the beginning and again at the end, and Mettler Instrument Corporation measured all sets near the middle of the series. Two sets of weights were sent to each laboratory at times separated by two months or more in order to provide data on errors made on the same day (within-group variance) and on errors between measurements at longer intervals (between-group variance). Each set of weights consisted of four pairs of one-piece stainless steel weights of 100 g, 25 g, 10 g, and 1 g. Data include weighing errors of the various laboratories and Youden plots of the measurements. Some errors proved to be larger than had been expected. The results illustrate the need for verifying the accuracy of measurement on some rational basis.

Key words: Between-group variance; mass comparisons of 1969; systematic and random weighing errors; within-group variance.

This round robin test is of especial interest because it includes 15 laboratories which do not participate in the NBS Measurement Analysis Program for Mass Measurement. Two laboratories which do participate in the NBS MAP program are also included. They are the IBM Measurement Standards Laboratory in San Jose, California, and Mettler Instrument Corporation in Princeton, New Jersey. There is very little information available about the capabilities for mass measurement in laboratories outside the NBS MAP program. These test comparisons provide a sample of the errors which occur in various standard laboratories.

Eighteen laboratories expressed a desire to take part in the mass comparison tests. One laboratory withdrew before the start, leaving 17. Measurements were made by the National Bureau of Standards Mass Laboratory at the beginning and again at the end, and by Mettler Instrument Corporation near the middle of each schedule, and by 16 other laboratories.

The test packages consist of pairs of weights of 100 g, 25 g, 10 g, and 1 g. Each participant received two packages at times separated by several weeks or months. In order to reduce the time required, the participants were divided into two groups. One group included the Midwest and far-West areas. The other included the East and South. Four packages were prepared and circulated, two for each group. All four packages were mailed from the National Bureau of Standards on December 2, 1968. Package A-1 (weights 1, 2) was completed in September 1969, Package A-2 (weights 3, 4) in October 1969, and Packages B-1 (weights 5, 6) and B-2 (weights 7, 8) were completed in April 1969. The weights are of one-piece stainless steel, which provides freedom from certain sources of variability which would be associated with screw-knob type of construction, and with plated or lacquered surface finish. We arranged to take test data on pairs of weights because of the advantages of analyzing data in pairs. Youden plots can show deviations within pairs taken on the same day or within pairs taken on different days. The NBS values also make it possible to plot the errors with reference to a "zero error."

Two questions are of especial interest: (1) What are the errors of measurement? and (2) How well is the uncertainty estimated? Each participant was instructed to weight the test weights as they would weigh standard weights. The method to be used was left entirely to the participant. Each participant was also asked to estimate the systematic and random components of the uncertainty.

The results of the test are shown in figures 1 through 8 for each of the four loads in the two packages. Weighing errors are plotted with reference to the NBS values and are shown as circles in groups of four for nominally identical weights. Measurements by the National Bureau of Standards and by Mettler are identified, while data for the other participants is designated by code number. The uncertainty as estimated by the participant is shown by a vertical line which represents the plus or minus sum of the estimates for the systematic and random components. The precision actually obtained is shown by the scatter within the groups of four. In 64 percent of the groups, the precision as indicated by the scatter is comparable to the scatter of the NBS measurements. By this I mean that the scatter is not greater than about two or three times the range of the NBS values.

Youden plots of the data in figures 9 to 13 show a pronounced tendency for the points to be scattered along a diagonal line, indicating the presence of systematic error. In these figures the NBS values are shown as stars and the group mean is shown as an asterisk. Comparison of figure 9, showing data taken for a pair on the same day, with figure 13, showing data taken for a pair on different days, indicates that the correlation effect is slight for 100 g weights.

To summarize these results, systematic error was larger than the estimates of uncertainty in eight of the groups of four, involving five different laboratories. Imprecision was larger than anticipated in nine of the groups of four, involving six different laboratories. It appears that in 36 percent of the groups the precision was such that it is subject to improvement if that is desired. In 14 groups of four, or 22 percent, the estimate of uncertainty was too small. In 12 groups of four, or 19 percent, the estimate of uncertainty seems unduly large. The measurements are much better than their estimates. Thus there is difficulty with either overestimation or underestimation of the uncertainty 43 percent of the time.

One way in which overestimation of the uncertainty can occur is by reliance on manufacturer's tolerances as the basis for accuracy statements. Any tolerance statement by a manufacturer applies to the limits on the error in a large number of items. Most of the individual items will have errors smaller than the limits for the entire group. In the case of a tolerance on the error of combinations of built-in weights, only certain combinations of dial settings can lead to the maximum error. The remaining combinations will have smaller errors. Tolerances have their proper place in purchase specifications, but more detailed information is needed for estimates of uncertainty.

Some simple, rational method is needed in order to provide a basis for estimating the uncertainty. The use of corrections for the individual weights of a reliable set of standard weights will provide more precise information than can be obtained by reference to the tolerances.

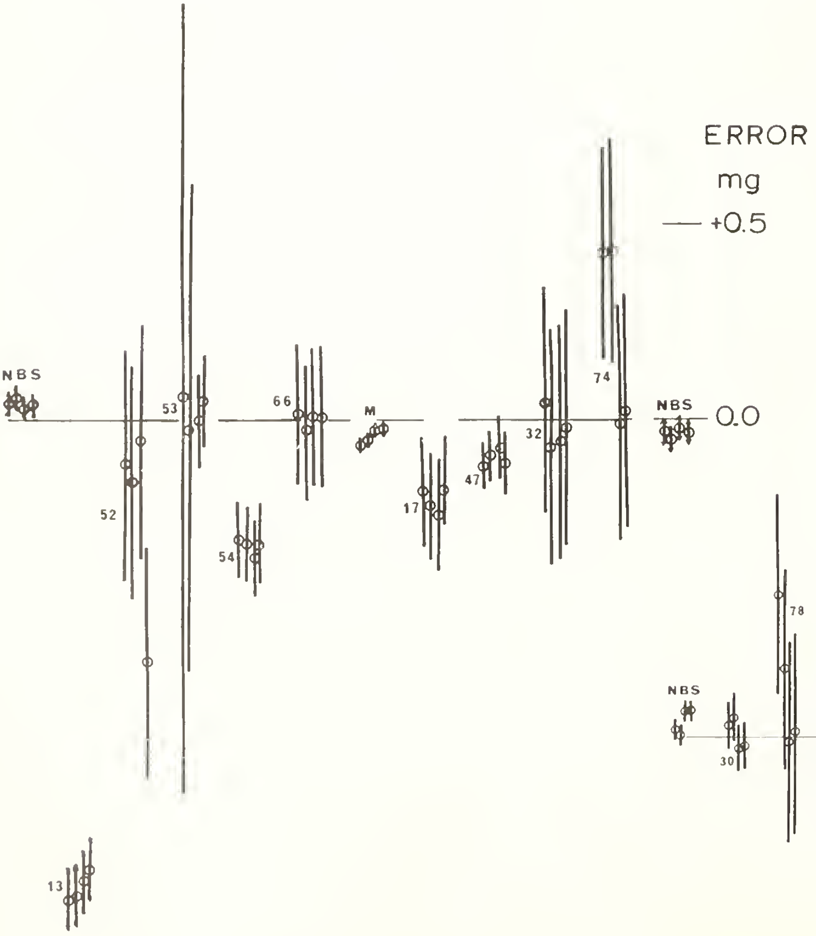


FIGURE 1. *Errors in weighing 100-g weights, group A.*

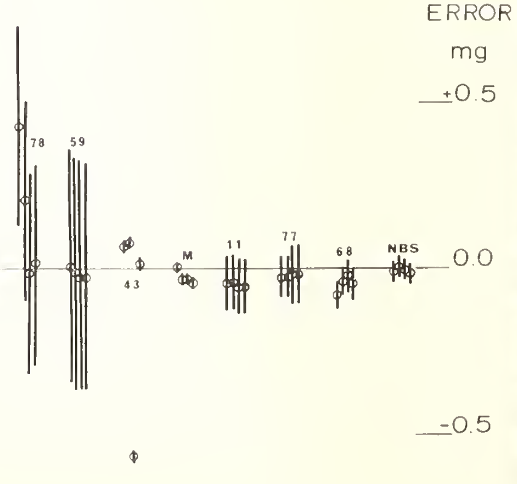


FIGURE 2. *Errors in weighing 100-g weights, group B.*

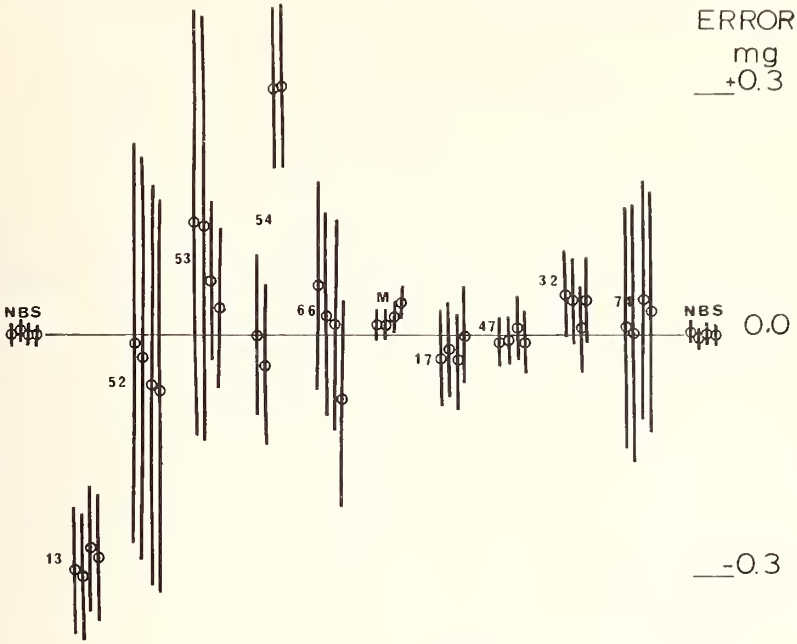


FIGURE 3. *Errors in weighing 25-g weights, group A.*

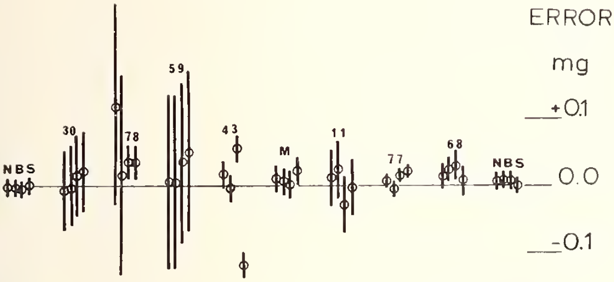


FIGURE 4. *Errors in weighing 25-g weights, group B.*

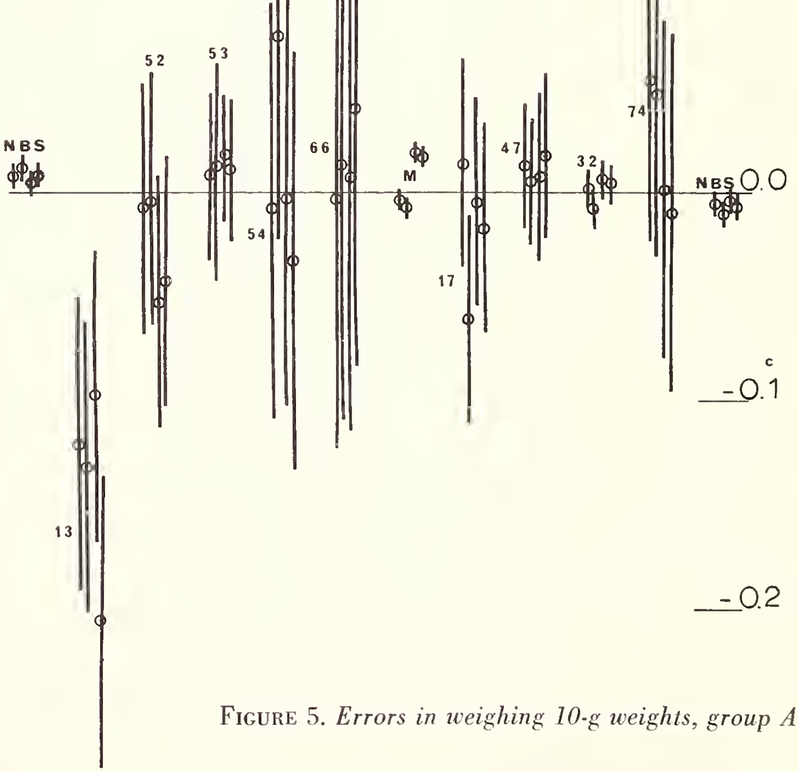


FIGURE 5. *Errors in weighing 10-g weights, group A.*

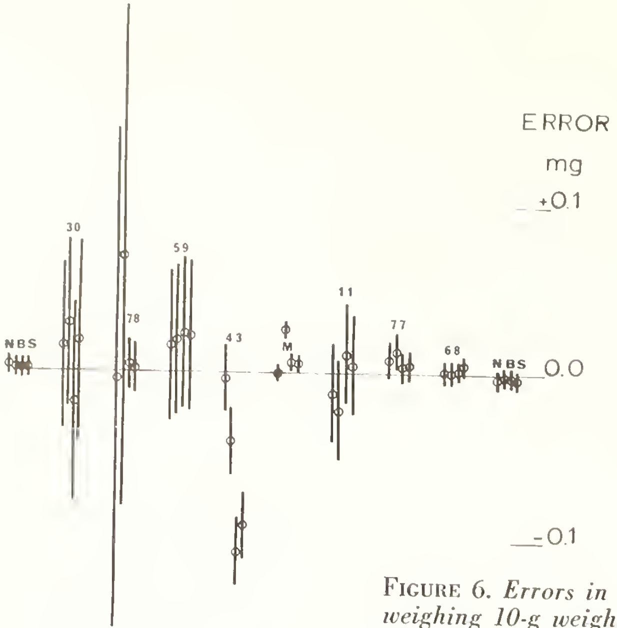


Figure 6. *Errors in weighing 10-g weights, group B.*

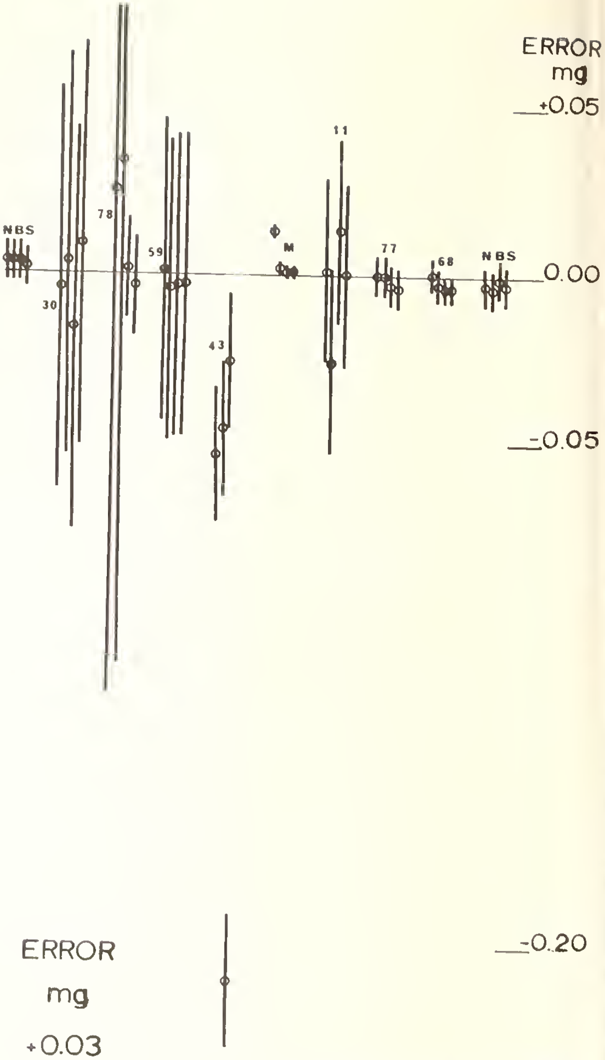


Figure 8. *Errors in weighing 1-g weights, group B.*

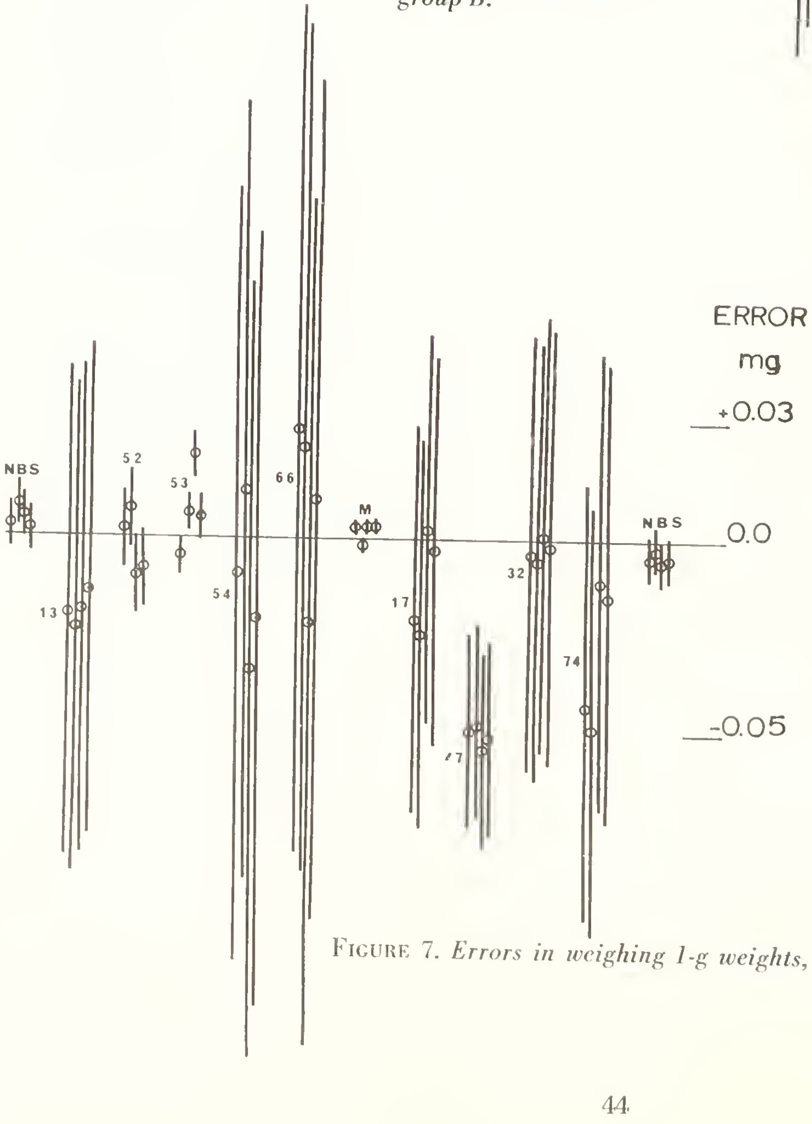


Figure 7. *Errors in weighing 1-g weights, group A.*

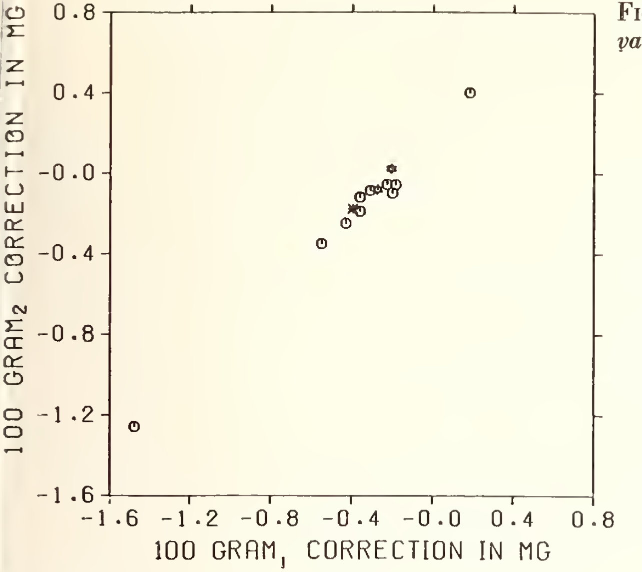


Figure 9. *Youden plot of 100-g values, package A–1.*

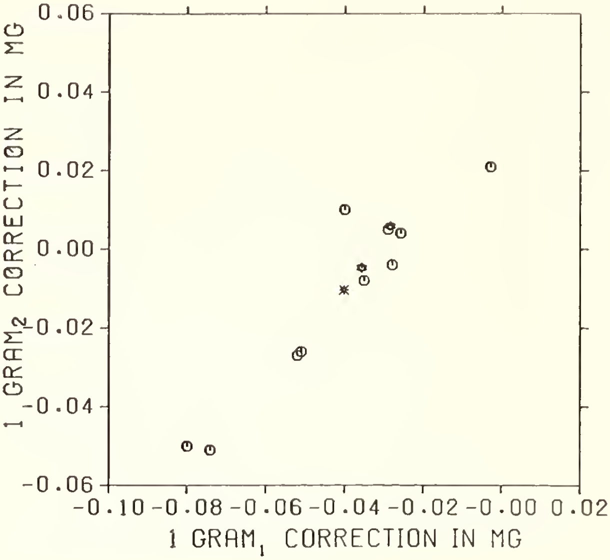


Figure 12. *Youden plot of 1-g values, package A–1.*

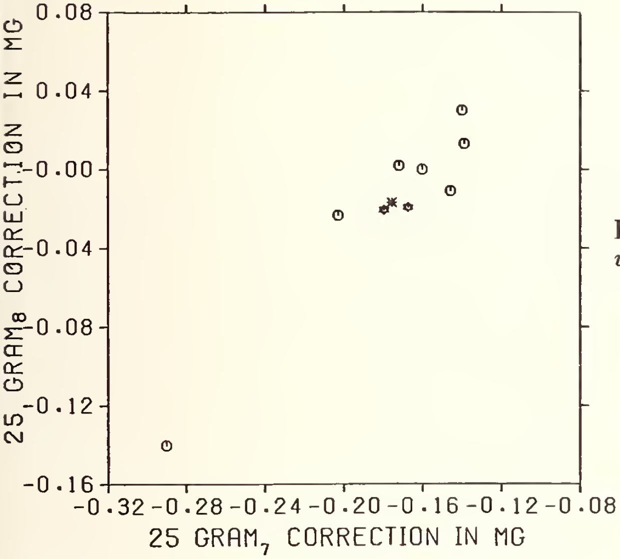


Figure 10. *Youden plot of 25-g values, package B–2.*

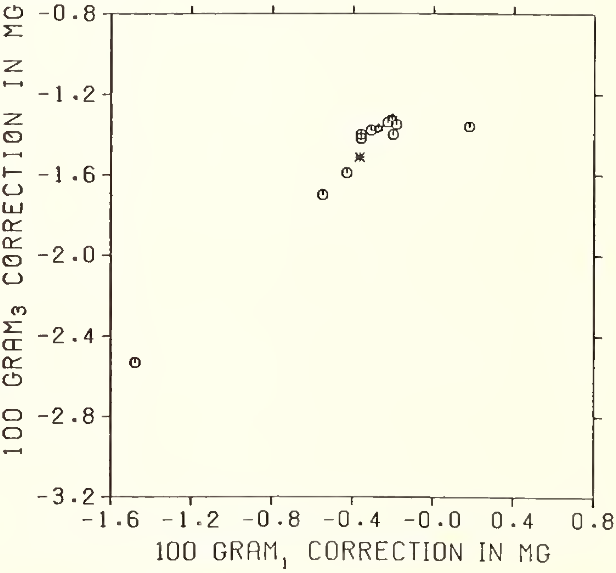


Figure 13. *Youden plot of 100-g data taken on different days, packages A–1 and A–2.*

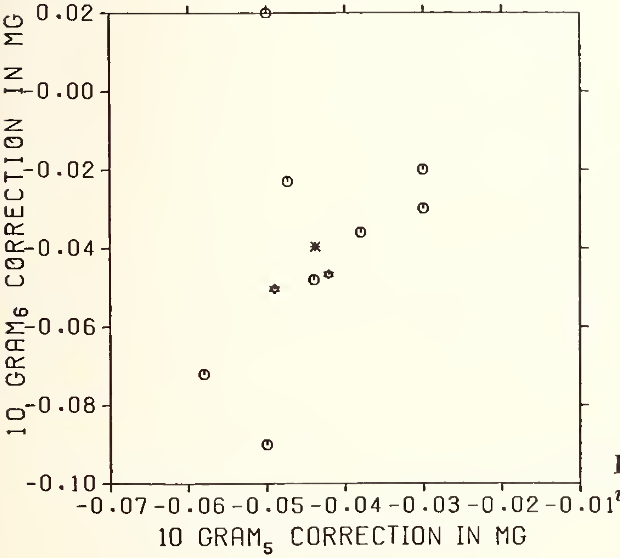


Figure 11. *Youden plot of 10-g values, packagt B–1.*

NCSL 70

NCSL SPECIFICATION PRESENTATION

Frank J. Dyce

Martin Marietta Company, Orlando, Fla. 32805

This paper describes in summary the requirements of the National Conference of Standards Laboratories "Calibration System Specification." It indicates how the specification was written by members of the NCSL Specifications Committee in answer to a DOD request. The specification contains the minimum essential requirements of a calibration system. The paper discusses the steps required to approve the specification as a recommended practice and to obtain Government approval and adoption.

Key words: Calibration records; calibration system specification; intervals; procedures; recall; reliability; traceability.

1. Introduction

In May of 1969, our committee published a compilation of ten government specifications which affect standards and calibration laboratories. A paper describing the compilation was presented at the 1968 Standards Laboratories' Conference at Boulder, Colorado; at that time several representatives from DOD suggested that NCSL should write its own specification. This request was followed up by a questionnaire which indicated unanimous support for the idea. The questionnaire results also revealed 19 specifications which were omitted from the original compilation, all of which had calibration system controls in them. The committee felt that our profession was not so complicated that we required 29 specifications to control ourselves. In addition, the specifications were, in some cases, conflicting and in many cases, ambiguous; therefore we have prepared a NCSL calibration system specification delineating the minimum essential requirements of a calibration system for control of measuring instruments and standards. This paper will describe in some detail that specification.

2. The Index

The first step in preparation of the specification was the decision as to what it should contain. The major categories discussed in the compilation were selected and with some combination and rearrangement, yielded the following index:

INDEX

1. Purpose
2. Government Audit
3. Subcontractor Controls
4. System Description
5. Records
6. Recall System
7. Calibration Intervals
8. Labeling
9. Calibration Procedures
10. Reliability
11. Traceability to National Standards
12. Environmental Controls

The task of preparing these sections was assigned to individual committee members. The results were compiled and circulated for comments among the entire committee. The following is a summary of the requirements specified. Reference is made to the authors of the original draft of each section.

1. *Purpose* Author: Frank J. Dyce

   This specification defines the minimum essential requirements of a calibration system for control of measuring instruments and standards. It applies to those laboratories which specify it as their governing document.

2. *Government Audit* Author: Frank J. Dyce

   Calibration system audits should be restricted to those items specifically covered by the applicable contract requirements.

3. *Subcontractor Controls* Author: Frank J. Dyce

   The prime contractor shall be responsible for his subcontractors having a calibration system that meets the requirements of this specification as it applies to the products furnished.

   (Since this specification covers the minimum essential requirements, it is the contractor's responsibility to insure that the subcontractor meets at least these requirements.)

4. *System Description* Author: John Skinner

A written description of the calibration system shall be maintained. It may be a single document or several documents which define how the requirements of this specification are met. It shall include at least the following items:

Organization: A basic statement which defines the responsibility and authority of the calibration laboratory.

Measurement Equipment Controls: Selection of initial intervals, recall procedures, records, labels.

Technical Control System: Outside sources, environment, interval adjustment.

Calibration Capability List

Terminology: Definitions of special terms having significant usage in the calibration system.

(This section states specifically that the system description will contain only those items necessary for a procedural review of a calibration program. It permits the use of several documents which may be standard company procedures. I have personally seen a 200-page book put together to meet previous system description requirements.)

5. *Records* Author: James Gilbert

Records shall be maintained for each item of measuring equipment upon which a calibration has been performed.

Records shall be maintained for a minimum of one year plus one calibration interval.

Equipment Identification Records: A nonrepetitive identification shall be assigned to each item of measuring equipment in the calibration system.

Equipment Location Records: Records shall be maintained to provide information necessary to locate equipment due for calibration or repair.

Calibration History Records: Records shall be maintained which indicate the present calibration status and previous calibration history of measuring equipment.

Calibration Control Records: Records shall be maintained on all measurement equipment requiring calibration to provide the information necessary for the control and audit of the calibration system.

(This section limits records to calibrated equipment and limits the length of time required for keeping the records. It provides flexibility in identifying and locating equipment and lists the minimum specific requirements of the record system.)

6. *Recall System* Author: William McCallum

A documented system shall be established with the purpose that no standards or measuring equipment with an expired calibration interval shall be used for a product measurement.

User Notification: The equipment user should be notified on or before the calibration due date.

Equipment Availability: Items must be made available for calibration on or before their calibration due date or be removed from service, conspicuously tagged, or restricted from use.

(This section clearly states the purpose and requirements of a mandatory recall system. It leaves no room for misinterpretation.)

7. *Calibration Intervals* Author: Don Greb

Measuring equipment and standards shall be calibrated at periodic intervals designed to assure that specified accuracy shall be maintained.

Interval Application: Intervals may be applied to single items or groups of items which are reasonably homogeneous with respect to family and reliability.

Interval Assignment: Calibration intervals shall be assigned for the maximum probability that the item(s) will be within accuracy specification when returned for calibration. This probability will be consistent with calibration system organizational requirements and resources. Reliability, failure, usage and cost should be factors considered in assigning calibration intervals.

Interval Adjustment: Calibration intervals shall be adjusted as necessary on the basis of calibration data or other information which may support a change.

Interval Shortening: Calibration intervals shall be shortened on time or usage dependent instruments to assure continued accuracy.

Interval Lengthening: Intervals may be lengthened when indications are that it will not reduce reliability below desired minimums.

Interval Extensions: Intervals may be extended by laboratory supervision due to critical test or production schedules or other requirements provided. Historical data support the extension and/or product acceptance is withheld pending the results of the eventual calibration.

(This section discusses assignment, adjustment and extension of intervals in a complete unambiguous format. It permits both fixed and variable intervals, and extensions within limitations.)

8. *Labeling* Author: Frank J. Dyce

All measurement equipment and standards shall be labeled or coded to indicate their calibration status. Labels shall include date calibrated, recalibration due date, identification of calibration personnel, equipment identification, calibration agency.

Label Impractical: When labels are impractical, codes should be used or recall records should be monitored.

Nonstandard Labels: "Calibration Deviation," "Not Required," "Do Not Use" and outside agency labels should be used as applicable to cover deviations from normal calibration technique.

9. *Calibration Procedures* Author: R. B. Willett

A current document shall exist containing sufficient information for the calibration of measuring instruments and standards to the required accuracy for product measurements.

Contents: It may be a local document, another company's procedure, a manufacturer's procedure or a composite of the three. It should be referenced under one cover with local approval.

Format: The local procedures shall include the following information—application, specification, preliminary operations, step-by-step procedure; calibration table, worksheet and appendix.

Usage: Locally approved calibration procedures shall be followed in the calibration of measuring equipment and standards and shall be available in the calibration area.

(This section basically combines the requirements from several specifications. It has sufficient flexibility to permit use of existing legitimate procedures, yet enough firmness to require complete procedures.)

10. *Reliability* Author: M. H. Brenner

The calibration program shall be conducted to maintain measurement equipment above a specified minimum acceptable reliability level such that instruments remain within their certified specification limits over their calibration interval.

Minimum Reliability Level: It shall be the objective of the calibration program to achieve and maintain a minimum documented reliability level consistent with organizational requirements and resources.

Family Reliability: An analysis on a manufacturer model number basis shall yield overall reliability numbers consistent with this goal.

Corrective Action: The individual instrument or family intervals shall be adjusted or the instrument specifications deviated (where usage requirements permit) as required to obtain the reliability goal.

Certified Specification Limits: Upon receipt for calibration, the instrument must be tested to determine if it is within tolerance prior to any adjustment or repair.

Reliability Records: Shall be monitored periodically for number of instruments, number of calibrations and reliability by instrument family.

Reliability Below Minimum: If the family reliability drops below the minimum level, one or more of the following should occur: interval adjustment, specification deviation, failure analyses, calibration procedure change, or application investigation.

Reliability Above Minimum: If the reliability remains consistently above the minimum level, the calibration interval should be increased to the point where the minimum level can be maintained with optimum equipment utilization and minimum service costs. (This is a requirement which is only briefly covered in most specifications; however, it is an area we felt needed strong coverage. Reliability emphasis separates the good from the bad programs. The actual minimum reliability level will vary between companies but it should be documented.)

11. *Traceability to National Standards*
Author: Carl Boyer

The calibration program shall provide the means to trace the accuracy of all calibrated measurement equipment through all echelons of standards to a value in terms of U. S. National Standards.

Documented Traceability: Where applicable, calibration of measurement equipment shall have documented traceability except for Ratio Standards, Natural Physical Constants, and Derived Standards.

Traceability Documentation: Documentation which substantiates and identifies the means of achieving traceability shall include as necessary: calibration agency, standards used, calibration technique, data, uncertainty, environmental conditions, date of calibration, and identification of the calibration personnel.

12. *Environmental Conditions* Author: Frank J. Dyce

The calibration environment should be controlled to the extent required by the most environmentally sensitive measurement made in the area.

Compensating Corrections: Where control is inadequate, compensating corrections should be added to the calibration results.

Environmental Records: Records of environmental conditions are only necessary when the requirements are tighter than the laboratory norm or the measurement is based solely on the environment it was calibrated within.

Environmental Considerations: Particular attention should be given to the following environmental conditions in developing calibration techniques and evaluating measurement data:
Temperature, voltage, humidity, dust, vibration, air currents, RFI, E.M.I., line voltage, grounding, and lighting.

(Environment has to be only as good as required by the measurements. Recording is performed only when necessary to interpret results and corrections are applied only when required.)

3. Conclusion

This specification delineates the minimum essential requirements of an equipment calibration system in an unambiguous format. We will have a committee meeting during this conference to make final changes to it. It will then be submitted to the NCSL Board of Directors for preliminary approval before presentation to DOD for their comments. The minimum we hope to achieve with this document is NCSL-recommended practice which will be adopted by laboratories not presently working to a Government specification. Several of our committee members indicated interest along these lines.

The maximum we hope to achieve with this document is to obtain DOD approval and have them specify it in lieu of the other 29 specifications.

We feel that with this document we have established a platform from which DOD can view what industry feels are the requirements of a calibration system. We have also given the new laboratories a general outline of what they must do to develop a calibration control system. The various sections of this document can be expanded into a recommended practice just as has been done with the recommended practices on calibration intervals and calibration procedures. We will then have a detailed document, corresponding to this general one, available to our membership.

The National Conference of Standards Laboratories
Specifications Committee

Frank J. Dyce, *Chairman*
Martin Marietta Corporation
Orlando, Florida

William McCallum
General Electric Co.
Daytona Beach, Florida

Robert B. Willett
Collins Radio Co.
Cedar Rapids, Iowa

James Gilbert
Vitro Laboratories
Silver Springs, Maryland

Marshall H. Brenner
Boeing Co. Aerospace Group
Seattle, Washington

R. J. Allen
Royco Instruments, Inc.
Menlo Park, California

L. B. Dunkleberger
Kaiser Aerospace & Electronics
Palo Alto, California

Bernard W. Busch
3M Company
St. Paul, Minnesota

Carl Boyer
Honeywell, Inc.
Annapolis, Maryland

John M. Skinner
General Dynamics
Pomona, California

Donald J. Greb
Lockheed Missiles & Space Co.
Sunnyvale, California

F. L. Swann
Systems Group of TRW Inc.
Redondo, Beach, California

J. A. Walz
General Electric
Bay St. Louis, Mississippi

D. J. Stemper
Holt Instrument Laboratories
Oconto, Wisconsin

NCSL 70

COST VISIBILITY EXCHANGE PROGRAM— A NEW APPROACH TO COOPERATIVE SAVINGS

R. J. Barra

Westinghouse Defense & Space Center, Baltimore, Md. 21203

A preliminary survey by the Calibration Systems Management Committee indicates 600,000 manhours per year spent on 9 types of instruments, including oscilloscopes. Member organizations are asked to contribute cost data with the objective of saving one million dollars in calibration and maintenance costs by 1972.

Key words: Calibration and maintenance manhours; digital counters; digital voltmeters; exchange program on costs; oscilloscopes.

The 1969 NCSL Directory listings show about 5,000 persons working primarily in standards laboratories. Assuming that a similar number of people are working in lower echelon laboratories, the total population becomes 10,000. At 2,000 manhours per man year, the total expenditure is twenty million manhours per year. As you can see, hundreds of millions of dollars are involved.

Why so much? What are we spending these manhours on? What instruments? If we knew what the dollars were being spent on, we might be able to do something about it. The Calibration Systems Management Committee of NCSL had to know the answers to these questions. To be most effective we have to concentrate on the high-cost areas. What we wanted was overall cost visibility. But the committee members alone should not be the only ones to benefit from this greater cost visibility. Each laboratory manager would like to know how his costs compare with costs in other laboratories. With the capability to make cost comparisons, we could detect otherwise hidden areas where cost reductions might be achieved. The exchange of cost data would not only provide broader visibility to all laboratory managers, but it would also provide first, a communication link between labs with common interests, and second, a foundation for cooperative action on improved methods and procedures leading to substantial cost reductions for all participating laboratories.

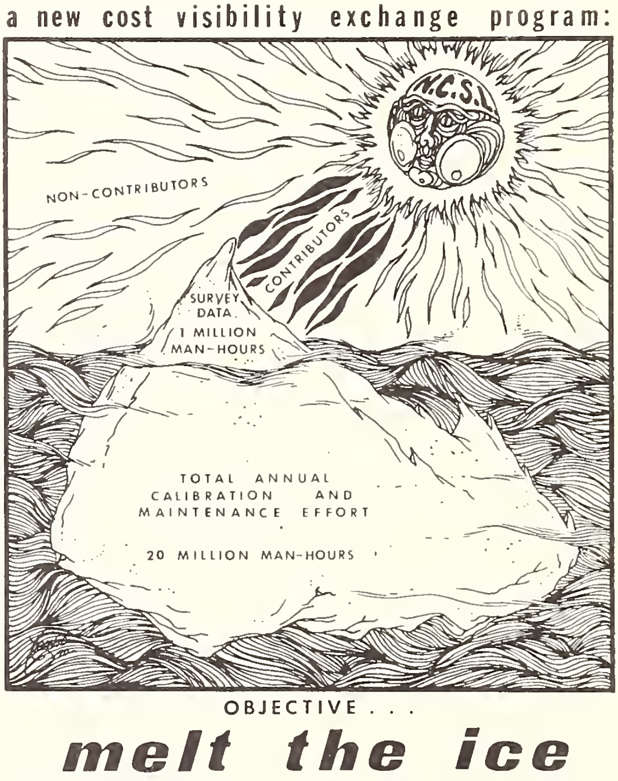


Figure 1. *A new cost visibility exchange program: objective . . . melt the ice.*

Recognizing (1) that hundreds of millions of dollars were involved, (2) that present cost visibility is quite limited, and (3) that cooperative action was almost non-existent, the committee established the following objectives:

- To develop the management control techniques required for optimum performance of calibration systems.
- To provide cost visibility to managers.
- To provide means to achieve cost reductions, without degradation of quality, through improved methods and procedures.

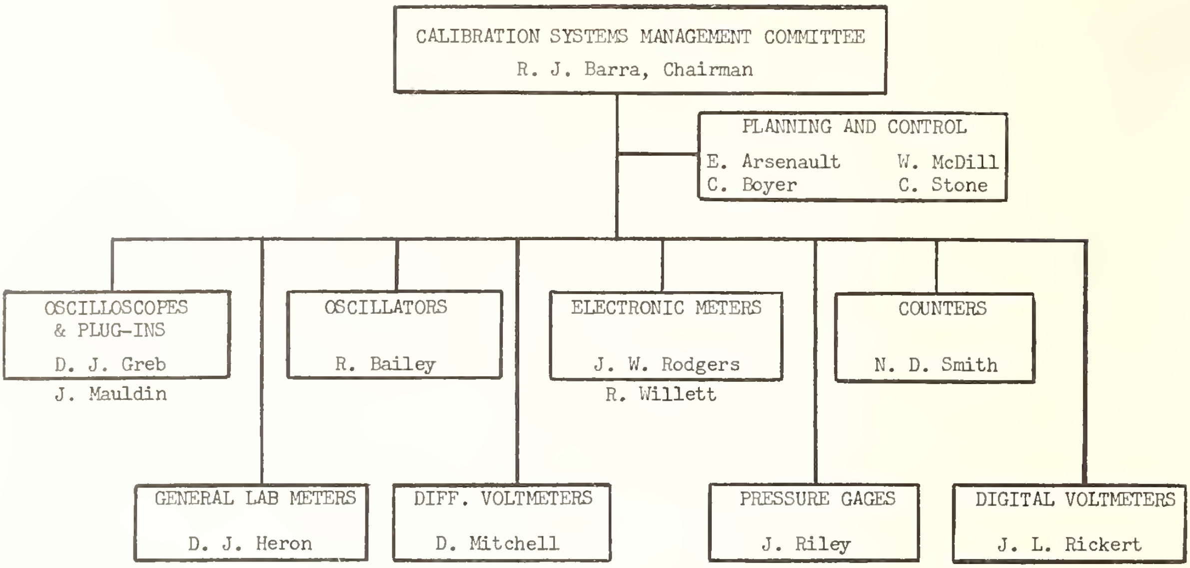


Figure 2. *Committee organization chart.*

Recognizing that the committee would be more effective if its members had clear and measurable goals, the following specific goals were established:

1. To collect 2 million manhours of specific cost data.
2. To disseminate these data to participating laboratories in the form of cost visibility reports.
3. To provide the means for NCSL members to save a *million dollars* before the 1973 NCSL Conference.

The committee's plan of action is as follows:

Phase 1—Determine where the calibration dollars are going. Conduct a survey to find those items which have the greatest potential cost reduction to the greatest number of NCSL members.

Phase 2—Collect, analyze and report the cost data on these groups of instruments.

Phase 3—Restructure the committee into sub-committees for in-depth probings.

Phase 4—Collect and develop cost reduction ideas, and provide a means to exchange them.

The committee's progress toward the attainment of our goals can best be measured by reviewing actions to date. Less than a year ago Phase 1 began. On July 30, 1969, a questionnaire on calibration interval versus cost was sent to all delegates and sponsors. About 25 percent of the membership responded. The data collected exceeded one million calibration and maintenance hours. Sixty percent of these hours were associated with just nine groups of instruments. The committee achieved one of its first objectives; that is, we found out where most of our calibration dollars were going. The committee's first cost visibility report, covering these nine groups of instruments, is given in the appendix. How does your lab compare with the data presented? Are your intervals longer or shorter? Are your annual calibration maintenance hours lower or higher?

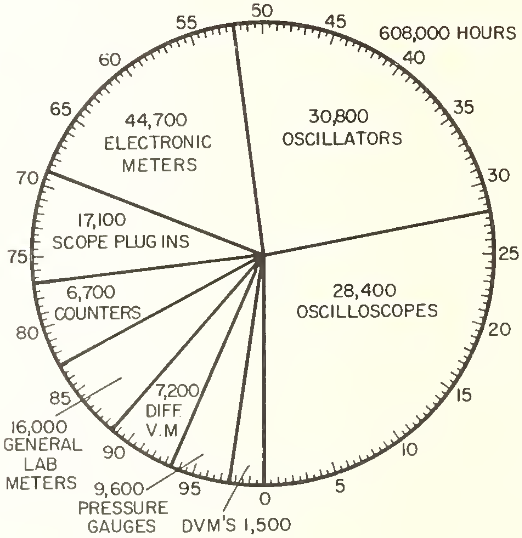


Figure 3. *Results of calibration cost survey, Fall 1969: Percent total hours.*

As listed in the report, the nine groups of instruments are:

Oscilloscopes
Oscillators/Generators
Electronic Meters
Oscilloscope Plug-ins
Electronic Counters
General Lab Meters
Differential Voltmeters
Pressure Gages
Digital Voltmeters

How large a sample did these data represent? Not too large. For example, a few comparative figures are given below:

A. Oscilloscopes—28,000 out of about 350,000
B. Counters (Digital)—6,700 out of 175,000
C. Digital Voltmeters—1,500 out of 75,000

Using the weighted average figures from the survey, the total calibration and maintenance effort for these instruments is over 3,300,000 manhours per year. The breakdown is as follows:

A. Oscilloscopes—350,000 at 5.8 manhours/year/scope equals 2 million manhours.
B. Counters—175,000 at 3.9 manhours/year/counter equals 700,000 manhours.
C. Digital Voltmeters—75,000 at 7.8 manhours/year/DVM equals 600,000 manhours.

As you can readily see, the cost reduction potential is significant. Assuming that the above figures are representative of the total population, the one million manhours of the survey is only about 5 percent of the total effort, which figures to be about 20 million manhours.

This first cost visibility report was just part of Phase 2. This month you will have a second chance to be a contributor to this program. The committee needs additional data to supplement the information received from the 1969 survey. Cost visibility exchange cards are being sent to all delegates. We are looking for specific cost information on these groups of instruments. Send in as many cards as you wish. If you are interested in getting data on all these groups of instruments, then a card for each group must be contributed. Each card is your ticket to greater cost visibility and an opportunity to achieve substantial cost reductions for your laboratory.

	QUANTITY	HRS/YR	AVG HRS/YR/ITEM
Oscilloscopes	28,373	169,912	5.8
Oscillators, Signal Generators & Function Generators	30,813	146,082	5.4
Electronic Meters (V.T.V.M.'s & Electronic Multimeters)	44,663	102,606	2.1
Scope Plug-Ins	17,073	47,870	2.2
Counters	6,741	36,642	3.9
General Lab Meters (Panel Meters, Portables & V.O.M's)	15,989	35,089	1.9
Differential Voltmeters	7,209	29,405	3.3
Pressure Gages	9,580	26,265	1.9
Digital Voltmeters	1,540	14,513	7.8
Totals	161,981	608,384	

Table 1. *Instruments with highest calibration/maintenance hours*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS)						TOTALS
	2	3	4	6	9	12	
2.2 - 5	— —	— 76	11,504 580	3641 —	47 125	67 —	15,259 781
8 - 8	— 159	— 759	6180 2428	25 523	— 65	64	6269 3934
9 - 12	— 653	— 312	42 43	— 380	34	— 76	76 1464
MORE THAN 12	— —	33 249	50 115	— 134	— —	— 1	83 499
TOTAL INST	812	1429	20,942	4711	271	208	28,373
TOTAL HRS	8253	15,095	117,803	25,688	1695	1378	169,912
AVG HRS/YR/INST	10.2	10.6	5.6	5.5	6.3	6.6	5.8 *

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

Table 2. *Oscilloscopes*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS)								TOTALS
	2	3	4	5	6	7	9	12	
2 - 4	— —	— 127	— 50	12,614 —	2302 —	1014 —	730 154	147 —	16,357 331
4 - 8	— —	— 490	2416 90	4628 6	3972 918	— —	— —	193 —	11,209 1504
9 - 12	— —	— 10	— 184	— —	— 115	— —	— —	— —	— 309
MORE THAN 12	— 488	— 52	505 57	— —	— 1	— —	— —	— —	505 598
TOTAL ITEMS	488	679	3302	16,798	7308	1014	884	340	30,813
TOTALS HRS	10,367	5227	26,428	64,066	31,967	3486	2833	1708	146,082
AVG HRS/INST/YR	21.2	7.7	8.0	3.8	4.4	3.4	3.2	5.0	5.4*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

Table 3. *Oscillators, signal and function generators*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS)								TOTALS
	1	2	3	4	5	6	9	12	
1.5 - 2.5	—	—	—	—	13,398	5534	21,674	—	40,606
	—	—	46	66	—	—	272	—	384
3 - 6	—	—	—	55	47	66	—	349	547
	—	150	613	33	72	806	127	90	1891
7 - 10	—	—	—	15	—	—	—	—	15
	90	6	27	416	33	72	9	—	653
11 - 100	—	—	—	12	—	—	—	—	12
	227	76	46	6	—	—	—	—	355
TOTAL ITEMS	317	232	732	603	13,650	6478	22,182	469	44,663
TOTAL HRS	4221	1786	4043	3759	30,922	15,850	40,368	1657	102,606
AVG HR/INST/YR	13.0	7.7	5.5	6.2	2.3	2.4	1.8	3.5	2.1*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

TABLE 4. *Electronic meters (pointer type, active circuit)*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS)						TOTALS
	2	3	4	5	6	12	
1.3 - 2.5	—	—	—	11,364	—	—	11,364
	—	—	—	—	114	—	114
2.6 - 5	—	—	—	—	2420	—	2420
	—	1254	65	90	604	210	2223
6 - 10							
	339	184	36	—	1	—	559
11 - 50	—	—	18	—	113	—	131
	229	2	5	—	25	—	262
TOTAL ITEMS	568	1440	124	11,454	3277	210	17,072
TOTAL HRS	7870	5098	974	20,773	12,578	604	47,870
AVG HRS/INST/YR	13.4	3.5	7.6	1.8	3.8	2.8	2.2*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

TABLE 5. *Scope plug-ins*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS)						TOTALS
	3 OR LESS	4	5	6	9	12	
0.8 - 0.9	—	—	—	—	—	—	—
	—	—	—	1048	—	—	1048
1 - 2	—	2576	—	6456	1452	—	10,484
	—	—	—	324	—	85	409
2.1 - 4	—	—	1794	—	—	562	2356
	300	—	—	406	570	1	1277
5 - 35	—	—	—	—	180	—	180
	232	—	—	2	—	1	235
TOTAL INST	532	2576	1794	8236	2202	649	15,989
TOTAL HRS	3201	5558	5918	12,194	6618	1600	35,089
AVG HRS/INST/YR	6.0	2.2	3.3	1.5	3.0	2.5	1.9*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

TABLE 7. *General lab meters (pointer type, passive circuit)*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS)					TOTALS
	3 OR LESS	4	5	6	12	
1.5 - 2	—	—	1310	—	—	1310
	—	—	—	—	—	—
3 - 5	—	2490	—	—	—	2490
	6	—	—	1	—	7
6 - 10	—	850	—	—	84	934
	117	1274	—	13	1	1405
11 - 20	—	—	—	—	—	—
	281	169	—	75	—	525
21 - 60	5	—	—	—	—	5
	57	8	—	—	—	65
TOTAL INST	466	4791	1310	89	85	6741
TOTAL HRS	7068	25,719	2210	1182	463	36,642
AVG HRS/INST/YR	15.2	5.4	1.7	13.3	5.4	3.9*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

TABLE 6. *Counters*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS) 1	2	3	4	6	TOTALS
2.4 - 3.0	— —	— 1314	3940 —	— —	— —	3940 1314
3.1 - 4	— —	— —	1310 —	— —	— 1	1310 1
5 - 10	— —	— —	— 297	— —	— 88	— 385
11 - 50	— 147	— 33	— 53	12 14	— —	12 247
TOTAL INST	147	33	5600	26	89	7209
TOTAL HRS	5662	4120	18,735	356	532	29,405
AVG HRS/INST/YR	38.5	3.1	3.3	13.7	6.0	3.3*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

TABLE 8. *Differential voltmeters*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVAL (MONTHS) 3	4	6	12	TOTALS
0.9 - 1.0	— —	— —	— —	164 2364	164 2364
2 - 3	— 396	— 57	3238 1000	— —	3238 1453
4 - 5	— —	— —	1615 —	— —	1615 —
6 OR MORE	— 111	— —	— 630	— 5	— 746
TOTAL INST	507	57	6483	2533	9580
TOTAL HRS	2232	179	21,323	2531	26,265
AVG HRS/INST/YR	4.4	3.0	3.3	0.9	1.9*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

TABLE 9. *Pressure gages*

CAL/MAINT HRS/INST/YR	CALIBRATION INTERVALS (MONTHS) 1	2	3	4	6	TOTALS
4 - 5	— —	— —	— 557	— 131	— 22	— 710
6 - 10	— —	— 141	— 17	— —	190 —	190 158
11 - 15	— 44	— 60	— 129	— —	— —	— 233
16 - 20	— —	— 81	— 7	— 5	— 4	— 93
21 - 35	— 92	16 14	— 30	— —	— —	16 136
TOTAL INST	136	312	740	136	216	1540
TOTAL HRS	3119	3945	5466	531	1450	14,513
AVG HRS/INST/YR	22.9	12.6	7.4	3.9	6.7	7.8*

GOVERNMENT
INDUSTRY

*WEIGHTED AVERAGE

TABLE 10. *Digital voltmeters*

Phase 3 has also been implemented. The committee has been restructured into an organization with eight sub-committees. The organization chart is shown in figure 2. Several delegates, who have contributed a large portion of the data on these instruments, have already been appointed to serve on subcommittees that are of major interest to them. A planning and control staff has also been established to assist the committee chairman in the establishment of common guidelines for the subcommittee chairmen to follow. However, each subcommittee chairman will be given maximum freedom to operate his subcommittee autonomously. As mentioned previously, the key objective of each subcommittee will be to provide the means for members to achieve cost reductions.

Phase 4 is just about to start. Each subcommittee chairman will be responsible for providing the means for NCSL members to achieve cost reductions associated with his instrument group. For example, some of the means are:

1. Collection, analysis, and reporting of cost data;
2. Operation of an information exchange program;
3. Operation of a trouble-shooting summary library;
4. A telephone directory linking delegates with common interests.

Each subcommittee will have its own goals, such as:

1. Collection of a specific amount of data;
2. Reporting of this data on schedule;
3. Helping members save a specific amount of dollars in a specific amount of time.

When all the subcommittee goals are put together they will meet or exceed the total goals of the committee. Once again, these goals are:

1. To collect 2 million manhours of cost data.
2. To help NCSL members save *one million dollars* before the 1972 NCSL conference.

Be a CONTRIBUTOR.

Help MELT THE ICE.

in
si
me
ur
tra
mo
wh
mo
br
re
ea

an
in
he
br
ti

te
to

NCSL 70

SESSION 3: NEW METHODS OF OPTIMIZING INTERVALS

Chairman: Carl Boyer

Honeywell, Inc., Annapolis, Md. 21404

KEYS TO OPTIMUM CALIBRATION INTERVALS

Rolf B. F. Schumacher

Autonetics Division, North American Rockwell, Anaheim, Calif. 92803

The search for optimum calibration intervals or for methods to obtain them can be frustrating. Our theories concerning the behavior of measuring instruments are deficient, and as a result, so are all theoretical models attempting to establish optimum intervals. Nor can we hope to determine empirically what opimum intervals should look like. The many variables in calibration control systems, affecting quality and behavior and performance evaluation of measuring instruments, forbid us to compare the meaning and merit of calibration intervals achieved in one calibration control system with those achieved in another such system. Time does not permit us to experiment in one system until we achieve calibration intervals which are even near optimum. We must be modest and practical. We must lower our sights.

This paper attempts to show the main sources of our ignorance about instrument behavior and about the influence of a calibration control system on instrument behavior and on our evaluation of this behavior. It offers seven keys to the establishment of an efficient method for calibration interval adjustment. Emphasis is on efficiency, practicability, economy. The purpose of adjusting calibration intervals is to maintain a given level of instrument quality level at the lowest cost. Having found a satisfactory calibration interval adjustment method, one should look to other components of the entire calibration control system for opportunities to lower costs.

Key words: Calibration intervals; economy in adjusting quality level; measurement uncertainty; reliability of working instruments.

1. Introduction

Calibration intervals and the problems of determining them have been with most of us in industry ever since the latter half of the 1950's when the Government began requiring periodic recalibration of measuring tools and instruments used by its defense contractors. The principle was sound: measuring instruments deteriorate with time and use; so, once in a while, they have to be recalibrated to make sure the measurements made with them are correct. Thus, calibration intervals were introduced, set, and adjusted, to recall measuring instruments periodically to insure that each is within its tolerances at all times when in use.

Soon, however, we found that this was not possible, and we had to be satisfied with keeping most measuring instruments in tolerance most of the time. But how many, and how much of the time? This question brought the two key problems of interval determination into clear focus, to wit:

1. Finding the function for time of instrument deterioration (when does a given instrument get out of tolerance?)
2. Finding the optimum quality level (how many instruments should we, and can we afford to, have in tolerance at any one time when in use?) [1][1]

Closely connected with the second problem, finding the optimum quality level, is the problem of measuring this quality level. This, in turn, leads to questions about the standards against which the quality level is measured, the tolerance specifications for the instruments, and the calibration procedures—are they controlled, stable, and adequate?—about policies, personnel, etc. How certain are we that an instrument stated to be in tolerance was really performing the way we wanted? Uncertainty afflicts the measurement of the quality level of our instrumentation and blurs our vision of instrument deterioration. Thus, the two key problems of interval adjustment, namely the determination of instrument quality level and the time-dependence of instrument deterioration, are connected by the same factors which introduce uncertainty in both.

We conclude that all elements of a calibration control system are inseparably linked together. An examination of calibration intervals leads to an examination of the entire system. In the following pages

---

[1] Figures in brackets indicate the literature references at the end of this paper.

we first examine the factors influencing calibration intervals and then see what we can say about methods of interval determination in general and how to develop a critique for them. Unfortunately, at the end of this critical examination, we shall not find a method for determining calibration intervals that can be generally recommended. But we shall see what we can do to select a calibration interval adjustment method that will permit optimizing our calibration control system.

To do that, we must first debunk the notion that any one mathematical approach can solve the problem of obtaining optimum calibration intervals. We must be fully aware of all the factors influencing calibration intervals in order to innovate methods which will yield optimum intervals and more cost-effective calibration control systems.

This paper deals only with the problems of calibration intervals for large numbers of working instruments. Where calibration intervals are determined on the basis of standards observed individually and analyzed in detail, other considerations enter and have been discussed elsewhere [2, 3].

2. Factors Determining the Length of a Calibration Interval

2.1. Time Dependence

At the basis of the concept of calibration intervals is the notion that a measuring tool or instrument deteriorates as the effects of chemical or physical action accumulate with time. But how do they accumulate? Does the instrument deteriorate faster when we use it frequently? Or does it deteriorate independently of usage?

In most cases we do not know. There will be some types whose deterioration is a function of usage alone. And there will be others whose deterioration will be a function of their exposure to the atmosphere. And there will be still others whose deterioration is a function of something else. What is the factor contributing most to their deterioration, and does the deterioration progress linearly, exponentially, stepwise, or how? For most measuring instruments it would be impossible to find the answers to these questions. And even if we could, we might find almost as many patterns of behavior as we have instrument types. Could we possibly have as many different interval adjustment methods? Certainly not.

Our ignorance concerning measuring instrument behavior will force us to make assumptions when establishing calibration intervals. We generally make those assumptions which appear plausible and which most likely apply to at least some of our instruments. So, let me propose that, in establishing calibration intervals, we make the assumptions that help us develop a method that is inexpensive to implement and use.

In a study to determine whether shorter calibration intervals produce instrument families with higher in-tolerance ratios, one large family of like instruments by one manufacturer, and with the same model designation, was divided into four groups of equal size. Each group was assigned a calibration interval of 5, 10, 15, or 20 weeks. Figure 1a is a compilation of the in-tolerance percentages of the groups measured at recall. (Obviously inoperative instruments were excluded from the count and charted separately.) The study on instrument type A was repeated with type B (fig. 1b). Were the calibration intervals a major factor determining the in-tolerance percentages of the instruments charted in figure 1? There is no clear answer, but the tolerance specifications against which the instruments are calibrated appear to be a more important factor than the calibration intervals in this limited situation.

One additional thought: The assumption that the moment at which an instrument slips out of tolerance is uniformly distributed over a period of time, rather than as some function of time, may lead us to some radically new methods of calibration control. However, for the purpose of the following discussion, I shall assume that there is at least some vague relationship between an instrument's calibration interval and its in-tolerance condition, and that a low in-tolerance percentage requires short calibration intervals and attendant high calibration costs. But let us remember that these statements of conventional wisdom deserve our most critical questioning.

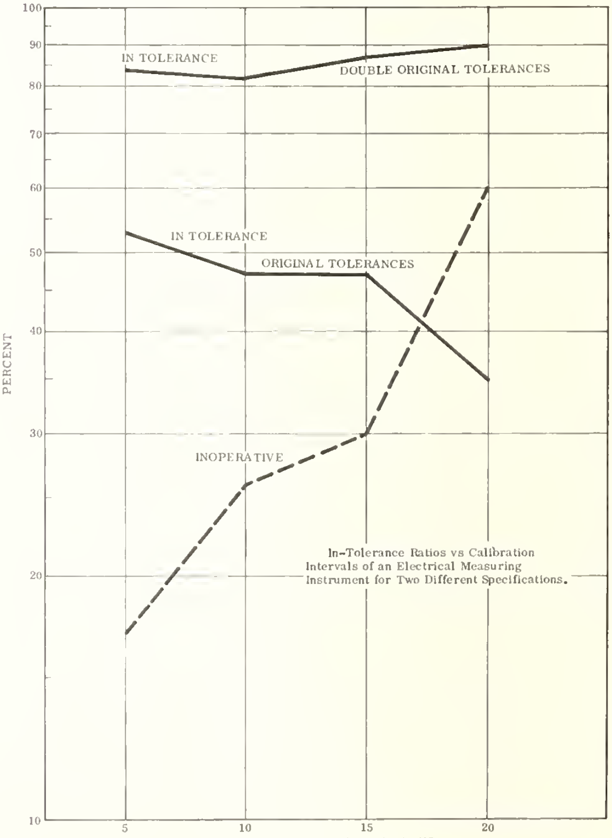


FIGURE 1a. *Instrument Type A.*

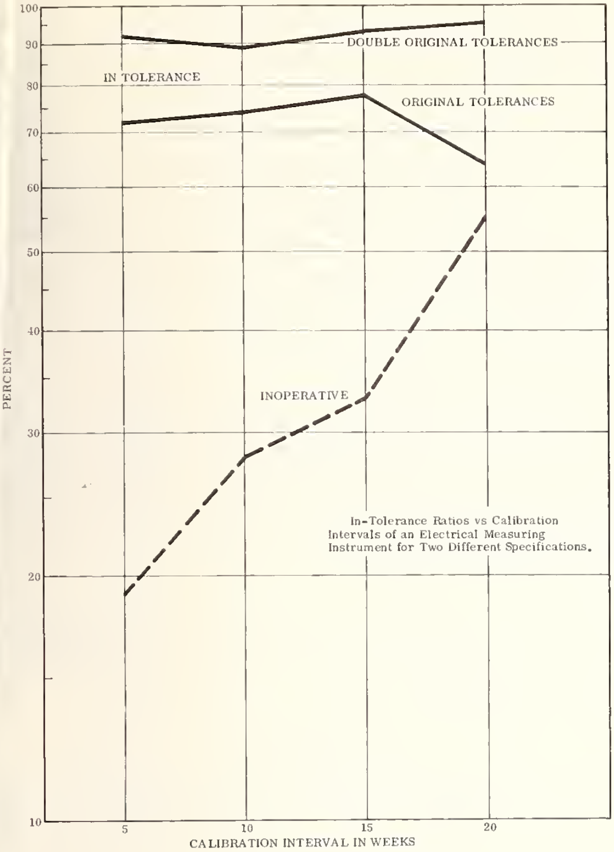


FIGURE 1b. *Instrument Type B.*

2.2. Quality Level

By instrument quality level I mean the number of measuring instruments in tolerance, as a percentage of all instruments under consideration. It is often assumed that this level is linked to calibration interval. Soon after it was realized that we will never be able to have all measuring instruments in tolerance all the time, arguments arose about how many we must have in tolerance. Some people maintain that 95 percent of all instruments should be in tolerance at recall. Some say this is too high a percentage; others maintain it is too low. For all practical purposes, we do not know what the quality level should be.

We should stop here for a moment and consider the predicament we are in. We do not know what is happening to measuring instruments (the question of time dependence), and we do not know what should happen (quality level). Are our calibration interval adjustment methods in sad shape? You bet they are!

What could be done is to calculate the cost of a calibration system producing a given quality level, say 90 percent, and also the cost of an alternate system producing, say 95 percent. We could also determine the dollar value of the reduced rework and scrap, and estimate the incommensurate effects, like increased customer satisfaction. If there are no incommensurates, the quality level we want is the one which minimizes the difference between the cost of obtaining it and the dollar value of the benefits. If there are incommensurates, the difference is the cost of the incommensurate benefits. Somebody in control over the system can then decide whether the benefits are worth the costs or whether he would like to buy additional benefits at the indicated rate.

Examples of how an optimum quality level may be determined are given in references [1] and [6]. This brings us to the question of how to measure this quality level.

2.3. Measuring the Quality Level

Like all measurements, the measurement of instrument quality level is associated with uncertainties. The sources of these uncertainties are found throughout the entire calibration control system. One large and unnecessary error stems from the practice of measuring quality level at recall, i.e., at a time when a measuring instrument is back in the calibration laboratory for recalibration. What we really want to know is whether the instrument was in tolerance when it was being used. Therefore, we should measure this quality level in use, i.e., at the time when the instruments are being used, when it does make a difference whether an instrument is in tolerance or not. The effects of measuring at recall or in use are discussed in detail in Appendix A.1.

Other main sources of uncertainties which prevent us from obtaining the instrument quality level we need are found in the tolerance specifications against which instruments are calibrated, and in the choice of characteristics the instrument must meet (as contrasted with those which are incidental). Also, the procedures we use when calibrating an instrument influence the magnitude and direction of systematic errors and the possible magnitude of random errors. These uncertainties becloud our decision as to whether an instrument is declared in tolerance or not, and whether or not to change calibration intervals. Then there are personnel policies, instrument-handling policies, treatment of tolerances, etc., which affect that decision. For a more detailed discussion of error sources, see Appendix A.2.

It stands to reason that all elements which are sources of uncertainty should be examined with a view to reducing the chances of making interval changes inadvisedly. But more than that, all elements must be compatible with the objectives of the calibration control system. For instance, instrument tolerances must be only as tight as product tolerances call for—not more, not less. And finally, all elements must be compatible with each other. For instance, if the interval adjustment method requires a technician to know the condition of an instrument when it was recalibrated previously, the system must make this information available to him.

Thus, there are many things which have a decisive influence on the calibration intervals which we finally assign to measuring instruments. And I submit that study of these holds more promise for minimizing calibration system costs and optimizing calibration intervals than a concentration on the mechanics of adjusting intervals.

3. How to Determine Optimum Calibration Intervals

As explained in the preceding paragraphs, we are confronted with a number of factors which we suspect will affect the quality level of measuring instruments. Since calibration intervals are a function of this quality level, they are also a function of all these factors and their unknown effects.

From the preceding discussion, we can derive the following seven "Keys to Optimum Calibration Intervals":

Key No. 1—There is no optimum calibration interval *per se*, and there is no optimum interval adjustment method *per se*.

Since we do not know how all important factors of a calibration control system interact, we cannot optimize calibration intervals or interval adjustment methods theoretically. And to do it empirically, by trial and error, we have neither the time nor the funds in general. Hence,

Key No. 2—We cannot hope to optimize, in the strictest sense of the word, a calibration interval; we can only hope to arrive at a reasonably satisfactory one.

"Optimum," i.e. "fairly cost-effective, satisfactory" calibration intervals are the result of an "optimization" of all important factors of a calibration control system, of which the interval adjustment method is only one.

Key No. 3—An interval adjustment method can be "optimized" only in relation to a specific calibration control system; a method satisfactory for one system may be unsatisfactory for another.

Key No. 4—An interval adjustment method "optimizing" intervals for a given control system

—is economical to establish and to operate,

—causes intervals to respond promptly to changes in the system,

—zeros in quickly on calibration intervals which optimize the quality-cost relationship of the system.

Key No. 4 states the main criteria for selecting a calibration interval adjustment method.

The largely unknown factors influencing calibration intervals cannot be described by a mathematical moded; assumptions will have to serve in lieu of missing knowledge. Hence,

Key No. 5—A satisfactory interval adjustment method is one which yields an acceptable quality level at low cost, regardless of the underlying assumptions, as long as such assumptions do not contradict our experience. There may be a number of equally satisfactory methods for any one calibration control system.

From this follows

Key No. 6—An established satisfactory interval adjustment method requires re-examination and possible changes whenever another major component of the calibration control system is changed.

The emphasis here is clearly on the economics of choosing and establishing an interval adjustment method. Let us not get carried away by elegant mathematics. Several plausible interval adjustment methods have appeared in various trade publications. Yet a check with the authors of several of these a few years after publication revealed that the methods were either never implemented or were abandoned after a short trial. They had failed the crucial tests of practicability or economy or both. In Appendix B, I describe an interval adjustment method which has met these tests, although its theory is assailable. But it works in the environment for which it was designed. It may not be suitable for adoption in other calibration control systems.

An interval adjustment method and the resulting calibration intervals must above all fulfill the requirements of Key No. 4, and be compatible with other components of the calibration control system. Once these conditions have been satisfied, our attention may then be diverted from calibration intervals toward other problem areas within the system. An important key towards Progress to Innovative Metrology becomes clearly visible:

Key No. 7—"Feed the opportunities" which the calibration control system offers for obtaining optimum intervals, "and starve the problems" presented by system components.[2]

4. Conclusion

Show me a calibration control system which achieves a given quality level for its measuring instruments at the lowest cost and I'll show you calibration intervals which are optimized in relation to all other parts of this system, and which permits you to direct your resources towards the solution of other problems. If your interval adjustment method reasonably meets the requirements of Key No.4, future effort will probably yield higher returns when applied to other problem areas.

Credit is due to Messrs. E. M. Hicks and J. D. Mitchell of Autonetics for their many valuable comments and suggestions.

Appendix A. Sources of Uncertainties of Instrument Quality Levels

A.1. Methods to Measure Instrument Quality Levels

(a) At Recall—This is the method that should *not* be used unless it has been shown that there is a known relationship between the quality level measured at recall and that found when the instruments are in use.

For the quality level measured at recall to bear a meaningful relationship to the quality level of the instrument population in use, we must first remove the bias which the calibration interval adds to the raw ratio of "instruments in tolerance" to the total of instruments recalled. Some instruments are recalled for calibration much more frequently than others, and ideally those instruments are recalled most often which need it the most. The bias may be removed by calcu-

---

[2] Quote by Peter Drucker, management consultant and lecturer at NYU Graduate School of Business.

lating the percentage in tolerance as shown in table 1, using the formula

Percent in tolerance =

$$\frac{n_1 i_1 + n_2 i_2 + n_3 i_3 + \ldots + n_k i_k + \ldots}{Q_1 i_1 + Q_2 i_2 + Q_3 i_3 + \ldots + Q_k i_k + \ldots} \times 100$$

where n_k is a recall interval in weeks and Q_k is the total number of instruments recalled at interval i_k.

TABLE 1. *The effect of the bias of calibration intervals on the apparent fraction of instruments in tolerance*

No. of instruments (Total)	Intervals in weeks	Fraction in tolerance at recall	No. of instruments in tolerance at recall	No. of recalls per instr. & per year	Total No. of recalls per year	No. of instr. recalled in tolerance per year (cols. 3 x 6)
1	2	3	4	5	6	7
100	5	0.70	70	10.4	1040	728
100	10	0.80	80	5.2	520	416
100	20	0.90	90	2.6	260	234
100	30	0.96	96	1.7	173	166
					1993	1544

Actual (unbiased) percent in tolerance:

$$\frac{70\times5 + 80\times10 + 90\times20 + 96\times30}{100\ (5 + 10 + 20 + 30)} \times 100 = 89.7\%$$

Apparent (biased) percent in tolerance:

$$\frac{1544}{1993} = 77.5\%$$

Another shortcoming of measuring the instrument quality levels at recall is that it does not tell us whether the system is taking appropriate actions with regard to individual instruments or instrument families. If it allows instruments which are usually in tolerance to be recalled very frequently, the percentage of instruments in tolerance would be deceivingly high, concealing serious problems. The main argument, however, against measuring the instrument quality level at recall is that the obtained figure *per se* is totally irrelevant. When measuring instruments are back in the calibration laboratory for recalibration, they cannot affect production cost and product quality.

(b) In Use—This is the percentage that is really of interest. We want to know what the quality of measuring of those instruments is at the time they are being used, when they could have affected production cost and product quality. To know this, however, we have to go out on the floor and measure it.

A practical approach to measuring the quality level of measuring instruments in use would be to select a small sample at random and calibrate it. Using time-honored methods of quality control, small sampling methods, and control charts [4], we could in due time determine whether our calibration control system is actually a process "under control," whether it is kept at the level which we have determined as being optimal, and how the calibration control system responds to changes, "corrective actions," etc.

This could be done at moderate costs which may be more than offset by savings, because we would not have to recall all instruments to measure the quality level. We could use the recall strictly to operate on the calibration control system, i.e., to do only that which is necessary to maintain the quality level of measuring instruments under control. These considerations may open the field to alternatives to the presently applied recall methods. However, regardless of whether we continue applying the old concepts of recall or use new ones, we should measure instrument quality levels "in use" rather than "at recall" to obtain meaningful figures.

A.2. Error Sources in the Measurement Process

To measure the actual quality level of measuring tools and instruments, one needs, as for all measurements, a standard, a comparison process, and decision criteria. These are discussed in the following paragraphs.

(a) *Decision Criteria: Attributes versus Variable Data.* The upper and lower limits of an acceptable quality level should be determined at the time when the optimum quality level is determined. In theory, the instrument maintenance program should then be designed so that the measurement process is in control within these limits. Practically, however, upper and lower control limits will be a compromise between what is economically desirable as far as the production process is concerned, and what is practically achievable as far as the instrument maintenance program is concerned.

Quality levels in instrument control systems are usually given in "percent in tolerance" figures. I personally prefer the use of "percentage defectives," because it is more in line with quality control lingo and suggests the use of systematic quality control methods. Either statistic is based on an attribute—it is either in tolerance or out of tolerance. And that is all that's needed for the measurement and control of quality level, since the vast majority of measuring instruments require the simultaneous control of a number of parameters or characteristics. What counts in the case of determining common calibration intervals are only the statistics which show how often the instruments are out of tolerance (and perhaps which parameters are out of tolerance) not by how much they were out of tolerance.

Variables data, although more costly to obtain and record, may be needed to analyze the behavior of unreliable instruments or instrument families. But these should be taken only when such analyses appear desirable. (It should be remembered that we are talking here about the bulk control of large quantities of working instruments, not about instruments which which must be controlled individually, like standards [2,3].) An enormous amount of variable data serves no purpose other than the satisfaction of some policy provisions. And that is no good reason to take such data.

Variables data are somewhat more prone to error than attributes data. Thus, recording of attributes data may enable us to measure the quality level of measuring instruments more accurately.

(b) *The Standard: Specifications.* The standards against which measuring instruments are tested are usually their specifications. Much is being done now to make specifications more meaningful; much more remains to be done. Problems commonly encountered in deciding what specifications to use and what they mean have been discussed in detail elsewhere [5]. I will, therefore, touch on some of these problems only peripherally where they have direct bearing on calibration intervals.

The specification we need to work with in a calibration control system must be a realistic one. Some tolerance specifications, as they are given by instrument manufacturers, are at best optimistic. Some instruments hold their quoted tolerance, say 1 percent, only in the laboratory; some seem to hold their quoted tolerance only in a random fashion; some others hold it for a short time and require frequent recalibration to remain useful; however, some instruments hold their manufacturers' quoted tolerance for very long intervals.

In the case of an instrument whose performance gradually deteriorates with time, we could select either tight tolerances and short intervals, or loose tolerances with long intervals, or something in between. Which tolerance-interval pair should we select?

Generally speaking, we should select tolerances and intervals which offer us the greatest return. The optimum tolerance specification depends on the quality, cost, and behavior of the instrument as well as the cost of its maintenance. Let us take, for instance, instrument A which costs $2,000 and which is capable of holding its maximum realistic tolerance of 0.1 percent of some characteristic only at the expense of considerable maintenance costs (perhaps frequent recalibration), say $700 a year. The same instrument may be capable of holding a lesser tolerance, say 0.15 percent, easily, requiring only one annual calibration of $100 a year. Now let's look at the alternatives.

If we need a 0.1 percent instrument and the next better one, instrument B, costs $5,000 with annual maintenance (including calibration) costs of $200, we may be better off with instrument A and high maintenance expenses and frequent recalibrations. On the other hand, there may be a less costly alternative available for the 0.1 percent instrument, but we may also need 0.15 percent instruments for which the alternative would be instrument C, a $1,000 instrument with $350 maintenance costs, including fairly frequent recalibrations. In this case, it may be better to use instrument A, assigning to it a 0.15 percent tolerance and calibration intervals of one year.

The optimum tolerance specification, like the optimum calibration interval, can be determined only in the context of economic alternatives—the requirements of the production process, the handling and care of the instruments in their use environment, the training of operators, etc. Calibration intervals change when specifications change, but specifications are functions of variables outside the calibration control system.

Figure 1 illustrates the effect of doubling the specification tolerance applied to a considerable number of a popular VTVM. At 15 weeks, for example, the percentage in-tolerance jumped from 46 to 86 for type A; while for type B it jumped from 78 to 93.

There is also the problem of what to include under the characteristics which determine whether an instrument is in tolerance or out. It may or may not matter whether an instrument with rated input impedance of infinity has actually an input impedance of 50 MΩ, whether an instrument with 5 μV minimum sensitivity has actually 6 μV sensitivity, whether a comparator with rated contact pressure of 10 g has only 7 g contact pressure. If it does not matter, such characteristics should be left out of the consideration of an instrument's in-tolerance condition. Many, many instruments have been labeled out of tolerance for failure of some inconsequential characteristic to be within manufacturer's specifications. Management can do much to lengthen calibration intervals by precisely defining which characteristics must be considered and which must be excluded when judging an instrument out of tolerance. The question of how to treat an instrument with a broken line cord or damaged line plug may be trivial to engineers and supervision, but not to the technician who may decide to call such an instrument out of tolerance because something was wrong with it.

(c) *The Comparison Process.* Calibration procedures are widely considered as crutches for dimwitted calibration technicians. Adequately staffed calibration laboratories frequently consider procedures unnecessary and the respective Government requirements a nuisance, but this is based on a misconception.

A calibration is a measurement process. A measurement deserves its name only if it is repeatable. The procedure describes the process and, therefore, makes it repeatable. Two different measurement processes, intended to measure the same quantity, may by chance yield the same numerical result. On the other hand, two measurements made by the same process may yield two different results. No result means much without a procedure which tells us how we got that result.

The measurement method which a procedure describes will influence the magnitude of systematic errors in the result. The number of relevant details in a procedure influences the magnitude of random errors. Therefore, adequate calibration procedures are prerequisites for meaningful interval adjustment methods. Calibration intervals can be expected to vary as calibration procedures change.

(d) *Policy.* The policies governing a calibration control system have a marked effect on calibration intervals and the methods for optimizing them, and it is in this area of policy where management can exert its greatest influence in reducing costs and maximizing output. We have already noted that the tolerance specifications against which an instrument will be judged must be carefully defined for cost-effective interval adjustment methods. But there are other policy elements which will affect results, e.g., the question of how to treat completely inoperable instruments, or instruments which are obviously malfunctioning, or how to treat the tolerances of calibration standards.

Some laboratories have a policy of subtracting the tolerance of the standard from the tolerance of the instrument under test if the tolerance ratio is larger than 1:4, for instance. One popular standard used to calibrate the VTVM's of figure 1 provides only a 1:2 ratio on the tolerances quoted by the manufacturer. By subtracting the tolerance of the standard, one would in effect cut the tolerance of the VTVM in half, or expect the instrument to perform within a tolerance it was not intended to meet. On the other hand, ignoring the tolerance of the standard would be tantamount to increasing the instrument's tolerance and increasing its percentage in-tolerance.

Other important factors by which laboratory policy influences the quality level for measuring instruments and tools concern the generation, maintenance, and use of data sheets from which quality decisions are made; the motivation of laboratory personnel to show high in-tolerance percentages; the motivation of laboratory personnel to charge time to uncontrollable repair.

Personnel selection and training are still other factors. In one instance, we have found that newcomers to the calibration laboratory were assigned to calibrate the common varieties of measuring instruments. As these technicians became more proficient, they "graduated" to more sophisticated types of measuring instruments. The result was that the common-type instruments had a lower quality level than when they were maintained by more experienced personnel. This had a marked effect on the overall quality level of measuring instruments, because of the relatively large number of common-type instruments.

Appendix B. An Empirical Interval Adjustment Method

The following describes an empirically developed method for the adjustment of calibration intervals of measuring tools and instruments. It is offered as an example of a method meeting all the requirements of the economics, practicability, and speed of response for a given calibration control system. It is not recommended for adaptation to other calibration control systems without careful analysis of compatibility with other system components and system objectives. The method achieves a given quality level in use within reasonably narrow bounds of uncertainty, even though the decisions concerning interval changes are based on the in-tolerance conditions of individual instruments at recall.

Exhibit 1 shows the Decision and Assignment Tables from which the calibration technician determines calibration intervals. With an instrument given him for calibration is a record of the most recent tolerance codes for that instrument. These codes—1, 3, or 5—are defined below. He checks the instrument and records its incoming tolerance code. Using the Decision Table, he selects either an asterisk or one of the letters *p*, *m*, *d*. The asterisk means "Do not change the instrument's current interval"; a letter refers him to the Assignment Table, from which he selects a new interval.

EXHIBIT 1. *Interval adjustment schedule*

DECISION TABLE

Previous Tolerance Codes CRIS TREND (Left to right)	Incoming Tolerance Code		
	1	3	5
111	p	d	*
311	*	d	*
511	p	d	*
#13	*	m	m
#15	*	m	m
#31	*	m	*
#33	*	m	m
#35	*	m	m
#51	*	d	*
#53	*	m	m
#55	*	m	m

ASSIGNMENT TABLE

	Current Interval	New Interval			Current Interval	Interval New			Current Interval	Interval New		
		p	m	d		p	m	d		p	m	d
Intervals in Weeks	5	7	**	5	21	25	14	19	37	42	25	33
	6	8	5	5	22	26	14	20	38	43	26	34
	7	9	5	6	23	27	15	21	39	44	27	35
	8	10	5	7	24	28	15	22	40	46	27	36
	9	11	6	8	25	29	16	22	41	47	28	37
	10	13	6	9	26	30	17	23	42	48	28	38
	11	14	7	10	27	31	18	24	43	49	29	39
	12	15	7	11	28	32	19	25	44	50	29	40
	13	16	8	12	29	33	20	26	45	51	30	41
	14	17	8	13	30	35	20	27	46	52	31	41
	15	18	9	14	31	36	21	28	47†	52	32	42
	16	19	10	14	32	37	21	29	48	52	33	43
	17	20	11	15	33	38	22	30	49	52	34	44
	18	21	12	16	34	39	22	31	50	52	35	45
	19	22	13	17	35	40	23	32	51	52	36	46
	20	24	13	18	36	41	24	32	52	52	37	47

*Do not change interval.

#Any or no entry.

**Do not release instrument; contact supervision for instructions.

†Instrument must be recalled at least once a year for service. Calibration schedule, however, may be determined as follows:
p—Add 10 weeks if Interval ≧47.
m or d—Assign 52 weeks if Interval >52.

The tolerance codes are defined as follows:

1—In tolerance (All calibrated characteristics of the instrument were in tolerance as received, and Code 5 does not apply).

3—Out of tolerance (At least one calibrated characteristic was out of tolerance, and Code 5 does not apply).

5—Any of the following:

a. Out of tolerance condition indicated by the instrument's user on the accompanying calibration requisition form and confirmed during calibration.

b. Malfunction; calibration impossible prior to repair, provided the required repair could have changed one or more calibrated characteristics of the instrument (excludes minor repairs not affecting calibrated characteristics, like line cord repair, blown fuse, etc.).

c. Instrument found out of tolerance when calibrated to a tighter specification than it was previously calibrated to.

The interval adjustment method does not provide for calibration intervals of less than five weeks, and any instruments for which a shorter interval is indicated are pulled out and subjected to individual analysis. The method also provides for a mandatory analysis of instrument types whose average calibration interval is seven weeks or less, to determine whether changes in specifications, calibration procedures, standards, or usage may improve the balance between maintenance costs and instrument utility. The five and seven week limits were arbitrarily selected. We feel that an instrument or type which needs recalibration so frequently is generally costing too much in periodic maintenance. We have annual data-processing reports listing the average calibration interval of each instrument type; a single instrument with a calibration interval significantly shorter than the typical average interval is also subject to examination.

References and Bibliography

[1] Schumacher, Rolf B. F., A unified approach to the maintenance and calibration of measuring instruments, paper presented at the 2d Natl. ISA Instrumentation Maintenance Symp. (Houston, Tex., 1967).

[2] Schumacher, Rolf B. F., Keeping standards and measurements under control in a standards laboratory, Paper #68-612, presented at the 23d Ann. ISA Conf. (New York, N.Y., 1968).

[3] Schumacher, Rolf B. F., Statistical control in a standards laboratory, Meas. and Data (May-June 1969).

[4] ASTM Manual on Quality Control of Materials, ASTM Spec. Tech. Publ. 15-C (Jan. 1951).

[5] Couture, R. J., and Held, T. M., Calibration/service specifications, an improved way to document test equipment specifications, Paper #68-607, presented at the 23d Ann. ISA Conf. (New York, N.Y., 1968).

[6] Hicks, E. M., On optimizing accuracy ratios and instrument quality levels, Engineering Rept., Metrology and Calibration Dept., Autonetics, Anaheim, Calif. (1970).

NCSL 70

INTERVALS BY EXCEPTION

Jerry Glassman

U.S. Navy Metrology Engineering Center, Pomona, Calif. 91766

"Intervals by exception" is a new approach devised at the Navy Metrology Engineering Center to control the evaluation and adjustment of calibration intervals for the Navy Calibration program. It furnishes management with a powerful tool with which to monitor calibration intervals and assure reliability of equipment.

What are some of the interesting features of this new technique?

1. It enables management to concentrate on problem equipment by pinpointing "dogs" and "gems," i.e., statistically poor and statistically good equipments.
2. It allows management to select "optimum" intervals based on automatically derived reliability tradeoffs.
3. It motivates laboratory personnel by providing an information feedback loop for problem instruments.
4. It lowers operating costs by funneling analysis and engineering effort into the areas of greatest needs and most promising returns.
5. It lowers costs by lengthening intervals on family types and stabilizing reliability levels.
6. It provides automatic computer monitoring of all decisions (cause-effect feedback).

This system is presented with charts that illustrate its operation, outputs, and management-oriented controls. The presentation includes data analyses, adjusting of intervals, detection of "dogs" and "gems," resultant changes in system operating characteristics, underlying mathematical assumptions, and mathematical models.

Key words: Calibration intervals; exponential distribution; reliability, systems effectiveness, tradeoffs.

1. Introduction

The manager of a calibration laboratory is faced with a multitude of decisions, many of whose effects can influence overall operations for years to come. The decision to change a calibration interval can affect numerous system operating characteristics, such as:

a. equipment reliability/maintainability,
b. laboratory operating costs,
c. repair time,
d. operational schedules,
e. calibration time,
f. manpower distribution,
g. equipment availability,
h. personnel motivation.

The complexity of the interactions of these important system characteristics makes it incumbent on the manager to avail himself of simple decision-making tools. Sophisticated system-effectiveness techniques are necessary to generate the tradeoff alternatives required by management. However, the decision-making apparatus and management-oriented monitoring functions should provide complete visibility and control, and immediate feedback of system effects.

An analytical method has been devised to evaluate equipment calibration intervals and provide justification for recommending changes based on the cumulated results of past calibrations. The approach is rigorously developed and contains several unique features not found in other systems. Additionally, this system provides management with tools with which to make difficult optimization decisions without referring to the underlying mathematical processes. The tradeoffs are made available to him, and the predicted system effects are provided for several alternatives.

A decision-making system is effective only if it is used to make decisions. It is a valuable management tool if it is easy to use and provides overall system visibility and direct feedback of effects. "Intervals by exception" offers new management decision-making approach to calibration interval determination and interpretation without compromising mathematical rigor.

2. Systems Based on Model Number or Serial Number

Most calibration interval analysis systems fall into one of two categories:

1. *Intervals by model number.* All equipments of the same model number are treated as if homogeneous, and a calibration interval is established for the model number family.

2. *Intervals by serial number.* Each unit of serially numbered equipment is assumed to function according to its own unique operating characteristics, and a calibration interval is established for each individual equipment.

Both of these general approaches betray serious shortcomings in application. If the deficiencies are not eliminated, the resulting decisions are seldom optimum and are often erroneous. If the deficiencies are eliminated, the systems become overcomplicated, and lose the characteristics that initially made them attractive.

Examples of deficiencies related to calibration interval systems based on model number or serial number are as follows:

Case 1. Intervals by Model Number

a. Different manufacturers might have produced equipments having the same model number.

b. Different fabrication methods might be used for equipments of the same model number.

c. Equipments might have experienced design modifications without model number changes.

d. Cumulative operating time is different for equipments of the same model number installed at various dates.

e. Operational/environmental differences may exist for equipments of the same model number.

These and other factors can cause significantly varying operating effects that should be considered or removed. The usual treatment entails subgrouping the equipments by significant factor levels, and then establishing separate intervals for each subgroup. Figure 1 is an example of the multiplicity of subgroups that arise when as few as three significant factors are considered. As can be seen, the magnitude of the problem rapidly becomes unmanageable as the number of significant factors increases. The serial number system evolves when it becomes advisable to consider all the factors contributing to the equipment operation.

Case 2. Intervals by Serial Number

a. Initial establishment of intervals for new equipments is at best an educated guess; when the serial number philosophy is used, the historical data available is of little use for establishing intervals.

b. The amount of calibration data accumulated for one serial number is generally insufficient for meaningful statistical analysis. Therefore, the assurance of equipment reliability is essentially impossible for most equipments.

c. Management control systems based on serial number data are completely meaningless in a system effectiveness context; i.e., the resultant decisions cannot be related to other system parameters, nor are meaningful tradeoffs available.

d. Administrative and routine controls are difficult.

As a result of the above shortcomings, serial-based interval evaluation systems tend to substitute ritualistic and arbitrary rules for rigorous statistical methods.

3. The New Approach

Recognition of these discrepancies precipitated an investigation of new approaches to calibration data analysis and interpretation in this vital area of metrology. "Intervals by exception" is the result of this

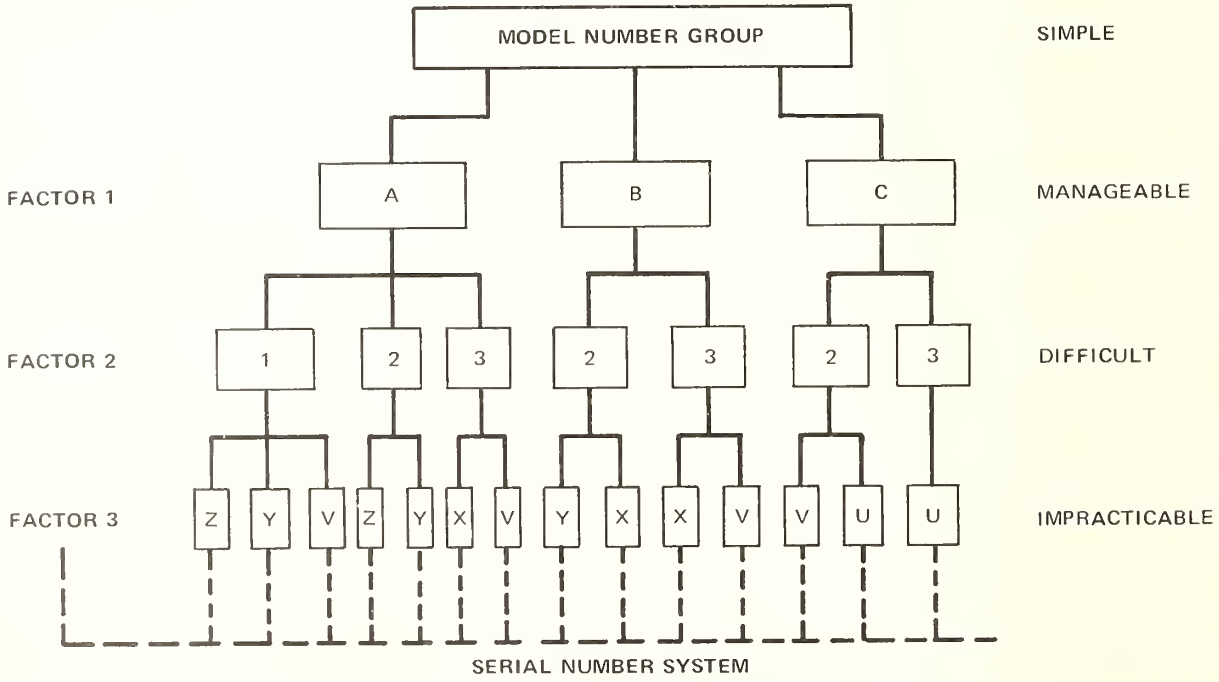


FIGURE 1. *System complexity induces conversion from a model number to a serial number system when the number of factors considered is increased.*

investigation conducted at the Navy Metrology Engineering Center for application to the Navy calibration program.

Imagine a group of instruments of a particular model number designation. Ideally, these equipments should be capable of achieving a specified reliability, when used as required for a given time between calibrations. However, because of the diverse influences of factors affecting equipment reliability, each serialized equipment of this model may follow a different pattern of failure.

The random interaction of factors causes most equipment to be influenced by a combination of elementary negative effects. Thus, compensatory factor-levels tend to balance and the residual effect varies slightly around the average. Hence, the majority of equipments have similar operating characteristics. The only equipments that display operating characteristics significantly different from the average are those having a preponderance of negative factor-levels or positive factor-levels. These "exceptions" in the model number group, and only these, need be considered for special interval treatment.

To illustrate the effect of this random interaction, suppose that the ratings and weights shown in table 1 are arbitrarily assigned to items, A, B, C at factor-level 1 in figure 1, to items 1, 2, 3 at factor-level 2, and to items Z, Y, X, V, U at factor-level 3. For example, subgroup A1Z consists of equipments manufactured by company A, using production method 1, and having an operating age of Z months; its rating would be −3 as shown in figure 2. At the other extreme, subgroup C2V rates as +3. Each of these two equipment subgroups would probably have an operating reliability deviating significantly from the average, one much poorer and one much better. We designate such equipments as "dogs" and "gems," respectively.

TABLE 1. *Assumed factors, levels, level ratings, and weights for a hypothetical model number.*

Factors	Levels	Ratings	Weights
Manufacturer	A	—	−1
	B	●	0
	C	+	+1
Production method	1	—	−1
	2	+	+1
	3	●	0
Operating age	Z	—	−1
	Y	●	0
	X	●	0
	V	+	+1
	U	●	0

Ratings legend:
- \+ better than average
- ● average
- — poorer than average

As can be seen in figure 2, most of the subgroups (10 of 14) have ratings of −1, 0, or +1; these would probably have near-average operating reliability, and may be considered to be "equivalent equipments." Subgroups with ratings −2 or +2 are borderline cases which may or may not show exceptional reliability.

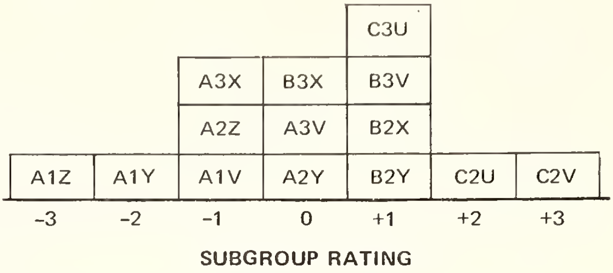


FIGURE 2. *Hypothetical histogram of equipment subgroups by subgroup rating.*

Figure 3 illustrates the simplicity in concept of "intervals by exception." Compare this to the complexity and multiplicity of subgroups generated in figure 1.

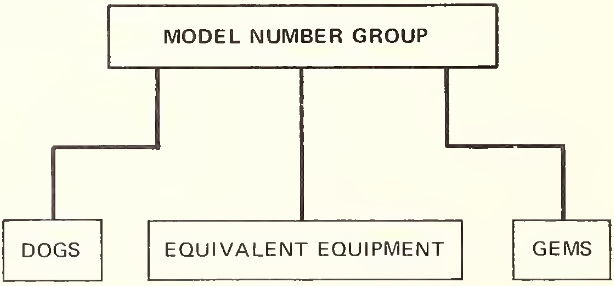


FIGURE 3. *Simplified representation of classification based on intervals by exception.*

"Intervals by exception" is a new approach devised to evaluate and adjust calibration intervals based on a compromise between the simplistic model number and the ritualistic serial number systems. Not only does it allow for statistical analysis of the majority of instruments by model number, but it pinpoints those equipments requiring special attention.

4. Norms, Dogs, and Gems

In general, equipment belonging to model number families exhibit similar operating characteristics if manufactured and operated under similar conditions. However, within any model number family, minor differences exist that cause particular serialized items to perform significantly better or worse than the model number norm. Differences in manufacturers, production method, operating time, or other factors can cause these variations. By isolating (excepting) these significantly deviating items, realistic calibration intervals can be determined for the remaining conforming equipment comprising the majority of the model number group.

Equipments that perform significantly differently than the norm are called "dogs" or "gems" according to whether they are, respectively, poorer than or better than the group average. These are the exceptions in the model number group:

1. Dogs—individual serialized items that yield a statistically poorer out-of-tolerance rate than the family average.
2. Gems—individual serialized items that yield a statistically better out-of-tolerance rate than the family average.

Analyses of these exceptional equipments provide a valuable potential for generating cost savings, improving equipment operation, and disclosing new areas of engineering knowledge related to equipment performance characteristics.

5. Mathematical Assumptions and Tests

The basic direction of "intervals by exception" is toward management-oriented control and monitoring features. However, there is a mathematical basis for the tradeoffs and decision criteria. The detailed mathematical models and statistical tests that are used are contained in the Appendix.

The following mathematical assumptions are made in applying this technique at Navy Metrology Engineering Center:

1. The times-to-out-of-tolerance are exponentially distributed according to the function ke^{-kt}.
2. The probability of out-of-tolerance increases monotonically as the time between calibrations is increased for a given equipment.
3. Failure characteristics for all equipments of a given model number are described by the same time-to-out-of-tolerance function, except for a small percentage of "dogs" and "gems."

The analyses of the records, for a given family of equipments and a given calibration interval, follow the general guidelines described below:

1. Data are purged of irrelevant and erroneous entries; i.e., obvious mistakes and human errors are removed from the data base.
2. The data are adjusted using criteria and requirements based on known or assumed system effects. For example, the tails of the time-to-failure distribution are truncated to avoid using nonrepresentative or heterogeneous data; the times to out-of-tolerance are estimated, because only times-to-discovery of out-of-tolerance are available, rather than actual times-to-driftout.
3. Statistical tests of significance are applied to detect changes in equipment operation. This requires computer grouping of data by calendar times and computer testing of the consistency of the out-of-tolerance rates. If a statistically significant change is detected, only the most recent consistent data are utilized for analyses. Therefore, the data used for analyses are homogeneous. The effects of design modification, procedural changes, and environmental/operational differences are discovered, isolated, and analyzed separately.
4. The cumulative Poisson probability distribution is used to test the relationship of the parameter for an individual serial number to the average for the model number. This detects statistical outliers; i.e., serial-numbered "dogs" and "gems."
5. An estimate of the out-of-tolerance rate is obtained for the remaining group of equivalent equipments.
6. Predictions of the probabilities that the equipments will remain in-tolerance are made for several different calibration intervals. This provides trade-

FIGURE 4. *Sample of a calibration interval analysis, 01/07/70.*

MODEL NUMBER 370 MFR: WEC

TIME BETWEEN SUBMISSIONS	N	OOT
4.5 — 5.4	2	0
* 5.5 — 6.4	11	2
6.5 — 7.4	6	0
7.5 — 8.4	8	1
8.5 — 9.4	25	2
9.5 — 10.4	13	1
10.5 — 11.4	15	0
11.5 — 12.4	7	0
12.5 — 13.4	5	1
*13.5 — 14.4	5	1
15.5 — 16.4	4	1
16.5 — 17.4	1	0
17.5 — 18.4	2	0
18.5 — 19.4	5	1

DATA USED *89.2 PERCENT*
YEARS = 1/67–12–68
N′ = 95
OOT′ = 8

ANALYSIS RESULTS
$K = 0.9055$ PERCENT
$T = 883.5$
ESTIMATED RELIABILITY .90 .85 .80 .75
CALIBRATION INTERVAL 12 18 25 32

CURRENT INTERVAL = 12

DOG AND GEM DETECTION—1/70	SERIAL NUMBER	NO. REPORTED	NO. OOT	LOCATION		
				CAL ACT	CUST	P
DOG	10432	6	3	TAX	SHOP–3	.029
DOG	19313	12	5	BBT	DB–14	.043
GEM	26813	10	0	AAA	PT–109	.019

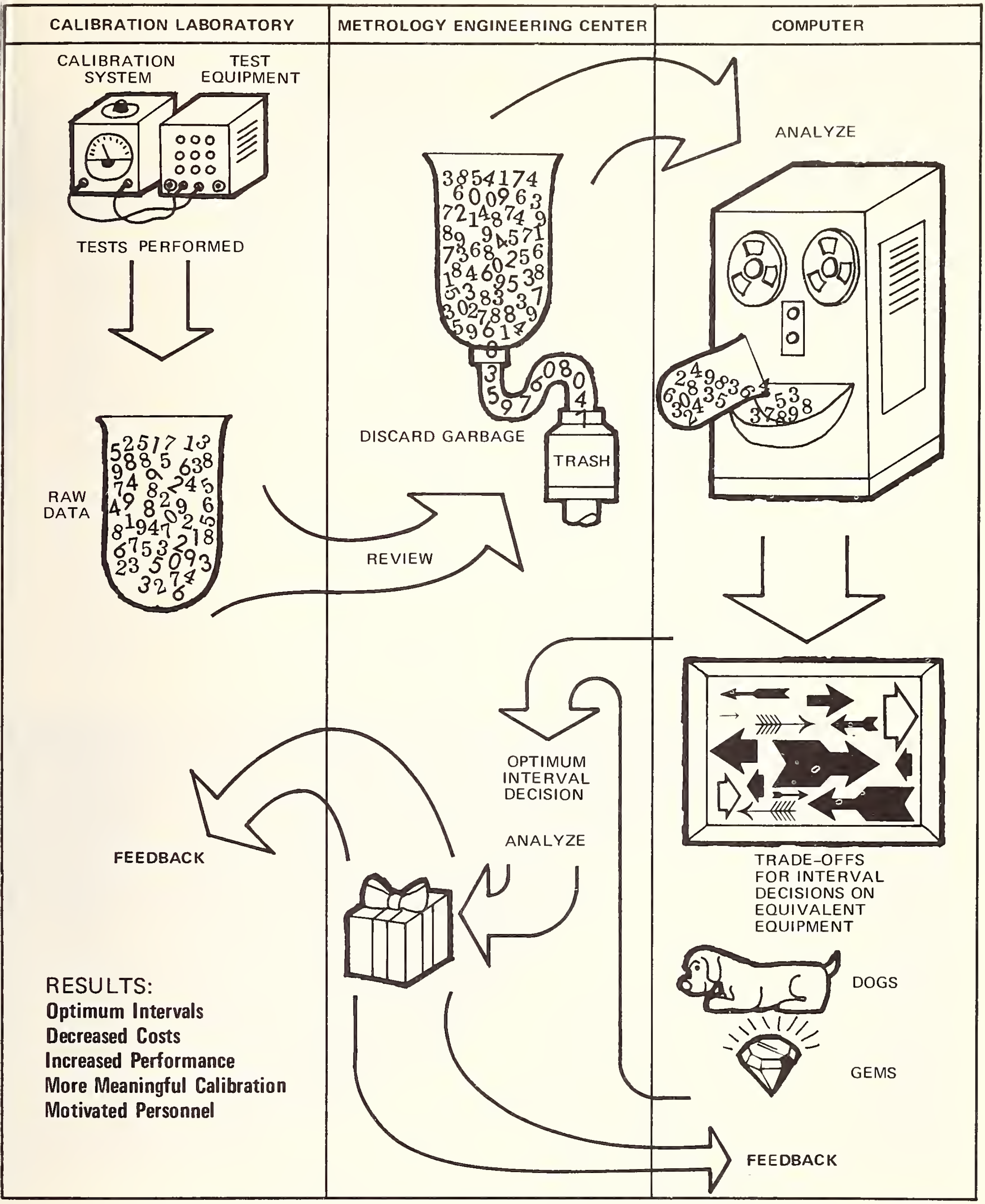


FIGURE 5. *Flowchart of closed-loop feedback system for intervals by exception.*

offs enabling management to make the decision for adjusting intervals with total visibility of the effect on reliability for the model number population.

7. New methods are being developed to derive reliability/effectiveness and interval/cost trade offs for determining optimum calibration practices. These trade-offs will allow management to consider the system effects of out-of-tolerance equipment and evolve criteria for repairing versus replacing items.

8. An original approach is being developed for estimating and applying confidence limits to reliability/interval decisions. Some equipments perform so well that few failures develop in them. Current methods do not provide a high degree of assurance for extending intervals on these kinds of "gems." The new confidence-limit approach allows extension of intervals with increased statistical assurance.

6. Results

It was necessary to design new computer output formats for the calibration interval analysis so that the results could be efficiently presented to management. These also provide prompt feedback of decisions to cognizant user activities, and facilitate engineering analyses of "dogs" and "gems."

Figure 4 is a sample presenting the purged calibration data, the estimated reliability/interval trade-offs, and the "dog" and "gem" serial numbers. Note that the data for "equivalent equipment" includes only the number reported and the number out-of-tolerance (OOT); reports of damaged and inoperative equipments do not appear.

The major computer analyses subprograms are:

a. Data truncation.

b. Data adjustment.

c. Statistical tests for significant differences between data groups and for the establishment of the data base.

d. Determination of "dogs" and "gems."

e. Calculation of reliability/calibration interval trade-off alternates.

Figure 5 is a flowchart of the closed-loop feedback system implemented for "intervals by exception."

Table 2 is an example of the input to management showing the interval/reliability trade-offs for selected values of out-of-tolerance rate.

OUT-OF-TOLERANCE RATE, K	CALIBRATION INTERVAL	RELIABILITY
.016	7	.894
	10	.852
	14	.799
	18	.750
.017	6	.903
	10	.844
	13	.802
	17	.749
.018	6	.898
	9	.850
	12	.806
	16	.750

TABLE 2. *Partial table of tradeoffs between estimated calibration intervals and reliability values, by out-of-tolerance rate,* k.

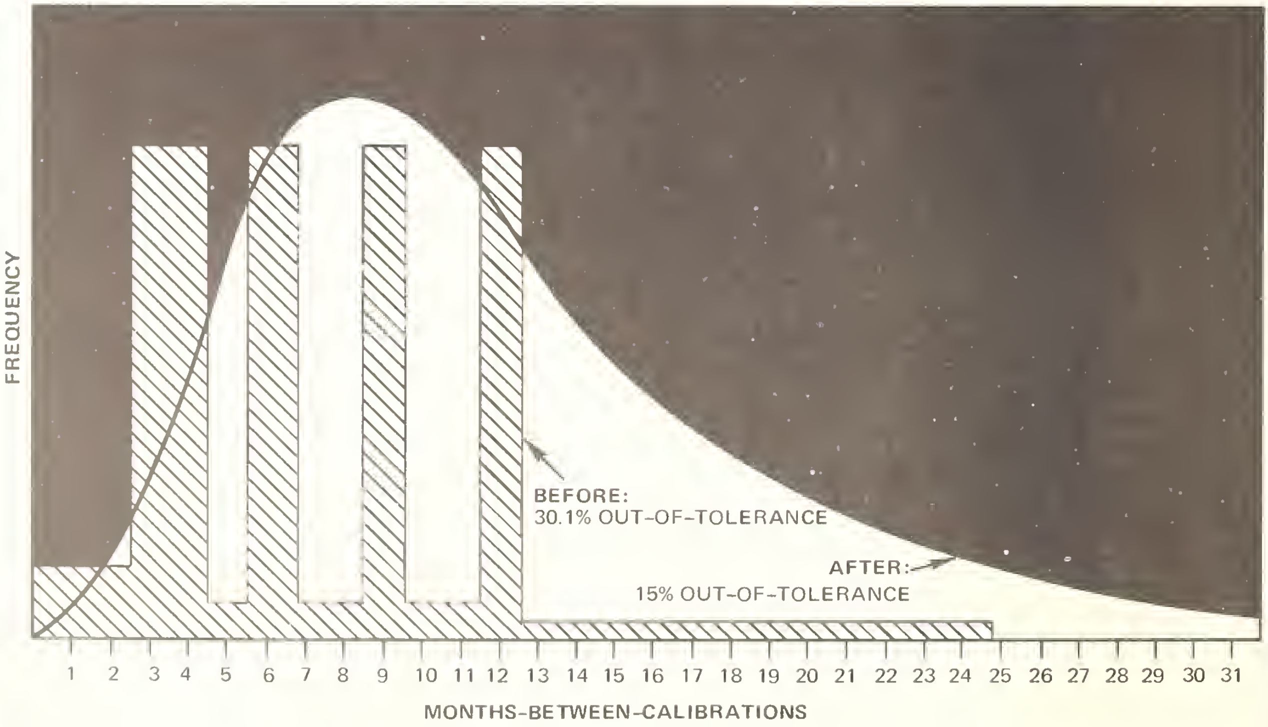


FIGURE 6. *Distributions of current and projected intervals for 60 families of equipments.*

7. Conclusions

A new philosophy has been presented for interpreting calibration intervals. This philosophy, called "intervals by exception," has been developed into an analytical system for evaluating calibration data. Statistical techniques, resourcefully applied, constitute the framework of this system. The system enables management to confidently make interval adjustment decisions with complete visibility of their probable effects on equipment reliability.

This system is being used at the Navy Metrology Engineering Center to evaluate calibration data and evolve decision criteria on which to change intervals. A test program was conducted on 60 equipment types submitted for calibration at short intervals. Optimum decisions were made for these 60 equipments; some intervals were increased, some decreased, and some not changed. The average interval for these 60 was increased from 6.8 months to 8.2 months. Figure 6 shows the exponential probability distribution of the 60 projected intervals superimposed on the distribution of the 60 intervals currently in use (equal numbers at 3, 4, 6, 9 and 12 months). As can be seen, there is a significant shift (increase) in the mean. Also, there are many more instruments at longer intervals on the projected curve, and the percentage out-of-tolerance has been reduced from 30.1 to 15. This is clear evidence of the long range (recurring) cost improvements generated as a result of using "intervals by exception."

It has been demonstrated that meaningful results can be obtained by approaching a problem in an original manner. It is hoped that this effort acts as a catalyst for imaginative inquiry into other problems in metrology in addition to its being used in its own right.

Acknowledgement is due Kim Bruce, mathematician, for reviewing and testing the mathematical models, manually demonstrating system performance characteristics, and proofreading the final draft.

8. Appendix

8.1. Reliability

It is hypothesized that the probability that an instrument remains in tolerance is a function of the elapsed time since it was last calibrated. This probability, called reliability $R(t)$, is equal to the complement of the cumulative probability distribution $P(t)$ for times-to-out-of-tolerance for all instruments of that family; i.e., $R(t)=1-P(t)$.

The underlying distribution of times-to-out-of-tolerance is generally assumed to be an exponential of the form.

$$\begin{aligned} f(t) &= ke^{-kt}, && 0 \leqq t < \infty, \\ &= 0 \quad , && \text{otherwise} \end{aligned}$$

where k is the out-of-tolerance rate; $k>0$, and e is the base of natural logarithms. The cumulative distribution function, which represents the probability that an equipment goes out-of-tolerance before time t is

$$P(t) = \int_0^t f(t)\,dt = \int_0^t ke^{-kt}dt = 1-e^{-kt}$$

The probability that an equipment remains in-tolerance for a time interval equal to t is

$$R(t) = \int_t^\infty f(t)\,dt = 1-\int_0^t f(t)\,dt = e^{-kt}$$

where $R(t)$ is the reliability. It can be seen that $R(t)+P(t)=1$. For a more detailed discussion, see reference [1].[1]

8.2. Data Consistency

If equipment of a given model number undergoes design, procedural, or operational revision, its out-of-tolerance rate may change. Only relevant calibration data should be utilized when decisions are made affecting the current configurations and uses of equipments. A statistical test is performed to detect significant changes in out-of-tolerance rates for data grouped by calendar time.

The probable occurrence of out-of-tolerance reports in any specified period can be mathematically described by a Poisson process with parameter equal to the expected number of out-of-tolerance reports.

$$f(X) = \frac{e^{-kt}(kt)^X}{X!}$$

where $f(X)$ is the probability of obtaining X out-of-tolerance reports, k is the family out-of-tolerance rate, kt is the expected number of out-of-tolerance reports, e is the base of natural logarithms.

An exact F-test of equivalency for two sets of Poisson-generated data on out-of-tolerance reports per unit time is derived in reference [2] and shown below:

$$F_{1-P}\,(2(X_2+1), 2X_1) = \frac{T_2}{X_2+1} \cdot \frac{X_1}{T_1};$$

where X_1 and X_2 are the number of out-of-tolerance reports for any two groups of data, T_1 and T_2 are the corresponding accumulated operating times for these groups, and

$$\frac{X_1}{T_1} > \frac{X_2}{T_2}.$$

8.3. Detecting Dogs and Gems

Tests of significance are performed to detect statistical "dogs" and "gems" by comparing data for each individual instrument with the model number failure rate estimate. The following computations are performed for each instrument:

1. The expected number of out-of-tolerance reports for a given serial number with operating time T_g is calculated:

$$kT_g = T_g \Sigma r_i / \Sigma T_i$$

where k is the estimated out-of-tolerance rate for the model number family; r_i is the cumulative number of

---

[1] Figures in brackets indicate the literature references at the end of this paper.

out-of-tolerance reports for the ith serial number, T_i is the cumulative operating time for the ith serial number.

2. The kT_g (expected number of out-of-tolerance reports for the given serial number) is compared to the r_g (observed number of out-of-tolerance reports for the given serial number).

3. If $kT_g < r_g$,

$$P_A = \sum_{j=r_g}^{\infty} \frac{e^{-kT_g} (kT_g)^j}{j!}$$

is calculated.

4. If $P_A \leqq 0.05$, the serial number being tested is a statistical "dog."

5. If $kT_g > r_g$,

$$P_B = \sum_{j=0}^{r_g} \frac{e^{-kT_g} (kT_g)^j}{j!}$$

is calculated.

6. If $P_B \leqq 0.05$, the serial number is a statistical "gem."

9. References

[1] Zelen, Marvin, Ed., Statistical Theory of Reliability, p. 15 (Univ. Wisconsin Press, Madison, 1963).

[2] Brownlee, K. A., Statistical Theory and Methodology In Science and Engineering, 2d ed., p. 145 (John Wiley & Sons, Inc., New York, 1965).

NCSL 70

OPTIMIZING CALIBRATION INTERVALS

Donald J. Greb

Manager, Metrology and Standard Tools, Lockheed Missiles and Space Company, Sunnyvale, Calif. 94088

This paper describes a two-method system for using simple attributes calibration data to adjust and optimize calibration intervals. Each method is used only where its superior characteristics predominate; the combination of methods produces a total system which exploits the advantages of each without having to suffer with the disadvantages. The "fixed interval through data" method is employed where there are at least 27 bits of data, the applicaion being unique in that the data is treated as a random sample from an infinite population, sampling variations are accounted for, and all decisions to extend calibration intervals are characterized by statistical validity. When there are only from 5 to 26 bits of data, statistical validity is not possible and the "fixed interval through engineering intuition" method is utilized. However, intuition and judgment are applied only to a set of decision rules, and strong, specific data support is required. The system has not been extended to less than 5 bits of data, although there would seem to be no problem in so doing. Net results in the first 18 months of use are 495 changes involving 34,200 units, with annual savings of 24,100 technician hours, and with no noticable deterioration in overall instrument reliability.

Key words: Data support; fixed calibration interval; instrument reliability; statistical validity; two-method optimization.

1. Introduction

The combination system of adjusting and optimizing calibration intervals described herein was developed over a period of about two years in the Lockheed Measurements and Standards Laboratory (MSL). The "fixed interval through data" method was worked out first, and after six months implementation it was evident that the method is highly satisfactory as applied to instrument groups for which a substantial amount of data is at hand. However, it also became obvious that the method was either woefully inadequate or totally unusable for families for which few data are available, and that a satisfactory means of handling the latter was badly needed. Out of this need evolved the second method and the combination of the two has quite satisfactorily solved a problem of very long standing.

2. Definitions

Operative/Inoperative. An instrument is operative when all performance parameters are functioning and capable of yielding data or information. An instrument is inoperative when one or more performance parameters are disabled and incapable of yielding data or information.

Operational Reliability. (R_0) for a particular group of instruments, over a given period of time, is the ratio of the number of operative units to the sum of operative and inoperative numbers of units.

In-tolerance/Out-of-tolerance. An instrument is in-tolerance when all performance parameters are functioning within specifications. An instrument is out-of-tolerance when one or more performance parameters are not functioning within specifications.

In-tolerance Reliability. (R_i) for a sample of units submitted for calibration is the ratio of the number in-tolerance to the total number operative.

Actual In-tolerance Reliability. (R_a) is unknown except where data are at hand for an entire population, and no sampling is involved. R_i is an estimate of R_a, and statistical limits for R_a with any desired degree of confidence can be determined from the data used to calculate R_i. Although R_a is unknown, its limits and the degree of confidence associated with the limits are highly useful.

3. Alpha-Code Data Base

The basic source of reliability information is the alpha-code marking, directly related to operational and in-tolerance reliability. The alpha-code is a single letter recorded by a technician on the Service Report and it provides significant information on the as-received condition, reason for submission, and work performed. The alpha-codes, instrument categories to which they apply, and category definitions are:

A—ACCEPTANCE — applicable to instruments which are
- New or serviced for the first time
- Returned from vendor, storage, or held for parts
- Put into hold for manual status

- Submitted by any facility external to Bay Area MSL
- Placed in calibration storage without calibration
- Sent by In-place to an MSL laboratory

D—DAMAGED—applicable to instruments which show evidence of physical damage or operational misuse.

F—INOPERATIVE — applicable to instruments showing one or more performance parameters incapable of yielding information.

C—OPERATIVE IN-TOLERANCE — applicable to instruments with all performance parameters functioning within specifications.

O—OPERATIVE OUT-OF-TOLERANCE — applicable to instruments with one or more performance parameters not functioning within specifications.

4. Reliability Computations

Figure 1 shows the logic and procedure used by the technician in assigning an alpha-code to the instruments submitted to MSL.

P = average population of an instrument group over a number of months, m.

$N = Pm$ = total number of units submitted to MSL in m months.

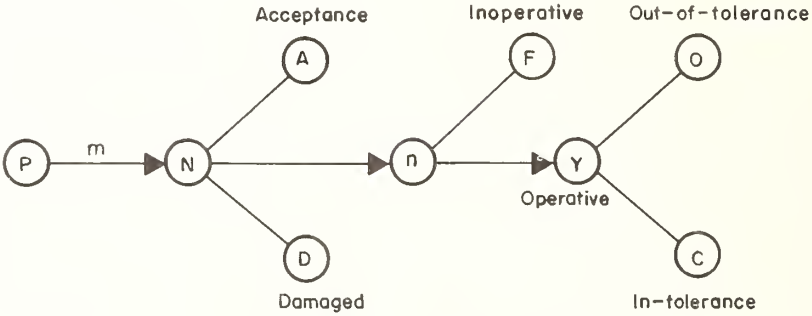


FIGURE 1. *Logic for assignment of alpha-code.*

These codes are mutually exclusive, so that there is one and only one correct alpha-code for each item. The only situation where the technician may have a difficult judgment is in determining whether an instrument has suffered physical damage or has been misused in operation. It should be noted that the in-tolerance/out-of-tolerance determination is made by comparing a quantitative measurement with specified parameter limit(s) and that each code provides substantial information on what the instrument is and what it is not. For example, the code "C" provides information that the instrument was operative, in-tolerance, had not been subjected to physical abuse or operational misuse, and was not in any one of the conditions classified as ACCEPTANCE.

The estimates of reliability are based on the numbers of instruments accumulated over a stated period in these various alpha-code categories. Operational reliability R_0 and in-tolerance reliability R_i are computed as:

$$R_o = \frac{P - \dfrac{A+D}{m} - \dfrac{F}{m}}{P - \dfrac{A+D}{m}}$$

$$R_i = \frac{C}{C+O} = \frac{Y-O}{Y} = \frac{C}{Y}$$

5. Fixed Interval Through Data

After literature search, discussion with our laboratory personnel and customer representatives, and examination of considerable data, the following criteria for extension of calibration intervals were set:

- R_i must be 95 percent minimum and R_0 must be 92 percent minimum.
- At the new interval, the probability that R_a is at least 92 percent must be 80 percent or more.

Originally, 90/90 percent was chosen for R_a rather than 92/80 percent because 90 percent is the midpoint of the 85 to 95 percent in-tolerance acceptability range. However, one of our customers uses an 80 percent confidence factor almost exclusively in reliability calculations, so in order to conform to their normal practice the confidence factor was dropped to 80 percent and the reliability figure raised to 92 percent to compensate. Figure 2 is the chart of in-tolerance reliability versus sample size available, used for determination of permissible calibration interval extensions in accordance with the criteria above. Zone 0 permits no change, Zone 1 permits an increase of one-third, Zone 2 permits an increase of 50 percent, and Zone 3 permits the interval to be doubled. (Extensions from 6 to 12 or 12 to 24 are not permitted because of other restraints.)

A minimum of 27 bits of data is required to satisfy the criteria and provide statistical validity. The 27-bit minimum is a function of the R_a 92/80 percent criteria and will be larger or smaller as these percentages are increased or decreased. An important point with respect to the criteria is that inoperatives (malfunctions or failures) are not ignored as they are in many calibration interval schemes. R_0 must be a

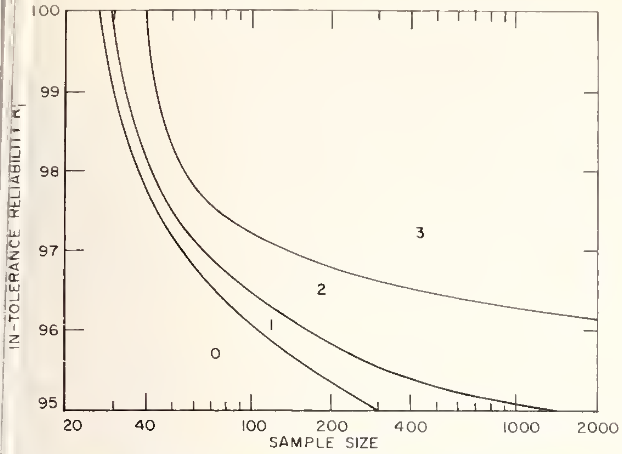


FIGURE 2. *Chart for determination of permissible extensions in calibration intervals.*

minimum of 92 percent and thus acts as a permissive/restraining factor in extension of calibration intervals but does not influence the magnitude of the extension since it has no influence on R_a.

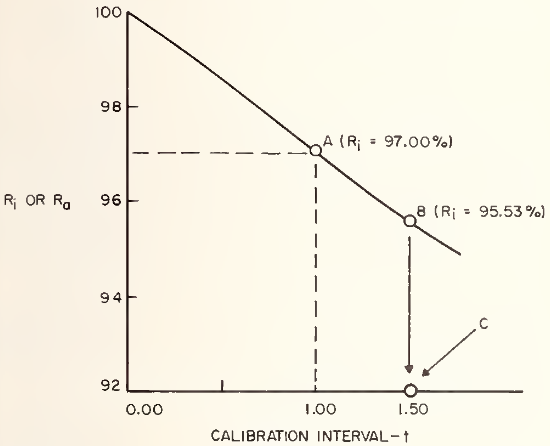


FIGURE 3. *Two-step process for determination of zone boundary lines in figure 2.*

Calculation of zone boundary lines. The method used to calculate the zone boundary lines of figure 2 is a straightforward two-step process involving elementary reliability statistics theory. Figure 3 illustrates the process. First, an R_i at 1.00 t (the current calibration interval) is assumed and noted as point A. Point B is calculated on the assumption that the failure[1] rate k is small and constant within bt (where b is 1.33, 1.50, or 2.00, depending on which zone boundary line is being calculated). In this situation the reliability equation $R = e^{-bkt}$ applies where R = reliability, e = base of natural logarithms, k is the failure rate, and t is a variable calibration interval. In our calculations the failure rate is assumed for points A and B. If $R_i = 97.00$ percent at A, then the number 1.00 kt can be read as 0.0305 from tables of the descending exponential (as in the NBS Applied Mathematics Series 14). Then kt is multiplied by the ratio of the new calibration interval to the old, and the new value of the R_i estimate is rated from the tables using exponent bkt. In figure 3, $b = 1.50$, whence $bkt = 0.04575$ and $R_i = 95.53$ percent; this is independent of sample size.

Now let us examine the second step. It is desired to calculate a sample size such that, when $R_i = 95.53$ percent, the probability is 80 percent that R_a is 92 percent or greater. This involves confidence limits, and for these calculations the booklet Confidence Limits for Attributes Data, a Lockheed document, has been used. (An alternate method is described on page 373 of Engineering Statistics by Bowker and Lieberman, Prentice-Hall, 1959. The Lockheed booklet is used because the calculations are much simpler and the range of available confidence limits is wider). A value of N is assumed, the number of failures calculated as $N(1 - R_i)$, and the 80 percent lower limit of R_a found in the tables. If R_a is over 92 percent, the assumed value of N was too high, and if R_a is less than 92 percent, it is too low. The N and R_i values thus found fix one point on a zone boundary line in figure 2 and the process is repeated for enough points to define each such line accurately. As might be deduced from the above discussion, point C of figure 3 is a function of point B, sample size, and the desired confidence level. When sample size becomes high enough so that $N(1 - R_i)$ is greater than 10, the Lockheed tables are no longer usable and some other method must be used. When sample size is large and percent defective small, the Poisson distribution may be used to calculate these confidence limits. For reference, see paragraph 2.4.5, page 438, Quality Control and Industrial Statistics, Acheson J. Duncan, Richard D. Irwin, Inc., 1959, or many other books on mathematical statistics. Sample calculations of two boundary line points are given in the Appendix.

The statistical techniques used to calculate boundary line sample sizes when there are no defectives in the sample ($R_i = 100\%$) are necessarily different from those above. When $R_i = 100$ percent, point A is always 100 percent and point B is also always 100 percent. However, the problem can be solved by approaching it through the combination of sample size and the magnitude of calibration interval change permitted in Zones 1, 2, and 3 respectively. Zone 3 will be used to demonstrate the logic involved in making the calculations. Zone 3 permits the calibration interval to be doubled and when the calibration interval is doubled, the rate of data input is approximately halved, assuming a constant population. Therefore, in the case of Zone 3 and $R_i = 100$ percent, we need to

---

[1] In this discussion the term "failure" refers to an out-of-tolerance condition, i.e., failure to meet accuracy specifications, rather than an operating failure where there is a complete malfunction. When Ri is high and failure rate is low (as is generally the case), it is valid to assume that the failure is of the "chance" or random variety and that the exponential relation applies. This subject is treated in many books on reliability. (For example, see pages 3–5 of Reliability Theory and Practice, by Igor Bazovsky, Prentice-Hall, 1961.) In particular, it should be noted that the calibration process is essentially identical to the "overall" process referred to on page 5.

answer the question. "What is the minimum sample size which, when divided by 2, provides that R_a is at least 92 percent with a probability of 80 percent?" The Lockheed tables are useful in making this determination. Using the 80 percent lower limit table, we see that a sample size of 19 with 0 failures has an 80 percent lower limit of only 91.88 percent but a sample size of 20 has an 80 percent lower limit of 92.27 percent. By doubling 20, we obtain 40 as the minimum sample for Zone 3 when $R_i = 100$ percent. Following the same logic, sample sizes for all three zones are determined as follows:

Zone	*A*	*B*	*C*	*D*
1	20	0.75	1.33	27
2	20	.67	1.50	30
3	20	.50	2.00	40

where $A =$ minimum sample at which $R_a = 92$ percent with a probability of 80 percent when $R_i = 100$ percent.

$B =$ Amount of data obtained after extension compared to that obtained prior to extension.

$C = 1/B =$ the factor by which A must be multiplied to obtain the sample size which permits extension.

$D = A \times C =$ Minimum sample sizes for Zones 1, 2, and 3 when $R_i = 100$ percent.

6. Fixed Interval Through Engineering Intuition

The use of the "fixed interval through data" method is limited to instrument families large enough so that at least 26 operative instruments are serviced in some arbitrary period of time and the zones of figure 2 are calculated on the assumption that the data are a sample and that sampling variations have been taken into consideration. However, there are many instrument families which take a very long period of time (2 to 5 years or more) before 27 operative instruments will be serviced, and it is therefore highly desirable to develop other criteria applicable to instrument families with fewer than 27 which will permit calibration interval extensions for them.

To proceed along these lines requires dependence to some degree on considerations other than statistical sampling theory. The most important of these considerations are:

1. The quantity of data exceeds, sometimes by a substantial amount, the instrument population, so that the uncertainties of sampling variation incorporated into the other method are diminished by a great amount, probably an order of magnitude.

2. The period of time over which the data are accumulated exceeds, sometimes by a substantial amount, a full calibration interval so that the chance that an active unit might not be included in the data is quite minimal.

3. No increase in calibration interval will be made if there are *any* out-of-tolerance units in the sample. R_0 is calculated in the normal manner and must be at least 92 percent.

4. The items being considered for interval extension will almost always have some comparable items on which the interval was extended, using data for which the sampling uncertainties were accounted for.

5. Engineering judgment and knowledge concerning instrument design, function, application, and usage is a legitimate substitute for recorded data, even though it is quite difficult to qualify that judgment.

6. The operational risks are relatively small because of the small instrument populations involved.

On the basis of these factors, table I identifies permissible interval extensions in terms of both the absolute and relative amount of data on hand. Examples of changes permissible under these rules:

Active population 9, calibration interval 3 months, sample size 23 —
Category I — Change to 6 months
Active population 14, calibration interval 6 months, sample size 19 —
Category II — Change to 9 months
Active population 3, calibration interval 4 months, sample size 8 —
Category III — Change to 6 months
Active population 7, calibration interval 9 months, sample size 11 —
Category IV — Change to 12 months

The decision matrix of table 1 has some characteristics which distinguish it from other schemes employing intuitive judgment:

1. All the intuition is applied to generation of a set of decision rules, thus allowing the application of judgment to specific cases to be precise and consistent.

2. Once the decision matrix is made, any clerk, technician, or laboratory personnel can apply the rules with ease.

3. All decisions are supported by a strong, well-defined data base.

TABLE 1. *Permissible extensions of calibration intervals with 5 to 26 bits of data, fixed interval through engineering intuition*

Category	Sample Size	Quantity of Data Relative to Active Population	Changes Permissible, months
I	16–26	Minimum of double	1–2, 2–4, 3–6,
II	16–26	Equal or greater, but less than double	2–3, 3–4, 4–6, 6–9, 9–12, 12–18, 18–24
III	5–15	Minimum of double	2–3, 4–6, 6–9, 12–18
IV	5–15	Equal or greater, but less than double	3–4, 9–12, 18–24

NOTE: Changes permissible in categories II and IV are also permissible when data are in categories I and III.

7. Calibration Interval Decreases

Theoretically, the logic and statistical methods for decreasing calibration intervals and thereby bringing R_i up to an acceptable level should be the same as those used for increasing intervals. As a practical matter, this does not work at all. Assume for the moment that the criteria for decreasing intervals are made comparable to those for increasing intervals:

- R_i must be less than 85 percent.
- At the new interval, the probability is 80 percent that R_a is at least 92 percent.

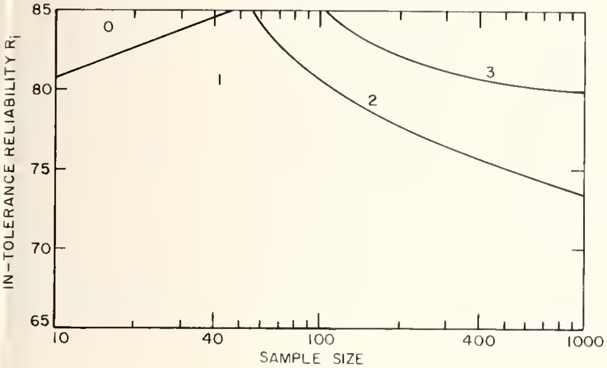


FIGURE 4. *Chart for determination of calibration interval decreases.*

Note that the second criterion is identical to that for increasing intervals. Using the same calculation methods as previously, zone boundary lines were calculated and are shown in figure 4. The differences between figure 2 and figure 4 are very startling:

- The "no change" zone is very small.
- The zones are reversed in that the most severe change zone (1) is next to the no change zone (0) and the least severe change zone (4) is farthest removed from the no change zone (0).
- Except for the no change zone, the smaller the sample, the more severe the change.
- There are no zones at all for reducing intervals by 25 percent (12 to 9 months, for example), 33 percent (9 to 6 months, for example), or 50 percent (12 to 6 months, for example).

The second and third points are explained by the fact that: the smaller the sample, the larger the uncertainty; and the larger the uncertainty, the more severe the necessary action to be sure that desired results are forthcoming. The last point shows that there is no value of R_i below 85 percent such that a 25, 33, or 50 percent decrease in interval will make $R_a = 92$ percent with any reasonable degree of certainty.

These conditions, therefore, show rather clearly the severe limitations of attempting to improve R_i by decreasing the interval and the prudence of exploring other, more fruitful corrective actions.

8. Procedure and Documentation

When a calibration interval change is to be made, a Reliability Bulletin is initiated by the Measurement Standards Laboratory (MSL) Reliability Engineer, who provides the required data, as shown in table 2. The bulletin is signed by the MSL Manager and approved by the cognizant Navy and Air Force Calibration Specialists. It thus provides the vehicle for generation and approval of a change and also provides permanent documentation for the change.

9. Limitations on Calibration Interval Extensions

There are several situations and conditions where it is prudent, at least in the initial phases of application, to impose specific arbitrary limitations on interval extensions, even though the data might permit greater or more frequent extensions:

1. The maximum individual extension is 3 months for all instruments except those with 12 or 18 month intervals, where an increase of 6 months is permitted.

2. The data used to support a change shall cover a period equal to at least one-half the current interval, regardless of how much might be available over a shorter period.

3. After an interval extension has been made, no further extension can be considered until a period of time equal to the sum of the old and new intervals has elapsed, and none of the data used to consider a second extension shall be older than the new calibration interval. If a change from 4 to 6 months is made, for example, no further extension can be considered for

TABLE 2. *A typical reliability bulletin*

NOTIFICATION OF RECALL PERIOD CHANGE

Manufacturer/Model — Electronic Measurement TO Series Power Supplies
Station Code — LEMK
Change to be Made — 09 to 12 months
Effectivity Date — 2 March 1970
Quantity Involved — 27
Data Supporting Change:
For the 13 months ending January 1970 —
Total calibrated — 68
Operative — 58, $R_o = 97.1\%$
In-tolerance — 57, $R_c = 98.2\%$
A = 7 D = 1 P = 27
Sample size 58, $R_c = 98.2$ percent falls into Zone 3 which permits extension of the recall period from 09 to 12 months.

10 months and the data for considering an extension at that time can be no more than 6 months old. This limitation accomplishes two things: (a) it allows the data bank to be purged of all data from the old interval period, and (b) it allows for a full cycle of the population to be processed and therefore assures that any subsequent consideration will be based on data from the entire population.

4. The calibration interval of an instrument powered by a battery with a limited life, an instrument needing regular mechanical attention, or one with similar functional time-dependent limitations, will be governed by those considerations and not by R_i/R_0.

5. Calibration interval extensions shall be made only four times per year on the first Monday of March, June, September, and December. These times coincide with the new printing of preprinted Service Reports, with calibration interval being part of the preprinted information.

10. Results

The family size for more than half the equipment reaching MSL is between 1 and 9 instruments; other percentages are 15 percent for 10 to 19 items; 18 percent for 20 to 49, 8 percent for 50 to 99, 4 percent for 100 to 199, and two percent for 200 or more. The first changes made by the two-method system described were effective 1 December 1968. Including those which were effective on 2 March 1970, results have been as follows:

- Total interval changes—495.
- Total instruments involved—34,200.
- Maintenance of 88–92 percent in-tolerance reliability, as shown by figure 5.
- Steady reduction in total scheduled calibrations per unit per year from 2.35 to 2.06, or 12.3 percent.
- Steady reduction in total scheduled calibrations per year—16.6 percent from 119,600 to 99,600 or 16.6 percent. The difference between 16.6 percent and 12.3 percent is accounted for by a 4.3 percent drop in active instrument population.
- Exponential reduction in annual technician hours. The reduction is expected to reach 24,100 hours by August 1971. Note that a full interval must elapse before the reduction associated with a specific change begins to be realized.
- Major changes in distribution of calibration intervals, as shown in figure 6, where each stepped column covers seven quarters. The pattern of changes is quite clear. Early in the program, emphasis was on changes from 3 to 4, 3 to 6, and 4 to 6 months, since 39 percent of the total population was on three-month intervals and the yield in hours is high. Later the emphasis shifted to changes from 6 to 9 and 9 to 12 months, and finally a substantial quantity from 12 to 18 months.

With the passage of time, many more extensions will be made and a considerable number of second and possibly even third extensions. It is estimated that by the end of 1972 the total saving in annual technician time will be on the order of 45,000 to 50,000 hours.

The writer wishes to acknowledge the large contribution of Messrs. D. B. Schneider, Research Specialist, and C. W. Gebhardt, Reliability Engineer, the Lockheed Measurement Standards Laboratories, to the theory and development of the statistical aspects of the system. Also instrumental in the overall formulation of these methods was Mr. M. L. Brink of the Navy Special Projects Office.

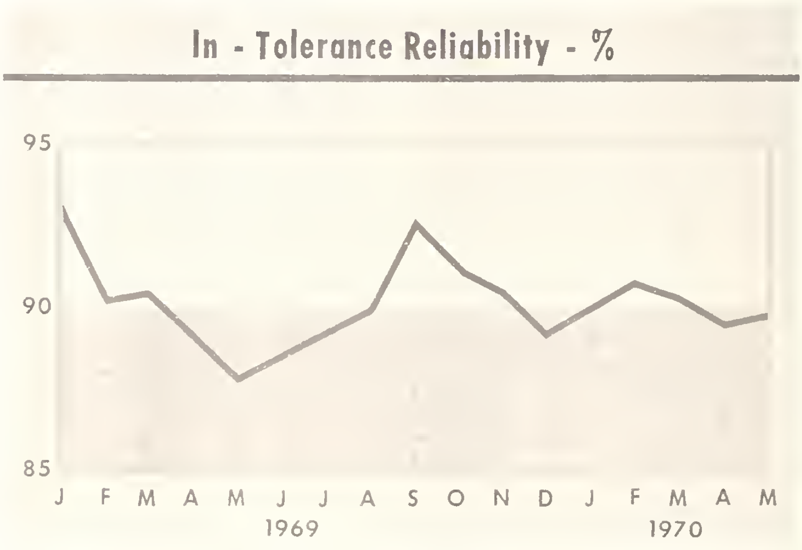


Figure 5. *In-tolerance reliability, 1969 and 1970.*

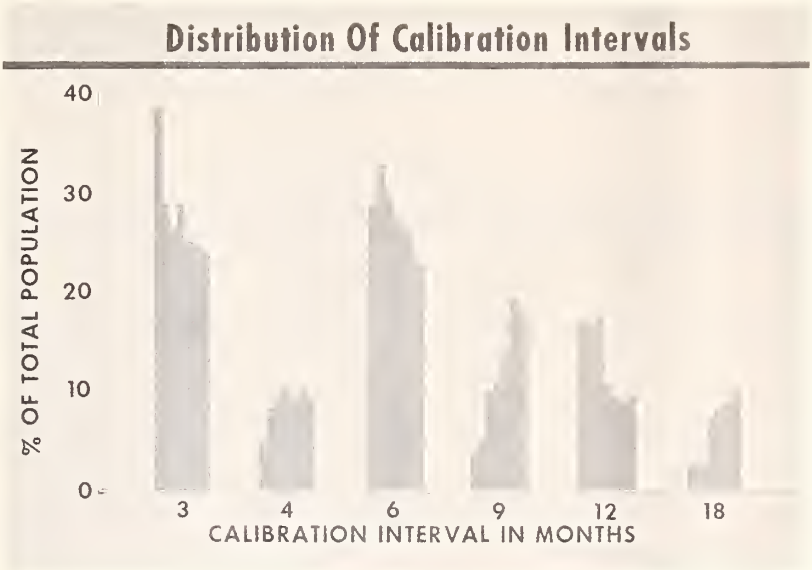


FIGURE 6. *Quarterly changes in distribution of calibration intervals.*

11. Appendix: Sample Calculations of Boundary Line Points

The calculations below show determination of two points on the 2.00 t boundary line (between Zone 2 and Zone 3) in figure 2.

Point 1

$R_i = 0.9800$ at 1.00 t
$R_i = 0.9604$ at 2.00 t, $p = 1 - 0.9604 = 0.0396$
$N = 60 \quad Np = 2.376 \quad R_a = 0.9225$
(assumed N too large)
$N = 50 \quad Np = 1.980 \quad R_a = 0.9169$
(assumed N too small)
$N = 55 \quad Np = 2.178 \quad R_a = 0.9199$
(assumed N slightly small)
$N = 56 \quad Np = 2.218 \quad R_a = 0.9205$

Therefore, $N = 56$, $R_i = 98$ percent are the coordinates.

Point 2 (using Molina's Tables of Poisson's Exponential Binomial Limit, D. Van Nostrand, 1947)

$R_i = 0.9650$ at 1.00 t
$R_i = 0.9312$ at 2.00 t, $p = 1 - 0.9312 = 0.0688$
$N = 726.7$[2] $\quad Np = 50 \quad Np\ (80\%) = 56.41$
$R_a = 1 - 56.41/726.7 = 0.9224$
$N = 581.4 \quad Np = 40 \quad Np\ (80\%) = 45.78$
$R_a = 1 - 45.78/581.4 = 0.9213$
$N = 436.0 \quad Np = 30 \quad Np\ (80\%) = 35.06$
$R_a = 1 - 35.06/436.0 = 0.9196$
$N = 465.1 \quad Np = 32 \quad Np\ (80\%) = 37.22$
$R_a = 1 - 37.22/465.1 = 0.9200$

Therefore, $N = 465$, $R_i = 0.965 = 96.5$ percent are the coordinates.

Zone 0—No change

Zone 1—1.33t
3 to 4 months
9 to 12 months
18 to 24 months

Zone 2—1.50t
2 to 3 months
4 to 6 months
6 to 9 months
12 to 18 months

Zone 3—2.00t
1 to 2 months
2 to 4 months
3 to 6 months

Example of use: sample size = 75; in-tolerance = 73; $R_i = 73/75 = 97.3$ percent; $t = 6$ months.
Sample size = 75 and $R_i = 97.3$ percent lies in Zone 2, permitting extension to 9 months.

Zone 0—No change; Zone 1—Reduce interval by more than 75 percent; Zone 2—Reduce interval by 75 percent; Zone 3—reduce interval by 66 percent.

Point $A = R_i$ at 1.00 t; point $B =$ best estimate of R_i at 1.50 t; point $C = R_a$ is equal to or greater than 92 percent over 80 percent of the time

---

[2] Non-integral sample sizes used so that Np can be integral to simplify interpolation in the tables.

NCSL 70

OPTIMUM CYCLES DETERMINED WITH CONFIDENCE

P. A. Seamans

Electronics Laboratory, General Electric Company, Syracuse, N.Y. 13201

The calibration history of a family of instruments provides data on how often the instruments were recertified and whether each was in calibration when recertified. These data permit the calculation of the optimum calibration interval for a desired level of confidence in the instrument readings. Three case histories (oscilloscope, RX meter, VTVM) show this method is effective. The histories of a family of oscilloscopes over a thirteen-year period show that calibration cost tends to be roughly constant with time and thus does not seem to follow the "bathtub curve." All instruments investigated seem to have equal likelihood of failure in all intervals, and thus the bathtub curve does not seem to hold in general.

Key words: Calibration histories; equal likelihood; oscilloscopes; RX meters; vacuum-tube voltmeters.

1. Introduction

For the past several years we have been using a technique for determining the optimum length of time between successive calibrations of different kinds of instruments. The technique uses data from the calibration history of a given family of instruments and allows a balance to be struck between the cost of errors due to possibly faulty equipment and the cost of calibrations. The technique gives a numerical measure of the level of confidence the instrument user can have in the readings his instrument gives. The technique has been proven effective for a wide variety of scientific equipment used in the electronics industry, and it is probably suitable for most instruments.

2. Collecting Instrument Data

We have established in the Instrumentation and Measurements Subsection at the General Electric Electronics Laboratory a computer-based system of keeping records on the calibration and maintenance of many kinds of instruments.[1] This system keeps histories of over 10,000 instruments with about 30 man-hours a week of effort, largely of a clerical nature. Data processing cards (DPC) that record pertinent information about the calibration of an instrument

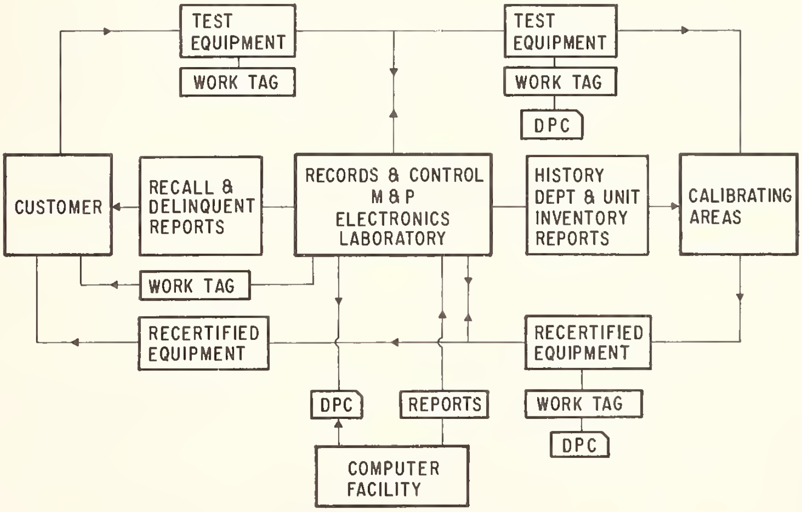


FIGURE 1. *Flow-chart of computer-based system for keeping instrument calibration records.*

---

[1] This computer-based system is fully described in a report, Instrument Calibration Records: Establishment of a High-Confidence Data Bank. Interested readers should write Technical Information, General Electric Company, Electronics Laboratory, Syracuse, N.Y. 13201, and request TIS Report R69ELS-115.

```
INST CODE  MANUF      MODEL     SERIAL#   WRK TAG   DATE CAL   TECH   STAT  TROUBLE   MATERIAL    LABOR  A    LABOR  B     TOTAL    C-CODE

   3380                            1129    83198    01/15/69    40      1   UXW            ,00         ,00       12,40     12,40    211132
   3380                            1129    83262    02/03/69    42      1   AU           10,51         ,00       24,80     35,31    211132
   3380                            1130    83246    01/29/69    42      0   U              ,00         ,00       12,40     12,40    211132
   3380                            1131    83237    02/03/69    42      1   AXSU          5,86         ,00       24,80     30,66    211132
   3380                            1133    83243    01/29/69    42      1   U              ,00         ,00       12,40     12,40    211132
   3380                            1134    84961    03/25/69    42      1   U              ,00         ,00        9,92      9,92    211132
   3380                            1134    88469    07/02/69    42      1   U              ,00         ,00        8,68      8,68    211112
   3380                            1134    89648    10/06/69    40      1   UXS            ,00         ,00       12,40     12,40    211112
   3380                            1135    83197    01/16/69    34      1   AU            8,00         ,00       16,12     24,12    211132
   3380                            1421    83336    07/24/69    42      9   U              ,00         ,00       12,40     12,40    228190
   3380                            2372    80421    04/07/69    42      0   AU            5,42         ,00       18,60     24,02    211485
   3380                            2372    88197    07/11/69    40      1   UXSA          2,70         ,00       18,60     21,30    211485
   3380                            2372    80650    10/14/69    40      1   UXS            ,00         ,00       12,40     12,40    211476
   3380                            2700    86006    01/29/69    42      0   U              ,00         ,00       12,40     12,40    218966
   3380                            2700    92080    10/09/69    34      9   XSU            ,00         ,00       12,40     12,40    218966
   3380                            2701    79937    01/23/69    42      1   U              ,00         ,00       12,40     12,40    218966
   3380                            2701    86772    07/14/69    42      1   U              ,00         ,00        8,68      8,68    218976
   3380                            2702    86893    09/03/69    42      9   BXSU          1,75         ,00       14,88     16,63    218966
   3380                            3475    84967    03/25/69    42      0   XSU            ,00         ,00       12,40     12,40    211132
   3380                            3475    88468    07/02/69    42      1   U              ,00         ,00        8,68      8,68    211112
   3380                            3475    89647    10/07/69    42      1   U              ,00         ,00       12,40     12,40    211112
   3380                            3482    83287    03/13/69    40      0   UXS            ,00         ,00       12,40     12,40    211132
   3380                            3482    88452    06/12/69    40      1   U              ,00         ,00       12,40     12,40    211112
   3380                            3482    89612    09/19/69    34      1   XSU            ,00         ,00       11,16     11,16    211112
   3380                            3484    83188    01/10/69    34      1   XSU            ,00         ,00       17,36     17,36    211132
   3380                            3484    83236    01/27/69    34      1   AU            3,26         ,00       11,16     14,42    211132
   3380                            5019    86982    09/15/69    40      0   UXS            ,00         ,00       12,40     12,40    218966
   3380                            5185    88180    07/07/69    34      0   XSU            ,00         ,00       14,88     14,88    211476
   3380                            5185    80643    10/09/69    40      1   U              ,00         ,00       12,40     12,40    211476
   3380                            6554    80447    05/01/69    40      4   WU           15,00         ,00       16,12     31,12    211476
   3380                            6555    88154    06/10/69    42      0   U              ,00         ,00       12,40     12,40    211478
   3380                            6555    80617    09/30/69    40      0   UXS            ,00         ,00       18,60     18,60    211476
   3380                            9449    83244    01/29/69    42      1   U              ,00         ,00       12,40     12,40    211132
   3380                            9449    87034    05/01/69    40      1   UXS            ,00         ,00       12,40     12,40    211132
   3380                            9449    89572    07/23/69    34      1   AXSU           ,67         ,00       11,16     11,83    211112
   3380                            9449    94484    10/30/69    40      1   UXS            ,00         ,00       12,40     12,40    211112
   3380                            9453    84975    04/02/69    42      0   U              ,00         ,00       12,40     12,40    211132
   3380                            9453    88481    07/21/69    42      1   XSU            ,00         ,00       12,40     12,40    211112
   3380                            9453    94485    10/30/69    40      1   UXS            ,00         ,00       12,40     12,40    211112
   3380                            9455    83257    02/03/69    34      0   US             ,00         ,00       12,40     12,40    211132
   3380                            9455    87049    05/13/69    40      1   UXS            ,00         ,00       12,40     12,40    211132
   3380                            9455    89591    08/21/69    34      1   XSU            ,00         ,00       11,16     11,16    211112
   3380                            9456    83297    03/18/69    40      1   UXS            ,00         ,00       12,40     12,40    211132
   3380                            9456    88457    06/27/69    42      1   U              ,00         ,00       12,40     12,40    211112
   3380                            9456    89630    09/30/69    40      1   UXS            ,00         ,00       12,40     12,40    211112
   3380                            9457    83239    02/03/69    42      1   WSU            ,00         ,00       12,40     12,40    211132
   3380                            9457    88403    05/12/69    40      1   UXS            ,00         ,00       12,40     12,40    211132
   3380                            9457    89587    08/22/69    34      1   XSU            ,00         ,00       11,16     11,16    211112
   3380                            9460    84965    03/24/69    40      1   AUXS          8,60         ,00       14,88     23,48    211132
   3380                            9460    88472    07/03/69    42      1   U              ,00         ,00        8,68      8,68    211112
   3380                            9460    89649    10/07/69    42      1   AXSWSU        8,27         ,00       31,00     39,27    211112
```

FIGURE 2. *A "history report," showing several months' calibration history of a type of oscilloscope plug-in.*

form the input to the computer (fig. 1) and "reports" of various kinds form an output which permits estimation of optimum calibration intervals.

One of the computer reports is a "history report," consisting of the calibration history of a given family of instruments and useful in calculating the optimum intervals between calibrations. Figure 2 shows a sample history report for a certain kind of oscilloscope plug-in. It includes an instrument code that corresponds to the family of instruments; the name of the manufacturer and his model designation; the identification serial number assigned to each different instrument; and a work tag number, there being one work tag for each job that is performed in our calibration area. Other entries indicate the date the calibration was performed, the technician who performed the calibration, the nature of the trouble, and the cost of calibration or repair. But of major interest to us in determining the optimum interval between calibrations are the date entries and the "status" entries, which indicate (among other things) whether an instrument was found to be in calibration when it was checked. These two entries are used to derive the actual number of calibrations per year and the actual number of calibrations per defect, which in turn are used to calculate the optimum number of calibrations per year.

After an instrument has been judged in or out of calibration, it is either recalibrated or given "preventive maintenance," whichever is appropriate. (Preventive maintenance might involve bringing the instrument's performance closer to nominal values even though it was within manufacturer's specifications; replacing a weak battery or tube to avoid failure before the next recertification date; or cleaning switch contacts or wiper arm contacts to permit intermittent readings during the time until the next calibration.)

Closely associated with the in-calibration or out-of-calibration status of an instrument is something we call "failure"—it occurs when the calibrating personnel determine that erroneous readings could have been made without the user's knowledge. An example might be a pointer that is bent, though not enough to be noticeable to the inattentive eye; or there might be friction or jewel roll present. "Failure" would have occurred if the instrument was out of balance and was used in several planes. A more subtle example might be a defect in an oscilloscope power supply that causes the rise-time trace to be incorrect, a "failure" that may be more serious than if the oscilloscope did not function at all. In fact, if the power supply had failed (in the conventional sense), then in accordance with our definition it would not be a "failure."

3. Calculating the Optimum Calibration Interval

The data found in the history report (fig. 2) enable us to calculate the actual number of calibrations per year, (C/t), for a given family of instruments, where C is the number of calibrations performed over a period of t years; and the actual number of calibrations per defect, (C/D), where D is the number of defects, or instances of an instrument's being out of calibration. Then it can be shown that the optimum number of calibrations per year can be expressed:

$$(C/t)_{\text{opt}} = (C/t)\,\frac{(C/D)_{\text{opt}}}{(C/D)}$$

where the term $(C/D)_{\text{opt}}$, the optimum number of calibrations per defect, is found by entering a Poisson distribution table for a given confidence level.

An example will indicate the utility of this expression: Suppose that, for a particular family of instruments, calibration takes place four times a year and that to date a total of 158 such calibrations have been made, including 46 "failures." Then we have $(C/t) = 4$, and $(C/D) = (158/46) = 3.43$. If we wish 90 percent of the instruments returning for calibration to be within manufacturer's specifications, then we find from the short Poisson table (table 1) that $(C/D)_{\text{opt}} = 3.9$, and the above expression becomes:

$$\begin{aligned}(C/t)_{\text{opt}} &= 4\left(\frac{3.9}{3.43}\right)\\ &= 4.55 \text{ calibrations per year}\\ &\quad\text{(calibration every } 11\tfrac{1}{2} \text{ weeks)}\end{aligned}$$

TABLE 1. *Poisson distribution for at least one failure occurring in interval*

Confidence Level	$(C/D)_{\text{opt}}$ (Calibrations Per Defect)
%	
99	6.7
95	4.7
90	3.9
85	3.4

4. Evaluation of the Technique

Our experience with this technique proves that it works and is applicable to test equipment. To demonstrate that we can predict optimum calibration intervals with confidence, I cite three examples:

Generators prior to 1968 had been calibrated every 26 weeks. When we first applied our method of finding optimum calibration intervals, we found that in order to maintain a 90 percent confidence level, the cycle should be shortened to 15 weeks. When we had collected a year's data at the new interval, we computed the optimum value again and found it to be 18 weeks. (The reason for the three-week discrepancy is unclear, but the important thing to note is that our first attempt to adjust the optimum value was in the correct direction.)

Perhaps a better example for illustrating the accuracy of this technique would be our experience with RX meters. As in the case of the generators, the calibration interval for these instruments had been 26 weeks. Our computations showed that the cycle should be shortened to 15.8 weeks. We thus shortened the cycle to 15 weeks; at the end of a year we checked the results and found the optimum to be 14.7 weeks—very close to the originally calculated value.

A third example, involving a lengthening rather than a shortening of the calibration interval, involves several families of VTVM's. One of these families was routinely calibrated every 13 weeks, but the others were calibrated every four weeks. After we studied the failure rate of these instruments, we found we could lengthen the calibration intervals 5, 7, or 10 weeks for those that had been calibrated every four weeks: and the thirteen-week instruments were now calibrated every 26 weeks. A subsequent study after a year's operation showed these revised calibration intervals still to be correct.

5. Discussion

Many readers are perhaps acquainted with the "bathtub curve" that is said to reflect the life and death of instruments (fig. 3). It is my opinion that this curve is not entirely applicable to the broad spectrum of test equipment, although perhaps some mechanical systems follow it. If test equipment obeyed the bathtub law. the age of a piece of equipment would be the determining factor of the calibration interval. Instruments would have to be segregated by age, and in a large calibration area the economics of instrument maintenance would be difficult. It would then be possible that instruments purchased this year would have a different calibration cycle than the same type purchased a year or two ago. But the technique I have described for determining the optimum calibration interval assumes a Poisson distribution, which is used when the same number of failures are expected in each interval. To me this suggests that test equipment failures might be a linear function of use, depending on environment and care, rather than on age as long as the age is reasonable.

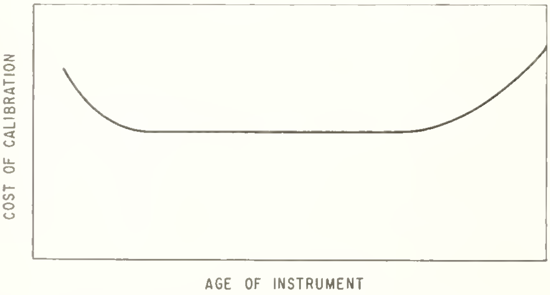


FIGURE 3. *The well-known "bathtub curve" that is said to reflect the useful life of instruments.*

I have recently completed a study of a well-known manufacturer's oscilloscope. I collected data on 29 instruments, including purchase date and the average cost of calibration for four years (1966–69). A total of 252 calibrations was included in the study of these instruments, some of which were purchased as long ago as 1957. A plot of these data is scattered about a horizontal line (fig. 4) rather than the bathtub mentioned above. The cost of calibrating instruments 12 years old was not much different from that of equipment purchased quite recently. The anomalous value at 10 years (*) results from a modification which involved expensive repairs.

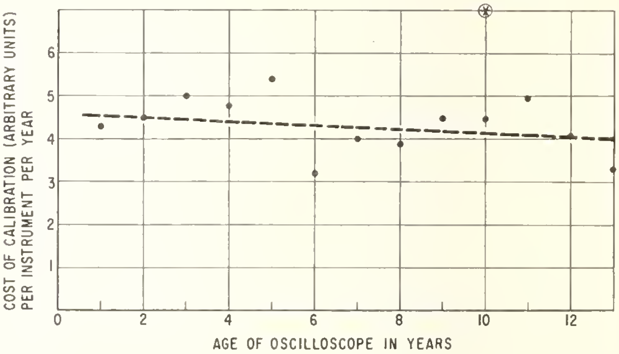


FIGURE 4. *The 1966–69 cost of calibrating 29 oscilloscopes aged 1 to 12 years scatters about a horizontal line and does not seem to follow the bathtub curve.*

The procedure described may bring about a possible savings by the mere fact that an analysis of the history of instruments may permit the elimination of "dogs." Furthermore, some cycles can perhaps be lengthened, resulting in further savings. The method is, of course, of little use if some sort of systematically scheduled calibration system is not in force. In reviewing any family of instruments, I include only those instruments that have been recalibrated at least half as often as the optimum calibration interval would require.

NCSL 70

SESSION 4: NEW WAYS OF MANAGING

Chairman: J. R. Van de Houten

Bell Aerosystems Corporation, Buffalo, N.Y. 14240

BREAKTHROUGH TECHNIQUES FOR METROLOGY WORK

Lloyd B. Wilson

Management Consultant, 145 Tanners Pond Road, Garden City, N.Y. 11530

Metrology work involves the conflicting and diametrically opposed problems of control versus breakthrough. Controls are vital to assure accuracy and reliability. However, breakthroughs are necessary to provide improved accuracies, ranges, and types of measurements. The dichotomy of this situation comes principally from the differences in attitudes involved. Ideally, control and breakthrough should be carried out by two different types of people because of these differences.

Breakthrough techniques, coupled with proper attitudes and a systematic method for establishing objectives and evaluating alternatives, provide a powerful set of new tools for improvement. Examples are given showing the possibilities for applying these tools to reduce costs and provide needed measurement and calibration services.

Key words: Managerial breakthrough techniques; personnel selection for metrology; steady control versus sudden change.

1. Introduction

This is a paper about problem solving. The type of problem which will be covered is breakthrough, where breakthrough is defined as a process by which improvements of a major nature are made rapidly. Breakthrough obviously relies heavily on creativity and innovation. However, it is more than this because of the rapidity of the change involved; breakthrough is a dynamic word which denotes a sudden or step-function type of change.

This paper stresses the achievement of breakthrough on a systematic basis. This is possible because breakthrough, like many other types of problem solving, has become a science which can be performed on a rational, step-by-step basis. Evidence of this is found in the literature on the subject of breakthrough itself, as well as on closely related subjects such as creativity, innovation, and various processes for analyzing situations and making decisions. The information in this paper is based on these key points which have been condensed into an integrated and relatively simple approach to breakthrough, with particular attention to its application in metrology work.

This paper has several purposes, as follows:

(a) To explain why breakthrough techniques are desirable and feasible for more extensive use in metrology work.

(b) To give information about how breakthrough can be achieved and to provide leads to sources of information about more detailed aspects of breakthrough.

(c) To suggest some metrology areas which need breakthroughs and also some possible ways of attaining such breakthroughs.

2. Characteristics of Metrology Problems Requiring Breakthrough

Breakthrough techniques, coupled with success-oriented attitudes and a systematic method of establishing objectives and evaluating alternatives, provides a powerful set of new tools for solving improvement type problems. Today there are increasing pressures to come up with faster and better solutions to such problems. These pressures arise from the following characteristics which many metrology problems have:

- Metrology work involves the conflicting and diametrically opposed problems of control versus breakthrough. Controls are vital to assure accuracy and reliability of metrology work. However, breakthroughs are necessary to provide improved accuracies, ranges, and types of measurements. The dichotomy of this situation comes from the differences in attitudes of the people involved. Ideally, control and breakthrough should be carried out by two different sets of people because of these differences.

- Metrology problems are complex; they have many variables.
- Metrology problems are generic in the sense that they apply in about the same way to many different organizations; i.e., they cross organizational lines and therefore appear not to be the responsibility of any one organization.
- Adequate attention and funding are difficult to justify because the problems are principally of a support nature. This means that they are far from the basic problem sources—i.e., the exotic technological requirements of space work, military work, etc.

3. Breakthrough Versus Control

One of the better explanations of breakthrough is that given in Dr. J. M. Juran's Book, Managerial Breakthrough [1].[1] This explanation is particularly good because breakthrough is described by comparing it with its opposite function—control. For example, Dr. Juran makes the statement that "All managerial activity is directed at either breakthrough or control. Managers are busy doing both of these things and nothing else." Dr. Juran also describes breakthrough as the creation of good or necessary changes, while control involves the prevention of undesirable changes. Obviously, both types of activities are necessary in an organization, although the type and amount of each will vary from time to time and from one organization to another.

The differences in the results expected from control and from breakthrough cause radical differences in the methods of obtaining each of them. This is particularly true in the use of people, for either breakthrough work or for control work. The selection of people for either breakthrough or control work should take into account their education, their work experience, their motivation, and their attitudes. However, people are rarely 100 percent control-oriented. Instead, there are many possible combinations, as are shown in the coordinate analysis chart of figure 1.

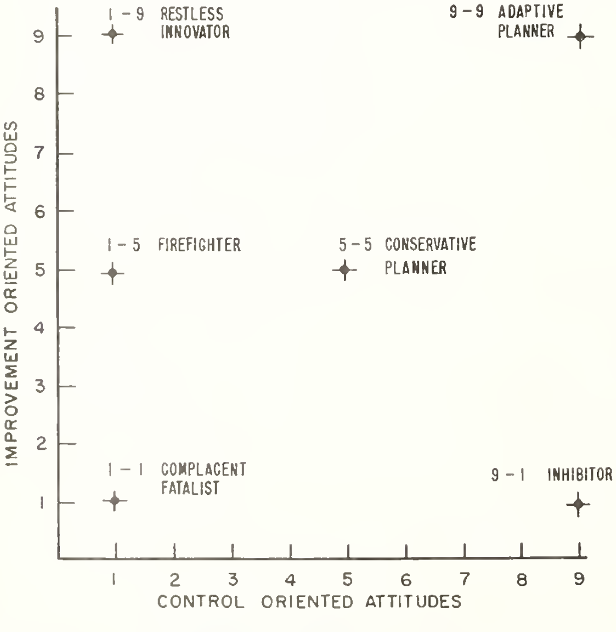


FIGURE 1. *Coordinate analysis of attitudes toward control versus improvement.*

4. Breakthrough Concepts

People are basically goal-oriented; that is, they continually set goals for themselves, work to reach such goals, and, when each goal is reached, select a new goal to work towards. Goals for achieving control are usually given highest priority, particularly for the solution of crisis or "firefighting" types of problems. However, when there is is additional time available, it is usually spent on improvement-type goals. Breakthrough, in its most general sense, is the technique used to attain improvement-type goals. In a more restricted sense, breakthrough is the technique used to attain improvement goals in a relatively short period of time—short, that is, with respect to the time such improvement changes might normally be expected to take on a strictly evolutionary basis.

Some of the important characteristics of breakthrough are as follows:

- A systematic approach is usually the best for achieving success in breakthrough work. The systematic approach increases the probability of reaching the breakthrough objectives and cuts the time requirements compared with a nonsystematic approach.
- For breakthrough to get started, there must first be a promoter or advocate—i.e., someone who feels that improvement is not only necessary but that it also is feasible.
- Breakthrough requires the following types of leadership qualities:
  —Constructive discontent with the status quo
  —Willingness to take risks
  —Good sense of timing
  —Aggressiveness
  —Decisiveness
  —Confidence.
- The amount and kinds of breakthrough which can be achieved are directly related to the favorability of the climate in the organization. A poor organizational climate will mean that breakthrough is likely to be either impossible or at least stunted and mediocre.
  —The most important climate factor in an organization is the attitudes towards breakthrough of top management and of the immediate boss of each person involved in breakthrough.
  —The second most important climate factor in an organization is the attitudes towards breakthrough of a person's peers as well as the attitudes of the people working for him on any aspect of a breakthrough task.

5. Steps for Achieving Breakthrough

The nature of breakthrough-type problem solving is shown in the block diagram of figure 2. Reading horizontally across the top of the diagram, we find a

---

[1] Figures in brackets indicate the literature references at the end of this paper.

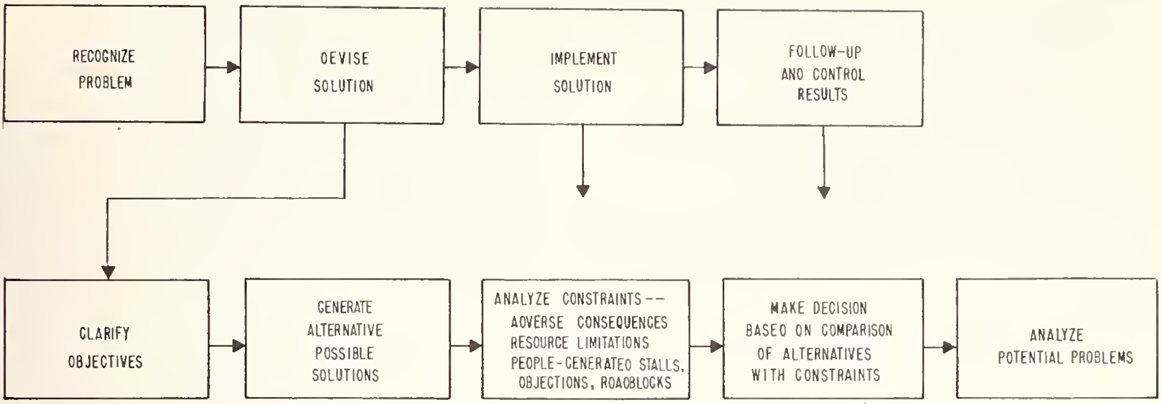


FIGURE 2. *Steps in breakthrough-type problem solving.*

simplified process for solving problems in the four steps—recognize problem, devise solution, implement solution, and follow up and control to get the desired results. However, under the "devise solution" step the diagram also shows an additional series of steps—i.e., clarify objectives; generate alternative possible solutions; analyze constraints in terms of adverse consequences, resource limitations, and people-generated stalls, objections, and roadblocks; make decision based on comparison of alternatives with constraints; and analyze potential problems. Ideally, all that should be necessary to do is go through the steps shown here and you will automatically be able to achieve breakthroughs in any problem area. However, unless care is taken the results will be far from ideal—usually because of (a) inadequate attention to the people-problems involved in achieving breakthrough, or (b) the difficulties imposed by state-of-the-art technology limitations. The approaches discussed here should be able to help avoid or overcome these limitations and obstacles to a considerable extent.

The basic approach to obtain breakthrough should involve the following key elements:

—Using a systematic approach based on the steps shown in the block diagram of figure 2.

—Paying attention to more than just getting the basic ideas on how to achieve the desired type of breakthrough. A "total" or systems approach must be used; this involves solving all of the subproblems necessary to convert the basic idea into a realistic service, method, procedure, or a working piece of hardware or software.

—Setting objectives or goals. To help these goals come true, they must be broken into sub-goals, with plans for achieving each of the sub-goals. The goals and sub-goals must be put in writing in order to clarify them and to make them understandable to people who must work to achieve them. These same people must identify with the goals by seeing the relationship of the breakthrough goals and sub-goals with their own personal goals and by using visualization techniques to keep the goals and sub-goals clearly in mind while working towards them. The concepts of selective perception and positive expectation come into play when goals are treated in this way. Selective perception helps people to become more sensitive to anything which will aid them in achieving goals which they understand and have identified with [2].

—Generating breakthrough-oriented attitudes in the people assigned to work on the breakthrough project. This includes inducing in each person a positive mental attitude and a self-image which is directed towards successful completion of the breakthrough project.

—Use of various creativity and innovation techniques to achieve a broad spectrum of alternative means of solving the main breakthrough problem and its subproblems.

—Clarifying the objectives through the use of techniques such as situation analysis, critical factor analysis, and function analysis. This helps avoid the effects of finding the right solution for the wrong objectives.

—Including in the decision-making criteria for a particular breakthrough not only the objectives to be achieved but also the difficulties likely to be encountered and ways of preventing or minimizing such difficulties. This requires consideration of possible undesirable side effects, limitations imposed by resources reasonably available, and people-generated stalls, objections, and roadblocks.

—Learning how to cope with breakthrough-type tasks by starting with a relatively small task on a sort of trial-run basis. Success in accomplishment of this task should be followed by progressively larger tasks, to increase the skill in handling breakthrough-type work. This gradual approach also helps to build confidence—a vital factor for attempting any type of breakthrough work [3].

—Screening the alternatives by systematically checking them against the objectives, undesirable side effects, resources and people-generated stalls, objections, and roadblocks. In addition, objectives should be categorized as either "musts" or "wants" [4].

—Recognizing the importance of motivation in getting people to work effectively on the breakthrough project. Motivation can be developed and improved, and in this way much of the dormant creative potential and other problem-solving skills of people can be released and effectively focused on the main problems and subproblems required to achieve the desired breakthrough [2].

6. Possibilities for Application of Breakthrough Techniques to Metrology Problems

Several areas which suggest themselves as good possibilities for application of the breakthrough techniques discussed in this paper are as follows:

- The calibration recall problem.
- The problem of traceability of calibration to NBS.
- Improved utilization of measuring equipment and standards.
- How to obtain a compatible system of measurements and tests throughout the United States.

7. References

[1] Juran, J. M., Managerial Breakthrough (McGraw-Hill, New York, N.Y., 1964).

[2] Williams, J. Clifton, Dynamics of Motivational Management (Success Motivation Institute, Waco, Tex., 1969).

[3] Bobbe, Richard A., and Schafer, Robert H., Mastering change: Breakthrough projects and beyond, Management Bull. No. 120 (Am. Management Assn., New York, N.Y., 1968).

[4] Kepner, Charles H., and Tregoe, Benjamin B., The Rational Manager (McGraw-Hill, New York, N.Y., 1965).

NCSL 70

THE NEW STATE STANDARDS PROGRAM

Robert Mills

Office of Weights and Measures, National Bureau of Standards, Washington, D.C. 20234

In 1965, Congress appropriated funds for new state standards and instruments in mass, length, and volume. The laboratories receiving this package are, in most cases, under the administration of state offices of weights and measures. These labs not only check the accuracy of field standards used by weights and measures inspectors, but also serve as local measurement centers to perform industrial tests. The equipment and training given to laboratory personnel are described in this paper, as well as some of the administrative details and the utilization we foresee for the state laboratories.

Key words: Length measurements; mass measurements; metrology; standards; state laboratories; volume measurements.

1. Introduction

In 1965 the United States Congress approved a two million dollar program to provide states with new physical standards and measuring instruments in mass, length, and volume. The National Bureau of Standards was charged with the responsibility of assisting the states in the development of state laboratories, design and procurement of standards and precision balances, and final installation. Today 40 states are participating in the State Standards Program.

These newly equipped metrology laboratories enable the states to assume their important role in our national measurement system during a time when science and technology are advancing at an accelerating rate. It is important that the membership of the National Conference of Standards Laboratories be informed about the New State Standards Program. Thus, it is my pleasure to discuss with you the program's origin, some of the administrative details, and the utilization we foresee for the state laboratories.

Men have endeavored to establish effective standards of measurements for many centuries. Edward II proclaimed in 1324 that the inch was equal to the length of three barley corns, taken from the center of an ear, placed end to end. In the 16th century, the rod was the length of the left feet of 16 men lined up as they left church on Sunday morning. Perhaps these standards sufficed in their time, but it is clear that they would not fulfill today's need for standardization.

In our country, there has long been a parallel between the existence of accurate standards and the establishment of effective weights and measures activities. The Constitution of the United States empowered Congress in Article 1, Section 8 to "fix the standards of weights and measures." In 1821, John Quincy Adams recommended that Congress act to bring about uniformity in weights and measures. The Senate passed a resolution in 1830 directing the Department of the Treasury to compare the standards of weights and measures in use at the principal customhouses. Large discrepancies were found to exist. As a result, Congress directed the Treasury to fabricate standards of weights and measures for the customhouses and States, thereby authorizing the distribution of the first State standards. This resolution also established the Office of Weights and Measures. Two additional distributions of standards to the States were authorized by Congress in 1866 and 1881.

By the beginning of the 20th century, the Industrial Revolution had produced a growing awareness of the need for uniform, nationwide measurement techniques and measurement standards in the United States. The Office of Weights and Measures was transferred to the National Bureau of Standards in 1901, the year the Bureau was established.

Traditionally, regulatory authority in weights and measures rests with the States rather than with the Federal Government. There are 50 state weights and measures jurisdictions, and in some cases local authorities within the States, separately exercising their authority to check supermarket scales, gasoline pumps, packages in the marketplace, taximeters, fabric and cordage measuring devices, farm milk tanks, truck scales, fuel oil meters—virtually every weighing and measuring device used commercially. Yet, despite this diversification of responsibility, measurement *accuracy* and *uniformity* must be maintained to protect both the buyer and seller, and to provide for orderly commerce on a national basis. *Uniformity* in specifications, tolerances, and test procedures is achieved in most states by accepting the recommendations [1] [1] of the National Conference on Weights

---

[1] Figures in brackets refer to the literature references at the end of this paper.

and Meaures, another conference sponsored by NBS. *Accurate* field test standards must also be used by weights and measures inspectors. This requirement implies the need for accurate laboratory standards. By 1965, the laboratory standards of many States were no longer adequate.

2. The Program

Congress responded to the need for State reference standards by establishing the State Standards Program. The National Bureau of Standards was given the responsibility of acquiring the new standards and instruments, training State laboratory personnel, and assisting the States to provide adequate laboratory facilities. Primary responsibility for the project lies with the NBS Office of Weights and Measures, which offers assistance and technical support to local and State weights and measures agencies. The NMS Metrology Division performs the calibrations of the new standards and provides technical counsel when needed.

States initiate the process of qualifying for receipt of the State Standards "package" by demonstrating the need, and by making a commitment to provide suitable laboratory space and personnel. NBS then discusses details of requirements for laboratory facilities with State architects or engineers, and provides additional technical assistance as construction proceeds. The construction may be modifications to existing facilities or the erection of a completely new building. Construction costs to the states have ranged from a few thousand dollars up to about $135,000. A minimum of 1,000 square feet is needed for a suitable laboratory facility.

The new standards have been furnished at the rate of approximately 10 states per year. To date, formal presentation ceremonies, usually attended by the NBS Director and by the Governor, have been held in 23 states. Table 1 lists the states in each group and the dates of the formal presentation ceremonies which have been held. The grouping of the states was determined by their needs, and the date on which they provided the required laboratory facilities and personnel.

The Office of Weights and Measures of NBS provides training for laboratory personnel at three levels: basic, intermediate, and advanced. The two weeks of basic training are completed before the official presentation of standards. The first week is conducted at the NBS Office of Weights and Measures laboratory, or, to accommodate distant States, at established State laboratories, usually just prior to the presentation ceremony and concurrently with the final installation of the new laboratory equipment. Metrologists who are replacements for previously trained personnel receive their basic training at NBS.

Intermediate seminars are intended for State metrologists who have completed basic training. These seminars are usually 40 hours long and can be held either at NBS or in regional seminars. They begin by reviewing basic subjects before continuing to more advanced material. The advanced seminars are for more experienced metrologists. They are held at NBS and provide a broad exposure to the Bureau's professional staff. Some thought has been given to scheduling advanced seminars the week just before or just after future NCSL dates so that State metrologists can attend this Conference.

TABLE 1. *Progress in presentation of new standards to the 50 States*

Group I	Presentation Date	Group II	Presentation Date
California	11/22/67	Arkansas	4/18/69
Connecticut	3/ 4/68	Florida	
Delaware	1/26/68	Georgia	10/21/69
Illinois	6 /9/67	Hawaii	8/ 2/68
Kentucky	7/19/68	Maine	5/21/69
New Mexico	12/ 8/67		
Ohio	6/ 8/67	North Carolina	2/25/69
Oregon	10/27/67	Pennsylvania	3 /3/69
Tennessee	5/ 2/68	West Virginia	5/19/70
Utah	10/30/67	Wisconsin	3/ 7/69
Group III	**Presentation Date**	**Group IV**	**Presentation Date**
Alabama		Alaska	
Idaho	5/ 4/70	Colorado	
Indiana		Massachusetts	
Maryland	4/ 4/70	Michigan	
New Jersey		Minnesota	
North Dakota		Nevada	
Oklahoma		New York	
Texas	6/ 4/70	South Carolina	
Vermont		South Dakota	
Wyoming	4/13/70	Virginia	
Remaining States and Territories			
Arizona Iowa Kansas Louisiana Mississippi Montana Nebraska New Hampshire Rhode Island Washington			
District of Columbia Puerto Rico Virgin Islands			

Our intermediate and advanced training programs are continuous in that metrologists are encouraged to attend a seminar once every year. Participants are carefully selected for each seminar so that experience and level of achievement are compatible. Seminars at all three levels have had, on the average, four or five participants. We expect to continue our present schedule of from 10 to 12 seminars a year.

3. State Standards

Table 2 lists the standards and instruments in the State Standards "package." Note that both metric and avoirdupois, or U.S. customary standards, are included. The mass standards in item (1) and (2) comprise a 5, 3, 2, 1 series (e.g., 5 g, 3 g, 2 g, 1 g, 0.5 g, etc) with duplicate 1 kg, 1 mg, 1 lb, and 1 μlb weights. The small flat weights (i.e., smaller than 1 g and 0.002 lb) are made of Nichrome or aluminum. Except for the 500 lb standards, which are 303 stainless steel, the larger weights are made of a stainless steel, developed especially for precision mass standards, having a density of 8.0 g/cm^3. The systematic uncertainties in the reports of calibration range from 30 mg for the 30 kg weight to 2.9 μg for the 1 mg weight. The five precision balances are the best present technology offers. The precision given in table 2 are manufacturers' tolerances and are included to indicate the capabilities of these instruments. Except for the 5,000 lb equal-arm Russell balance, all of these instruments are single-pan, substitution balances. Prior to the beginning of this program, the standards and balances were developed through the cooperative efforts of NBS and the manufacturers. Reference [2] discusses the development of the 30 kg balance.

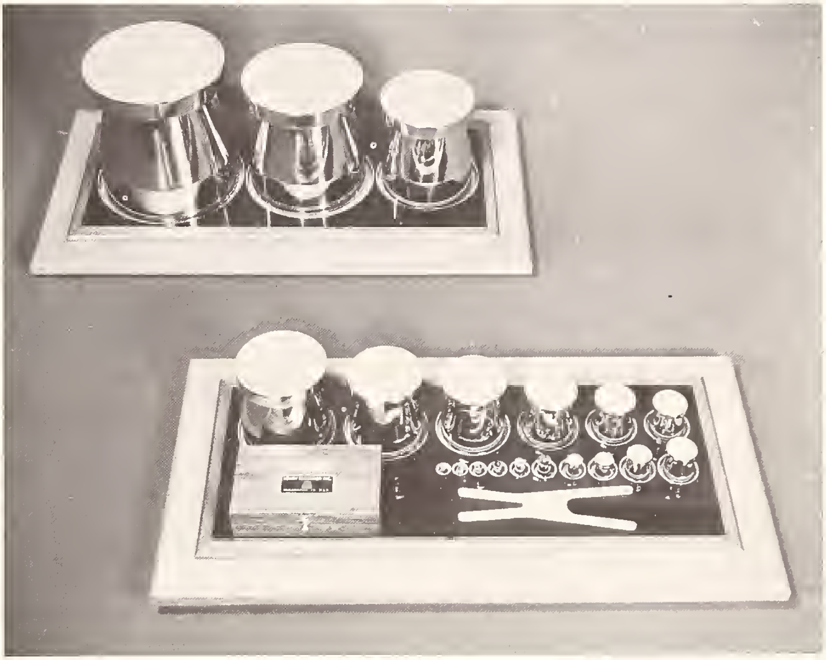


FIGURE 1. *The avoirdupois mass standards.*
Small flat weights are inside the box.

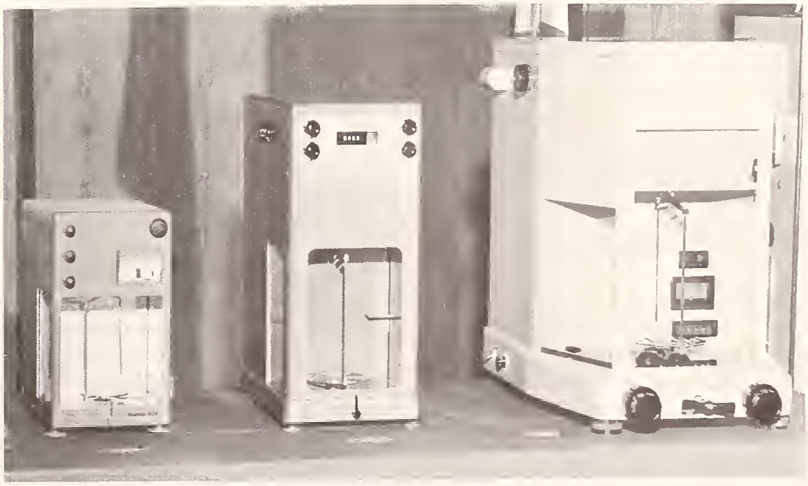


FIGURE 2. *The 160-g, 1-kg, and 3-kg precision balances.*

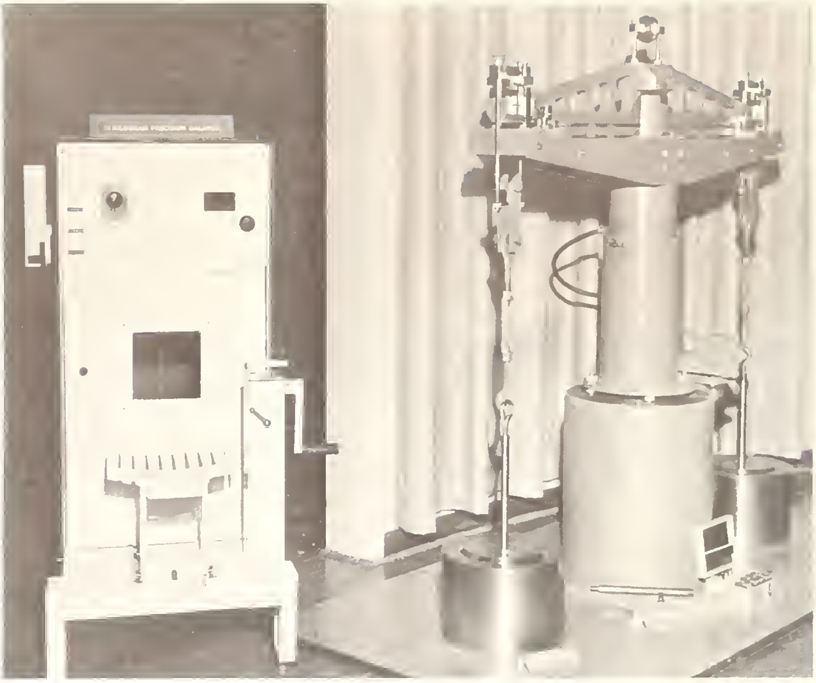


FIGURE 3. *The 30 kg and Russell balance.*

TABLE 2. *State Standards*

1. METRIC MASS STANDARDS—30 kg to 1 mg, fig. 1
2. AVOIRDUPOIS MASS STANDARDS—50 lb to 1 μlb
3. 500 LB MASS STANDARDS (2)
4. PRECISION BALANCES, figs. 2 and 3:
    - 160 g capacity—0.02 mg precision
    - 1 kg capacity—0.2 mg precision
    - 3 kg capacity—1 mg precision
    - 30 kg capacity—2 mg precision
    - 5000 lb capacity—0.01 mg precision
5. LENGTH BENCH—5 meter/16 feet
6. TENSION WEIGHTS—20 lb
7. LABORATORY MICROSCOPE—0.300 inch × 0.002 inch
8. PRECISION STEEL TAPE—7 meter/25 feet
9. STEEL TAPE—30 meter/100 feet
10. PRECISION STEEL RULE—18 inches × 0.01 inch
11. METRIC PIPET-BURET ASSEMBLY—5 liters to 10 milliliters
12. U.S. CUSTOMARY PIPET-BURET ASSEMBLY—1 gallon to 120 minims
13. FIVE GALLON STANDARD—slicker plate type

Items (8) and (10) are the state primary length standards. The report of calibration for the 25 ft/7m tape gives an uncertainty of 0.002 in. and 0.05 mm for any interval. Uncertainty of the 18 in. scale is reported as 0.001 in. For the volumetric standards, the reported uncertainty is 0.001 gal for the 5-gal slicker plate measure, 0.1 minim for the 120-minim buret, and 0.005 ml for the 10-ml buret.

4. Utilization of Laboratories

The primary role of a State measurement center is to serve as a reference laboratory for weights and measures field standards. In almost every case, the State standards equipment is received by the State weights and measures department. State laboratories also check the standards used by other State agencies and officials, such as the state chemist; veterinarian; dairy, feed, and fertilizer inspector; public health inspector; highway department; and petroleum laboratory.

From the outset there was no intention to restrict activities of the State Standards Laboratories to weights and measures activities, or to other state regulatory agencies. Rather, the policy has been to encourage states to serve within their capability the measurement needs of industry and commerce as well as educational and research institutions.

There was evidence of an industrial demand at State metrology laboratories even before the initiation of the State Standards Program. Massachusetts, for one, has had an active program of providing calibrations for their industries. They are just now beginning to receive their new standards, and anticipate an increase in both the quality and quantity of the measurement services provided to industry. The demand for industrial calibrations at the State laboratories has been made apparent by the activities of some of the labs which have received their new standards. Arkansas is a good case in point. Table 3 indicates the scope of the industrial tests conducted there in addition to tests of their own field standards and tests for other State agencies. Admittedly, the development of the Arkansas laboratory is exceptional. Few industrial tests were performed before the new Arkansas standards were presented in April of 1969; the table covers the period up to March 1970. Of course, Arkansas is not one of our most industrialized States. Several other States having a more industrialized economy, such as California, Illinois, or Pennsylvania, perform even more industrial tests.

Most States charge fees for the industrial tests they perform. Thus, costs are paid by industries which have the need for tests with standards traceable to NBS. Of course, the States pay the costs for testing their own field standards.

TABLE 3. *Arkansas weights and measures laboratory industrial customers*

1. Electronic Companies	Weights and weight kits from 2 kg to 1 g (Class S) and 50 lb to 1/32 oz (Class F).
2. Petroleum Equipment Companies	Metal volumetric test measures from 1 gal to 500 gal. All tests were certified to 1 part in 2000.
3. Pipe Line Companies	Metal test provers; two 600 gal and one 1,015 gal. Accuracy 1 part in 2000.
4. Bottling Companies	Testing of graduated neck flasks used to spot check fill machines.
5. Scale Companies	Weights and weight kits from 1/32 oz to 1,000 lb and 1 g to 25 kg. Class S, F, and T tolerances were required
6. Pharmaceutical Laboratories	Weights and weight kits from 1 mg to 20 kg. Class S tolerances.
7. Electrical Companies	Various weights, Class T tolerance.
8. Oil Refining Companies	Calibration of tank trucks: Accuracy 1 part in 2000.
9. Manufacturing Companies	Weight kits from 1 mg to 5 kg: Class S tolerance was requested.
10. Milling Companies	Weights from 4 oz to 5 lb; Class F tolerance were requested.
11. Transport Companies	Calibration of tank trucks: Accuracy 1 part in 2000.

NOTE: The Arkansas Laboratory has seven large-capacity provers having nominal capacities between 29 and 1,000 gallons.

In the training program, State metrologists are encouraged to consult with NBS about tests that are other than routine. Our office has a policy of being as helpful as possible in such situations. Jobs which are beyond the capabilities of particular State laboratories are referred to NBS. Clearly it is important to know the capabilities of each State laboratory. This surveillance is accomplished, at present, through the Laboratory Auditing Program (LAP), which provides for tests to monitor the performance of the instruments, personnel, and environment. Table 4 indicates the nature of LAP exercises by listing the titles of the first ten problems. Problems 4 and 9 involve the exchange of test kits between our laboratory and the States. Data from all LAP exercises are sent to us for review and comments. Certificates are awarded annually to States which have met minimum requirements of participation.

TABLE 4. *Laboratory auditing program problems*

1	Sensitivity test
2	Tolerance test (direct-reading)
3	Precision test of 1-kg balance
4	Tolerance test and weight calibration
5	100-g balance precision
6	3-kg balance precision
7	30-kg palance precision
8	Calibration of length bench
9	Testing of a steel tape
10	Precision of Russell balance

5. The Future

The surveillance effort will have to be increased as the measurements performed by the State laboratories become more sophisticated. States should record a continuous flow of surveillance data so that control charts can be maintained. The more advanced State metrologists are presently doing this. They receive an analysis of their control chart data from the Office of Weights and Measures. In this way, the capability of their laboratory can be determined realistically. Our intention is to make this a more universal practice in the State laboratories.

Insufficient surveillance data will result in a large uncertainty as to a State laboratory's performance capability. The proper surveillance effort will be determined by the calibration demands on that laboratory. Time required to accumulate surveillance data will probably range from one to ten man-hours per week (not necessarily time spent by the metrologists; data can be taken and compiled by an aide).

There has been an increasing number of inquiries recently concerning the possible extension of State laboratories into fields of measurement other than mass, length, and volume. The greatest interest is in temperature and gage-block measurements. The Massachusetts laboratory has been in the business of testing thermometers for some time. California is testing electric meters in addition to other measurements. We at the National Bureau of Standards are preparing to advise the States, upon request, concerning test equipment, test procedures, and test uncertainties in fields where the need can be demonstrated.

Getting back to the State Standards Program, the future offers a triple challenge to the states, to the National Bureau of Standards, and to potential industrial users if full utiliztion of these State measurement centers is to be realized. The States must, of course provide adequate financial and administrative support for their laboratories. They must staff their laboratories with high-caliber personnel. The National Bureau of Standards must maintain a vigorous support program in training and consulting services. Potential industrial customers must be informed about their State laboratory and make available information on their future measurement requirements. Industrial interest and support can be helpful in encouraging the states to properly fulfill many of their measurement requirements. The NBS Office of Weights and Measures invites inquiries from any interested parties concerning the current status of the laboratory program in their particular state. Comments and suggestions are, of course, welcome.

6. References

[1] Nat. Bur. Stand. (U.S.), Handb. 44, 3d ed., Specifications, Tolerances, and Other Technical Requirements for Commercial Weighing and Measuring Devices.

[2] Almer, H. E., Bowman, H. A., Jensen, M. W., Macurdy, L. B., Peiser, H. S., and Wasko, B., A direct-reading two-knife 50-pound balance of high precision suitable for State weights and measures laboratories, J. Res. Nat. Bur. Stand. (U.S.), **68C** (Eng. and Instr.), 141 (1964).

NCSL 70

THE IMPORTANCE OF VISIBILITY AND CONTROL IN LABORATORY MANAGEMENT SYSTEMS

John L. King

Standards and Calibration Laboratories, General Dynamics/Convair Division, San Diego, Calif. 92112

The Test Equipment Control Engineering Section has overall responsibility for 2719 different models of 40,000 items, from purchase to final disposition. Computerized system shows decision-makers the history of costs, locations, and interface with operations; yields savings of $800,000 per year.

Key words: Data for decision; standards laboratory management; test equipment records; use, storage, or surplus.

In the present economic environment, the application of new and improved methods of visibility and control in the standards and calibration laboratory becomes a high-priority goal. The methods of visibility and control we are going to explore have evolved over a period of years and are presently operational in the Standards and Calibration Laboratories at the General Dynamics Convair Division. They were developed during the best possible environment for designing a control system; namely, a continuing decrease in the departmental budget, an increase in responsibility, and a demand for continued product quality. Such conditions certainly cause one to look around for new controls to maintain quality and optimize cost!

Understandably, the methods developed are tailored to Convair operations. Convair calibration laboratories may or may not be similar to those in other companies, but one thing is certain . . . many of the problems and the customer requirements will be very familiar to everyone.

Before we discuss these methods, it will be necessary to acquaint you with Convair's basic philosophy of operation and organization of calibration activities. The Standards and Calibration Laboratories are a department of Reliability Control. They are further divided into three sections; Electronic Metrology, Mechanical Metrology, and Test Equipment Control Engineering. The Electronic and Mechanical Metrology sections include the calibration laboratories. These laboratories are further segregated into 10 major laboratory areas and 21 subgroups identified by the category of equipment they service. Each laboratory is operated under the technical direction of a graduate engineer, with highly skilled technicians doing the actual calibration and maintenance. The Engineer-in-Charge of each laboratory approves all work done. He certifies the work by means of a Reliability Control Department metrology stamp assigned to him. There are no regular inspection department or other quality control personnel assigned to the standards and calibration laboratories.

The laboratories under the Electronic and Mechanical Metrology sections service approximately 40,000 items of test and measuring squipment, of which approximately 30,000 items are in continuous use in Convair operations.

The Test Equipment Control Engineering section is the group most pertinent to this discussion, since it plays a dynamic role in the control system. Consequently, though each section is involved in control to some extent, we will examine the responsibilities and operations of the Test Equipment Control Engineering section in detail. The primary responsibilities of the Test Equipment Control Engineering section are to:

1. Develop and provide policy procedures for the entire Standards and Calibration Laboratories Department.
2. Respond to Convair Division requirements for general-purpose measuring and test equipment, whether for new applications or replacement purposes. This response includes "cradle to the grave" activities, such as acquisition, control, storage, and eventual final disposition of the equipment.
3. Provide a central record control system for all work entering or leaving the Department.
4. Maintain all calibration history and traceability records for each item of equipment and provide calibration recall schedules.
5. Establish all calibration intervals and initiate or approve any status change in measuring or test equipment.
6. Maintain general-purpose measuring and test equipment issuance stockrooms at practical and appropriate locations throughout the Division.
7. Provide engineering technical support for the solution of Division measurement problems.

To fulfill these assignments, the Test Equipment Control Engineering section is composed of:

1. A part-time staff technical and management policy writer.
2. A records and data group.
3. A test equipment stockroom operations group.
4. A test equipment applications engineering group. All applications engineers are graduate engineers with laboratory experience.

Now, let's discuss visibility and control problems and solutions. The question may be raised as to why the "cradle to the grave" responsibility for general-purpose measuring and test equipment is vested in a calibration laboratory operation. Why? Because this concept permits overall visibility and control leading directly to continuous cost optimization opportunities for the company. Let's investigate the truth of this statement.

If a company allows any individual user or designer to specify his test equipment preferences by manufacturer and model, a high-cost chain reaction is set in motion. Start with the unit itself. It may not meet the task requirements or even its own published specifications. Get your money back? Hardly. The cost of the unit is probably a fraction of the cost of maintaining the production schedules involved in our businesses. Next, consider spares. Spares must be purchased for all the different models that are specified and subsequently purchased. Then calibration procedures must be obtained for all different models. Calibration equipment must be obtained for all different models. By now, our chain reaction is well under way. Calibrating and operating technicians must be trained on the different models. There is also the possibility that once the unit has served its original purpose it may be useless for other applications. These considerations are seldom considered by the individual designer or test equipment user, simply because he lacks an overall view. ,

What is necessary for a group to provide a rational, standardized test equipment program for a large company? It must have complete responsibility and control over the entire program. It must have expert technical knowledge of all measuring and test equipment used in the company and of the costs of maintaining such equipment. It must have intimate knowledge of vendor reputations in the various fields, gained from actual instrument comparisons. It must be able to communicate on the technical level of the engineer.

Where can you find a group with these capabilities? If your calibration laboratories are manned with graduate engineers, each one a technical expert on a particular category of equipment, which he also maintains for the company . . . then you certainly have the base for such a group.

As an example of what can be accomplished, the test equipment applications group developed computer lab-run listings of all test equipment in the Convair Division. Results showed 7,326 different models in the 40,000 items of equipment. By working closely with users to determine application requirements, and with calibration laboratory engineers regarding specifications and choice of equipment, it was determined that only 2,179 different models were actually required. And this was only the first look! Some of the 5,147 unwanted models were replaced immediately by preferred models that were in storage status. The remaining unwanted models were marked for surplus on a systematic basis. This was accomplished by establishing a zero retention level for the unwanted units on the storage control lists. Consequently, if a user does not have an immediate need for a unit, it is declared surplus rather than being stored for backup purposes.

On the subject of test equipment disposition, how many of us have pondered over the question of whether to dispose, or not to dispose, of test equipment? More to the point is the pertinent question: Who makes the decision? Certainly the decision to use, store, or dispose of a unit of test equipment will either save, or cost, the company money. There is no middle ground. It will be one or the other. Without a capable control group, the decision is usually made by those least qualified to make it, usually a test equipment stockroom operation. Furthermore, their decision is usually to store the unit, since this is a pretty safe decision. In fact, the buck can get passed pretty far up the management ladder before someone will commit himself on this apparently simple decision. Why does this hold true? Because no company-wide visibility on the matter is available to the decision maker; therefore, no decision rules have been formulated.

About three years ago the Test Equipment Control Engineering section was confronted with this problem by one of our customers. The customer pointed out to management various contractual clauses which required customer-owned equipment to be returned within a certain period of time after it had been declared excess. Moreover, he claimed we were keeping his equipment in storage for years as potential backup equipment. Unfortunately, the allegations proved true. A fast check showed that not only was the storage inventory huge, it was snowballing rapidly. The inventory included both customer and company equipments which a cursory investigation showed were worthless for future requirements. Economically, the inventory was almost a disaster. The lesson was driven deeper when other equipment was located in storage that was superior to equipment in use.

Today, the decision to use, store, or declare equipment surplus is made within one to two days after the user decides the unit is excess to his needs. The decision is made as a matter of routine, with complete confidence that it is correct. An engineer from the test equipment applications group uses management-designed decision rules, along with engineering judgment regarding the condition of the instrument, to arrive at his decision within a few minutes after the question arises.

Visibility makes this possible: visibility of all test equipment in the company and where it is, visibility of present and known future needs of all users in the company. Visibility of preferred test equipment. Visibility of the desired number of like units for backup capability, the current headcount of like units in storage, and the precise condition of each one.

Of course, we are talking about a computerized test equipment control system with inputs of all parameters of test equipment cost, control, and life-history on every interface of the equipment with operations. Outputs are obtained in the form of tab runs and listings, in the formats required for intelligent decision-rule formulation or equipment control. These outputs are then placed in the hands of all those requiring the information for decision making or equipment control. This point may seem trite, but all too often information is available within a company but its existence is unknown to the poor soul who really needs it.

Some of the management tools provided by the computerized test equipment control system are:

1. Purchase cost of the unit.
2. Maintenance cost for the unit.
3. Chronological history of the unit, including numbers and dates of calibration, numbers and dates of failures, types of failures, and whether or not the failure was detected by the user.
4. User and location of equipment.
5. Equipment stored and whether operational or needing repair. Also the maximum number of each type to be held in storage.
6. Calibration and maintenance time on all equipment serviced by the individual technician.
7. Preferred test equipment for standardization.
8. Backlogs of individual laboratories.
9. Future workload, both total and individual laboratories.

Inputs regarding user requirements, immediate and future, are also provided to the section by means of test equipment requests.

Management use of these tools in their various possible combinations and forms will:

1. Provide the Standards and Calibration Laboratory management, higher management, and the user with actual cost information, including test equipment calibration and maintenance costs for each user in the company.
2. Provide calibration recall listings for all users and the various calibration laboratories.
3. Determine the types of equipment needed for purchase both as new requirements and replacements.
4. Determine department and individual laboratory efficiencies.
5. Determine training requirements for department engineers and technicians and possible user training requirements.
6. Provide decision rules for equipment disposition.
7. Determine total and individual laboratory manpower requirements, both present and future.
8. Determine calibration intervals from statistical and user information.

A few comments on calibration intervals seem in order here, not from the viewpoint of the methods to use to determine correct intervals but for the application of interval control. Often failure rates are used to determine calibration intervals which will then satisfy a specified quality level. Of course, this process is reversible and the calibration interval can be used to predict the failure rate. If a high failure rate on certain test equipment does not affect the quality of the end product, and if such high failure rate would optimize the total company cost (i.e., user cost due to the high failure rate versus calibration costs at shorter intervals), then by all means such equipment should be calibrated at intervals allowing the higher failure rate. Government specification MIL–C–45662A contains the requirements for control of a calibration system for Government contractors. This military specification states: "All measuring and test equipment applicable to the contract shall be subject to such control as is necessary to assure conformance of supplies and services to contractual requirements." Therefore, if the contractor can show complete control of those instruments which determine conformance of supplies and services to the satisfaction of the customer, a higher failure rate on other equipment might be appropriate for cost optimizing.

In this regard, Convair has a program which segregates critical application test equipment (CATE) from all other test equipment in the company. The CATE equipment is then placed on intervals conforming to customer requirements for such equipment. The rest of the equipment is placed on intervals to give a failure rate which management has determined will optimize company cost. Here again, the segregation of CATE is made possible by visibility of the equipment and the requirements as they apply to both Convair and the customer.

The computer listing which is supplied to management and users, identifying the users' monthly equipment costs, is a powerful tool. Making these costs visible to the user and to higher management provides a great incentive for the return of unnecessary test equipment. Infrequently used equipment tends to assume storage status if it is not needed at calibration time. These costs include those items checked out of the test equipment stockrooms on a daily basis. The listing provides a mechanism to tie calibration budget to equipment in use.

The manpower-forecasting tab runs can show, based on present intervals, the predicted manpower required for items due for calibration in any future time period. The runs also show the manpower required for irregular repair work, based on statistical probabilities compiled from the past history of presently used equipment.

The computerized test equipment control system can provide calibration and repair targets, based on statistical analysis of past performance, to any formula desired by management. Summaries of the individual, laboratory, or department performance against those targets for any time period can be provided as desired. Thus, it replaces the manual computation and reporting of work measurement.

I have tried to highlight some points of visibility and control which may be of help in analyzing another company's system. The basic philosophy is that if one can obtain total visibility of the system in all its parameters and interfaces, then management can make correct decisions and decision rules. It seems obvious that in a large company total control of general-purpose test equipment should be a function of the Standards and Calibration Laboratory.

For those who seek a "magic formula" I suggest that very few exist in actual practice. As engineers, we have a great propensity for formulas because we recognize them in our engineering work as being exact relationships between different parameters. In management, a strict formula generally means that a compromise has been made in the name of uniformity and often at high cost. This is not to advocate that management textbook formulas are no good. They are very good for their intent, which is mainly to give insight into the relationships of various operations parameters. Such formulas generally presuppose certain necessary assumptions which preclude their being applied in actual practice. Just as an example, consider the development of the most efficient system of reducing a calibration backlog. According to the textbook theory on the waiting-line problem, if you always take those items first which have the shortest calibration time, then you will have the most efficient system in every respect except one. That one exception is that somebody is going to wait an awfully long time for his particular equipment to get calibrated. Yet, if a rule is added to the system stating that no unit will wait longer than a specified time, the efficiency of the original system is reduced by up to 100 percent (in comparison to a first-come, first-served, system) and it may no longer be the most efficient system. How these management rules and practices can be modified to give the most efficient operation depends upon each company's particular circumstances.

Management systems should be as flexible as possible, yet still provide the necessary control. System feedback should impact the working group as little as possible, just as we strive to have our measuring instruments affect the basic parameter being measured as little as possible. And last, but certainly not least, the system should be designed for people.

I am aware that figures on cost reductions achieved by one company, even in the form of percentages, may not mean much to another company. This is understandable since there is no way to compare what each was formerly doing and their relative efficiencies, with what they are presently doing and their relative efficiencies. However, as a matter of possible interest, I may say that the cost savings of our present system over the previous operational method are approximately $803,000 per year. This saving began about two years after we started gathering data for analysis.

Another interesting monetary item is the computer cost. The charges for computer service for the issuance of all work forms and tab runs in their individual and combined variations comes to $0.33 per unit of active test equipment per year. This charge was $0.40 until we switched from a card system to a tape system. Tape also provides much greater flexibility and faster service.

Is our system optimized at this point? We don't think so. There are several areas in which we believe we can make improvements to our present system, and we are working on them. We can testify that the present system has been a great improvement over the previous operation and has led us to additional ideas for future changes.

NCSL 70

DATA SYSTEM FOR IMPROVING INSTRUMENT RELIABILITY

Frank J. Dyce

Metrology Laboratory, Martin Marietta Corporation, Orlando, Fla. 32805

This paper discusses the importance of monitoring and control of instrument reliability. It suggests that a minimum reliability level be set as a goal. It discusses the interval adjustment scheme used at Martin Marietta wherein individual instrument performance determines calibration interval as well as repair and surplus. A thorough explanation is given of the computerized data system used at Martin Marietta to monitor instrument reliability and to isolate repetitive problem areas. Several examples are given of reliability problems which were solved through use of the system.

A unique standardization committee is discussed which justifies the company's sole-source purchase of general-purpose, reliable electronic test equipment.

The paper concludes that striving towards a reliability goal will result in improved reliability and reduced cost.

Key words: Calibration data system; calibration interval adjustment method; instrument reliability; instrument standardization.

1. Introduction

Instrument reliability is a subject of much concern to metrologists today. The 95 percent reliability requirement *implied* by Military Handbook 52 has caused some laboratories to develop elaborate mathematical formulations and contrived definitions of typical instrument reliability to meet it. These manipulations were initially undertaken to meet the *implied* specification. Now we are coming of age and can better appreciate the importance of reliability. We know it is impossible to achieve 100 percent reliability; however, there is a definite reason to strive for an optimum level. This optimum level is dependent on the laboratories' resources and capabilities. It should be a published goal capable of measurement.

Reliable equipment:

1. can make reliable measurements;
2. needs to be calibrated less frequently;
3. requires less repair time;
4. requires fewer replacement parts;
5. has a higher utilization rate.

Probably the major reason for having reliable equipment is that most instrument users assume instruments are absolutely accurate. To protect them and the product, instruments should be made as reliable as feasible.

The disadvantages of high reliability are:

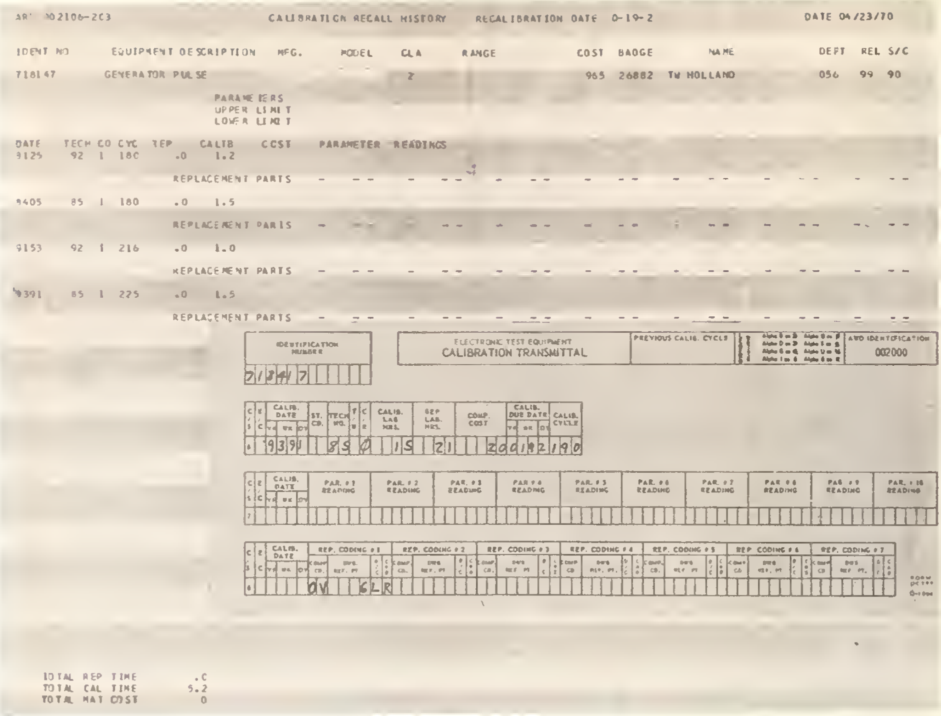
1. Calibration intervals might be shorter.
2. Utilization rate might be lower.
3. Calibration time might be longer.

We have made 95 percent reliability our goal and we are getting close to it. We measure reliability in a very basic way: number of instruments received for calibration which are in-tolerance (with respect to published specification) versus number of instruments calibrated.

Our laboratory strives for this goal, using two basic approaches: an interval adjustment scheme based on individual instrument reliability; and a minimum-input automatic data processing system.

2. Interval Adjustment Scheme

The initial calibration interval is based on the average interval for instruments of the same manufacturing model number or on experience with instruments of the same type. Each time an instrument is calibrated its past calibration history accompanies it (fig. 1). The calibration technician examines the history and the condition of the equipment to determine its next calibration interval as well as to determine repetitive failures. If the instrument is out of tolerance, the interval is reduced 20 percent; if it is in tolerance three consecutive times, the interval is increased 20 percent for each time thereafter. (The intervals vary in the following steps: 30, 40, 50, 60, 70, 90, 110, 130, 160, 190, 225, 270, 320, 365 days). Thus, our major effort is expended on unreliable equipment and our workload is balanced, since an instrument never out-of-tolerance is calibrated only once a year. When two consecutive out-of-tolerances occur, repair is mandatory; adjustment is obviously inadequate. The faulty components must be replaced and the instrument checked for stability for two days. When three consecutive out-of-tolerances occur, the instrument is considered for surplus. Figure 2 shows that by using this system, our lab is now doing fewer actual calibrations (solid line) on twice as many pieces of equipment (dashed line) as we were eight years ago; we



```
AR' 02106-2C3               CALIBRATICN RECALL HISTORY   RECALIBRATION DATE  0-19-2              DATE 04/23/70

IDENT NO      EQUIPMENT DESCRIPTION   MFG.     MODEL    CLA     RANGE             COST  BADGE       NAME           DEPT  REL S/C
718147       GENERATOR PULSE                             2                          965  26882  TW HOLLAND          056    99  90

                                 PARAMETERS
                                 UPPER LIMIT
                                 LOWER LIMIT

DATE    TECH CO CYC  REP     CALIB     COST    PARAMETER  READINGS
9125     92   1  180     .0     1.2

                           REPLACEMENT PARTS   -   - -    -   - -   -   - -   -   - -   -   - -   -   - -   -   - -

9405     85   1  180     .0     1.5

                           REPLACEMENT PARTS   -   - -    -   - -   -   - -   -   - -   -   - -   -   - -   -   - -

9153     92   1  216     .0     1.0

                           REPLACEMENT PARTS   -   - -    -   - -   -   - -   -   - -   -   - -   -   - -   -   - -

9391     85   1  225     .0     1.5

                           REPLACEMENT PARTS   -   - -    -   - -   -   - -   -   - -   -   - -   -   - -   -   - -

TOTAL REP TIME       .C
TOTAL CAL TIME      5.2
TOTAL MAT COST        0
```

IDENTIFICATION NUMBER 71847

ELECTRONIC TEST EQUIPMENT
CALIBRATION TRANSMITTAL

PREVIOUS CALIB. CYCLE

AWO IDENTIFICATION 002000

C/S	E/C	CALIB. DATE	ST. CD.	TECH NO.	T/W	C/R	CALIB. LAB HRS.	REP LAB. HRS.	COMP. COST	CALIB. DUE DATE	CALIB. CYCLE
6		9391		85		Ø	15	21		2001 82	190

C/S	E/C	CALIB. DATE	PAR. #1 READING	PAR. #2 READING	PAR. #3 READING	PAR. #4 READING	PAR. #5 READING	PAR. #6 READING	PAR. #7 READING	PAR. #8 READING	PAR. #9 READING	PAR. #10 READING
7												

C/S	E/C	CALIB. DATE	REP. CODING #1	REP. CODING #2	REP. CODING #3	REP. CODING #4	REP. CODING #5	REP. CODING #6	REP. CODING #7
6			OV 6LR						

FIGURE 1. *Calibration history and transmittal.*

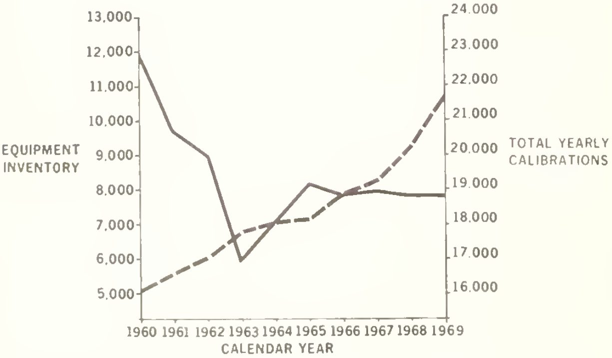


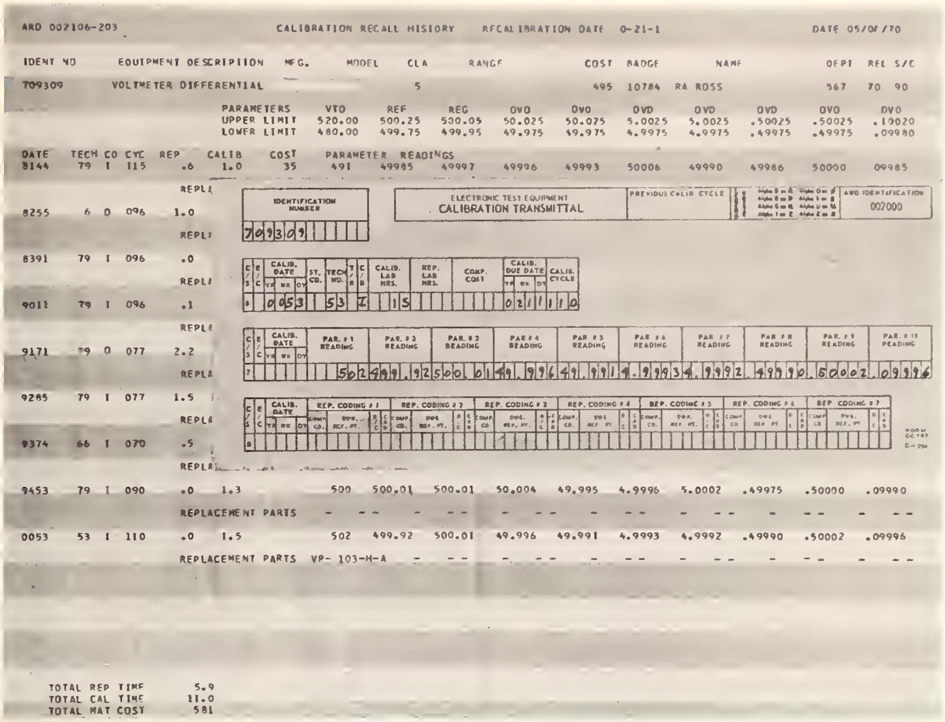
FIGURE 2. *Annual calibrations* (solid line) *versus equipment inventory* (dashed line).

have improved reliability and lowered costs simultaneously. Our current reliability, 90.3 percent, is 9 percent higher than our total past reliability and is steadily increasing.

3. Automatic Data Processing System

A calibration data system is required to indicate the past condition of the equipment, to determine the need for interval adjustments, and to meet inventory and Mil Spec requirements. Our data system was designed to collect only data that we would actually use. The input data transmittal (fig. 1) is designed for minimum data handling and minimum chance for error. For an in-tolerance instrument, the technician enters the following data: equipment identification number, condition as received (I in tolerance, Ø out of tolerance), calibration date, recalibration due date, calibration interval, stamp number, and calibration hours. For an out-of-tolerance instrument, he adds the repair hours, replacement-part cost, and coded defect. The coded defect is the only complicated part of the system. Each technician has a mnemonic code book with codes listed for the family of instruments he repairs. The technician codes each system failure; What was wrong, how it was wrong, what part caused the failure, and what was done to the part. For example, if a signal generator had low output and vacuum tube V6 was replaced to correct it, it would be coded OLV6R; which reads Output (O) Low (L) Vacuum Tube (V) Circuit Symbol 6 Replaced (R). The disadvantage that the coding complicates the data transmittal is offset by the data's availability for later computer analysis.

We have 40 families of instruments for which we record discrete parameter data. There are many philosophies on how much data to collect. Our philosophy is that it is pointless to collect data on reliable instruments; therefore we have established the 10 most critical parameters on our most unreliable families of instruments. These parameters and their upper and lower tolerance limits are inserted in the calibration recall history header (fig. 3). Each time an instrument is calibrated, the technician records the parameters prior to adjustment or repair. He compares the parameters against the limits and the previous readings to determine the instrument's drift characteristics



```
ARO 002106-203            CALIBRATION RECALL HISTORY   RECALIBRATION DATE  0-21-1                    DATE 05/01/70

IDENT NO       EQUIPMENT DESCRIPTION    MFG.     MODEL    CLA      RANGE             COST  BADGE      NAME            DEPT  REL S/C

709309        VOLTMETER DIFFERENTIAL                       5                          495  10784  RA ROSS             567   70  90

                                PARAMETERS    VTO     REF     REG     OVO     OVO     OVD     OVD     OVD     OVO     DVO
                                UPPER LIMIT  520.00  500.25  500.05  50.025  50.025  5.0025  5.0025  .50025  .50025  .10020
                                LOWER LIMIT  480.00  499.75  499.95  49.975  49.975  4.9975  4.9975  .49975  .49975  .09980

DATE   TECH CO CYC  REP    CALIB    COST    PARAMETER  READINGS
8144    79  I  115    .6    1.0      35      491    49985   49997   49996   49993   50006   49990   49986   50000   09985
                         REPL
8255     6  0  096   1.0
                         REPL
8391    79  I  096    .0
                         REPL
9011    79  I  096    .1
                         REPL
9171    79  0  077   2.2
                         REPL
9285    79  I  077   1.5
                         REPL
9374    66  I  070    .5
                         REPL
9453    79  I  090    .0    1.3             500    500.01  500.01  50.004  49.995  4.9996  5.0002  .49975  .50000  .09990
                         REPLACEMENT PARTS  -    - -     -   - -     -   - -     -   - -     -   - -     -   - -     -   - -
0053    53  I  110    .0    1.5             502    499.92  500.01  49.996  49.991  4.9993  4.9992  .49990  .50002  .09996
                         REPLACEMENT PARTS  VP- 103-H-A  -   - -     -   - -     -   - -     -   - -     -   - -     -   - -

   TOTAL REP TIME        5.9
   TOTAL CAL TIME       11.0
   TOTAL MAT COST        581
```

IDENTIFICATION NUMBER 709309

ELECTRONIC TEST EQUIPMENT CALIBRATION TRANSMITTAL

PREVIOUS CALIB CYCLE

ARO IDENTIFICATION 002000

C/S	E/C	CALIB. DATE	ST. CD.	TECH NO.	T/R	C/B	CALIB. LAB HRS.	REP. LAB HRS.	COMP. COST	CALIB. DUE DATE	CALIB. CYCLE
1		0053		53	I		15			0211	110

C/S	E/C	CALIB. DATE	PAR. # 1 READING	PAR. # 2 READING	PAR. # 3 READING	PAR. # 4 READING	PAR. # 5 READING	PAR. # 6 READING	PAR. # 7 READING	PAR. # 8 READING	PAR. # 9 READING	PAR. # 10 READING
7			502	499.92	500.01	49.996	49.991	4.9993	4.9992	.49990	.50002	.09996

C/S	E/C	CALIB. DATE	REP. CODING # 1	REP. CODING # 2	REP. CODING # 3	REP. CODING # 4	REP. CODING # 5	REP. CODING # 6	REP. CODING # 7
8									

FIGURE 3. *Parameter history.*

and the necessity for adjustment. We have a directive which dictates that if a measurement is within half its tolerance limit, leave it alone. If it is outside half its limit, adjust it to nominal. This permits adjustments to settle at a stable value. The computer analyzes this discrete data on a family basis and produces a report which we use to pinpoint instrument problem areas and to eliminate unnecessary steps in the calibration procedure. Both Mil Spec and customer requirements require us to maintain a data system for recall. The computer does this with a simple inventory technique; however, we feel that the systems that perform recall alone fail to make full use of the computer's potential. We use the computer for inventory, recall, history and records, and, most importantly, special reports. We have several reports which are used to improve reliability; the first is the Reliability Summary Report described below.

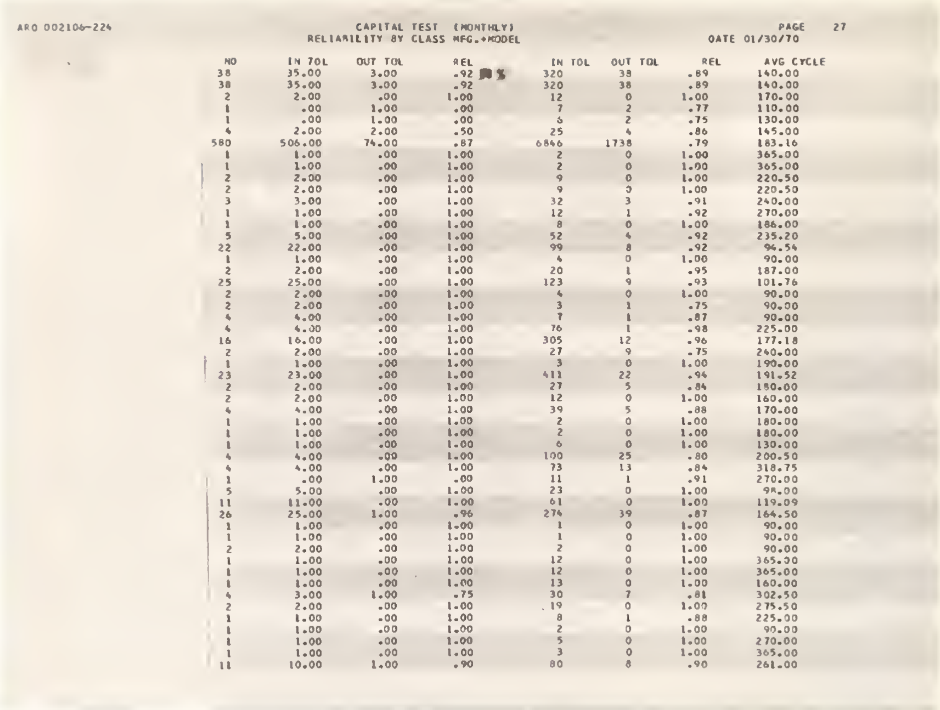
4. Reliability Summary Report

This report is our measurement of reliability. It is required since, in order to strive towards our goal, we must have a measure of performance. This report (fig. 4) lists reliability by class, manufacturer, and model number. It tells us first how reliable we are, and it pinpoints problem areas and isolates them to classes of instruments, manufacturers, and model numbers. The report is examined monthly to isolate our least reliable major families of instruments, the families which are causing our reliability to be less than 95 percent. It also lists the family reliability based on the last calibration, to indicate what our current reliability is. Monitoring this report, we noted that the current reliability of a family of 38 function generators had decreased from its overall level of 89 percent to a reliability of 66 percent over a period of several months. An investigation revealed the major cause of failure was signal distortion which required adjustment. A further check revealed the distortion analyzer used in the calibration was defective, causing the generators to be adjusted to an order of magnitude less distortion than what they actually required. The analyzer was repaired and the current reliability of the function generators has improved to 99 percent.

The summary report indicated one family of 44 rf signal generators had an historical reliability of 66 percent and a current reliability of 64 percent. This indicated not only that the reliability was bad, but that it was getting worse. The Quarterly Reliability Report had to be consulted to determine if we had an individual instrument problem or a family problem.

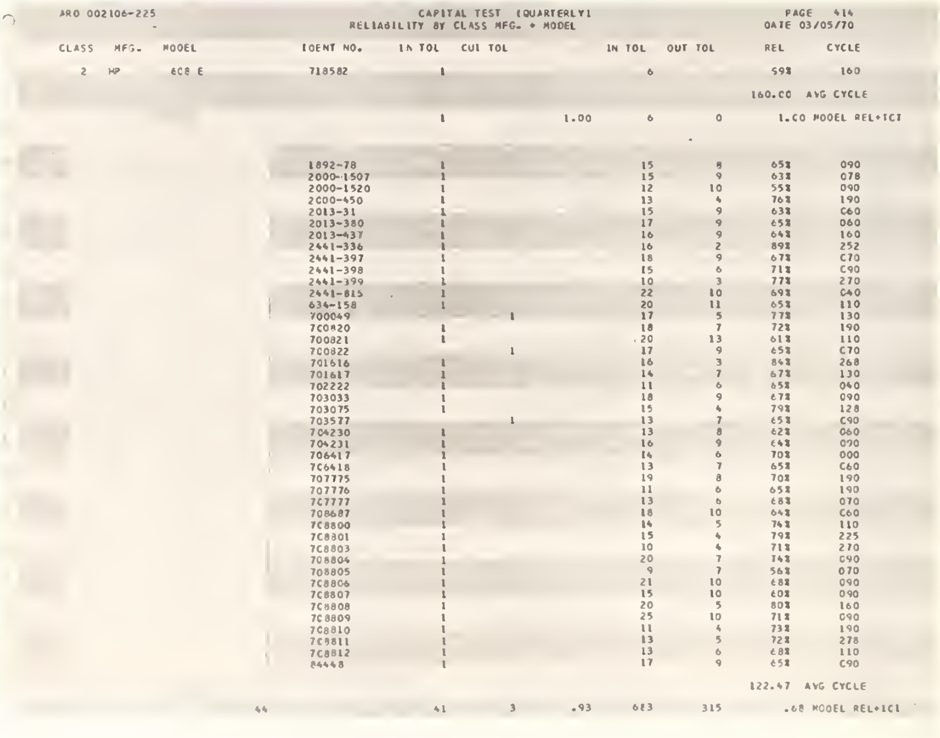
5. Quarterly Reliability Report

The Quarterly Reliability Report has the same basic information and format as the summary report but it includes each individual instrument's reliability by identification number. This report (see fig. 5) indicated the individual instruments' reliabilities varied between 54 and 88 percent with an overall reliability of 64 percent. It is difficult to prove what causes instruments to fail—whether it is misuse, mishandling, poor design, etc.; however, if all instruments of the same type have poor reliability, the problem is likely to be endemic in the type, and that is what should be



```
ARO 002106-224                          CAPITAL TEST  (MONTHLY)                                PAGE     27
                                   RELIABILITY BY CLASS MFG.+MODEL                      DATE 01/30/70

                      NO       IN TOL     OUT TOL       REL        IN TOL  OUT TOL      REL      AVG CYCLE
                      38        35.00       3.00        .92 %        320      38        .89       140.00
                      38        35.00       3.00        .92          320      38        .89       140.00
                       2         2.00        .00       1.00           12       0       1.00       170.00
                       1          .00       1.00        .00            7       2        .77       110.00
                       1          .00       1.00        .00            6       2        .75       130.00
                       4         2.00       2.00        .50           25       4        .86       145.00
                     580       506.00      74.00        .87         6846    1738        .79       183.16
                       1         1.00        .00       1.00            2       0       1.00       365.00
                       1         1.00        .00       1.00            2       0       1.00       365.00
                       2         2.00        .00       1.00            9       0       1.00       220.50
                       2         2.00        .00       1.00            9       0       1.00       220.50
                       3         3.00        .00       1.00           32       3        .91       240.00
                       1         1.00        .00       1.00           12       1        .92       270.00
                       1         1.00        .00       1.00            8       0       1.00       186.00
                       5         5.00        .00       1.00           52       4        .92       235.20
                      22        22.00        .00       1.00           99       8        .92        94.54
                       1         1.00        .00       1.00            4       0       1.00        90.00
                       2         2.00        .00       1.00           20       1        .95       187.00
                      25        25.00        .00       1.00          123       9        .93       101.76
                       2         2.00        .00       1.00            4       0       1.00        90.00
                       2         2.00        .00       1.00            3       1        .75        90.00
                       4         4.00        .00       1.00            7       1        .87        90.00
                       4         4.00        .00       1.00           76       1        .98       225.00
                      16        16.00        .00       1.00          305      12        .96       177.18
                       2         2.00        .00       1.00           27       9        .75       240.00
                       1         1.00        .00       1.00            3       0       1.00       190.00
                      23        23.00        .00       1.00          411      22        .94       191.52
                       2         2.00        .00       1.00           27       5        .84       180.00
                       2         2.00        .00       1.00           12       0       1.00       160.00
                       4         4.00        .00       1.00           39       5        .88       170.00
                       1         1.00        .00       1.00            2       0       1.00       180.00
                       1         1.00        .00       1.00            2       0       1.00       180.00
                       1         1.00        .00       1.00            6       0       1.00       130.00
                       4         4.00        .00       1.00          100      25        .80       200.50
                       4         4.00        .00       1.00           73      13        .84       318.75
                       1          .00       1.00        .00           11       1        .91       270.00
                       5         5.00        .00       1.00           23       0       1.00        98.00
                      11        11.00        .00       1.00           61       0       1.00       119.09
                      26        25.00       1.00        .96          274      39        .87       164.50
                       1         1.00        .00       1.00            1       0       1.00        90.00
                       1         1.00        .00       1.00            1       0       1.00        90.00
                       2         2.00        .00       1.00            2       0       1.00        90.00
                       1         1.00        .00       1.00           12       0       1.00       365.00
                       1         1.00        .00       1.00           12       0       1.00       365.00
                       1         1.00        .00       1.00           13       0       1.00       160.00
                       4         3.00       1.00        .75           30       7        .81       302.50
                       2         2.00        .00       1.00           19       0       1.00       275.50
                       1         1.00        .00       1.00            8       1        .88       225.00
                       1         1.00        .00       1.00            2       0       1.00        90.00
                       1         1.00        .00       1.00            5       0       1.00       270.00
                       1         1.00        .00       1.00            3       0       1.00       365.00
                      11        10.00       1.00        .90           80       8        .90       261.00
```

Figure 4. *Reliability Summary Report.*



```
ARO 002106-225                              CAPITAL TEST  (QUARTERLY)                        PAGE   414
      -                               RELIABILITY BY CLASS MFG. + MODEL                  DATE 03/05/70

CLASS   MFG.    MODEL           IDENT NO.     IN TOL   OUT TOL            IN TOL   OUT TOL      REL      CYCLE

  2     HP      608 E           718582           1                           6                  59%       160

                                                                                           160.00  AVG CYCLE

                                                 1                1.00       6        0       1.00 MODEL REL+ICT


                                1892-78          1                          15        8         65%       090
                                2000-1507        1                          15        9         63%       078
                                2000-1520        1                          12       10         55%       090
                                2000-450         1                          13        4         76%       190
                                2013-31          1                          15        9         63%       060
                                2013-380         1                          17        9         65%       060
                                2013-437         1                          16        9         64%       160
                                2441-336         1                          16        2         89%       252
                                2441-397         1                          18        9         67%       070
                                2441-398         1                          15        6         71%       090
                                2441-399         1                          10        3         77%       270
                                2441-815         1                          22       10         69%       040
                                634-158          1                          20       11         65%       110
                                700049                    1                 17        5         77%       130
                                700820           1                          18        7         72%       190
                                700821           1                          20       13         61%       110
                                700822                    1                 17        9         65%       070
                                701616           1                          16        3         84%       268
                                701617           1                          14        7         67%       130
                                702222           1                          11        6         65%       040
                                703033           1                          18        9         67%       090
                                703075           1                          15        4         79%       128
                                703577                    1                 13        7         65%       090
                                704230           1                          13        8         62%       060
                                704231           1                          16        9         64%       070
                                706417           1                          14        6         70%       000
                                706418           1                          13        7         65%       060
                                707775           1                          19        8         70%       190
                                707776           1                          11        6         65%       190
                                707777           1                          13        6         68%       070
                                708687           1                          18       10         64%       060
                                708800           1                          14        5         74%       110
                                708801           1                          15        4         79%       225
                                708803           1                          10        4         71%       270
                                708804           1                          20        7         74%       090
                                708805           1                           9        7         56%       070
                                708806           1                          21       10         68%       090
                                708807           1                          15       10         60%       090
                                708808           1                          20        5         80%       160
                                708809           1                          25       10         71%       090
                                708810           1                          11        4         73%       190
                                708811           1                          13        5         72%       278
                                708812           1                          13        6         68%       110
                                84448            1                          17        9         65%       090

                                                                                           122.47  AVG CYCLE

                    44                          41        3        .93     683      315        .68 MODEL REL+ICT
```

Figure 5. *Quarterly Reliability Report.*

investigated. The problem in our example appeared to be a family problem and it was examined accordingly. The investigation required the use of another report, the Trouble-Shooting Summary Report.

6. Trouble-Shooting Summary Report

The Trouble-Shooting Summary Report summarizes all instrument repair information by manufacturing model number. It sorts the repair information and lists it in alphanumeric sequence, with like codes totaled by manufacturing model number.

The family of signal generators we investigated had a repetitive problem (see fig. 6). The problems were OLV8 out of tolerance 40 times and OLV6 out of tolerance 30 times, both requiring corrective action of R. Using the mnemonic code book. these failures are decoded as Output Low Vacuum Tube 8 replaced 40 times and Output Low Vacuum Tube 6 replaced 30 times; i.e., tubes V6 and V8 were replaced 70 times on 44 generators in one year. This represented 50 percent of the problems with this family of instruments. A further investigation of the individual histories revealed that V6 and V8 had been replaced in several instruments on consecutive calibrations. These instruments were recalled and an examination revealed that supply voltages to V6 and V8 were off by over 20 percent. This caused the tubes to operate in an overloaded condition with reduced output and a very short life. Identical conditions were found on 4 out of the 5 generators recalled; the cause of the difficulty was that technicians inadvisedly replaced weak output tubes when the trouble was improper supply voltages. The instruments were in tolerance when they left the lab but the tubes rapidly deteriorated so that the output dropped off. The technicians were informed of the trouble, an instruction to check all supply voltages was added to the calibration procedure, and a filament voltage parameter was added to the calibration transmittal. Using these steps, we improved the reliability from 66 percent to the current 97 percent. The data were monitored to determine how often low output occurred and to note the drift in filament voltage. They both appeared stable after the corrective action.

```
ARO 002106-726  TROUBLE SHOOTING SUMMARY REPORT    PAGE   718
                                                 DATE 04/02/70

MFG.      MODEL      S/C  D/C   COMPS  OUT TOL.  IN  TOL.  CAD

                      O    L                 1         O    D


                                D   4        1         O    R


                                D   5        2         O    R


                                D   6        1         O    R


                                I  12        1         O    A


                                P  87        1         O    A


                                V            1         O    O


                                V   8       40         O    R


                                V   5        1         O    R


                                V   6       30         1    R
```

Figure 6. *Trouble-Shooting Summary Report.*

7. Surplus Selection

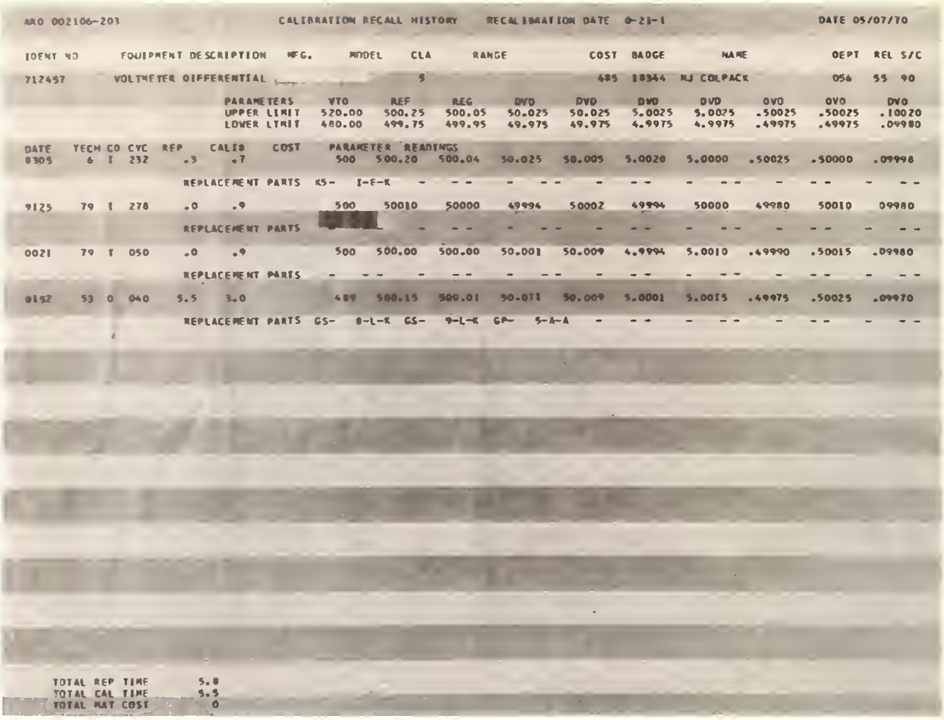
The reliability report is also used to segregate instruments for surplus. An arbitrary value of 50 percent reliability was selected and a report listed all instruments below that value. Further study was then conducted, utilizing cost information previously stored in the computer, to make the surplus decision. In this way we eliminated our most unreliable instruments which had the highest maintenance costs. We have a set rule that no instrument less than 50 percent reliable may be used for acceptance testing; we will not certify it. This accelerates an otherwise slow process of designating equipment surplus.

8. Manpower Adjustment

We have been able to reduce manpower by examining calibration intervals versus reliability. We extended intervals on with good reliability until they equalled those for older instruments of the same type with similar reliability. We also reduced intervals on instruments with poor reliability. This has represented one-year savings of 3,000 hours calibration time on 8,000 instruments. The method of extension was facilitated by manipulating the computer printout. An interval change code (CI50) was attached to the recall history (fig. 7), so that when the instrument came due for calibration, the technician noted the CI50, changed the interval to 50 days, and removed the change code. In this way we did not have to locate the instrument physically or depend on a checklist. The basic interval adjustment was derived from an algebraic sum of the conditions as received; e.g., IIØIIØIIII would yield zero net interval increase and the interval would remain at 90 days, say, whereas IIIIIIIIØØ would yield a net increase of 80 percent and an interval of 190 days. Even though both instruments are equally reliable, their intervals will differ by a factor of two.

9. Standardization Committee

Our company has an Equipment Standardization Committee made up of representatives from Engineering, Manufacturing, Procurement, Facilities and Metrology. The Committee's purpose is to generate a Standardization List of equipment recommended for purchase. Before any general-purpose electronic test equipment can be purchased, it must be on our Standardization List. The committee meets bi-weekly and prepares a comparison matrix to evaluate equipment specifications, performance, reliability, and price. A matrix is made for each general item—oscilloscopes, counters, digital voltmeters, etc. Once selected by the Committee, an item must be evalauted by the Metrology Laboratory before being included on the list. In



```
ARO 002106-203                    CALIBRATION RECALL HISTORY    RECALIBRATION DATE  0-21-1                    DATE 05/07/70

IDENT NO      EQUIPMENT DESCRIPTION   MFG.     MODEL    CLA       RANGE               COST  BADGE       NAME          DEPT  REL S/C

712457        VOLTMETER DIFFERENTIAL                      S                            485  18344  MJ COLPACK          056   55  90

                              PARAMETERS     VTO      REF       REG       DVD      DVD      DVD      DVD      OVO      OVO      DVO
                              UPPER LIMIT  520.00   500.25    500.05    50.025   50.025   5.0025   5.0025   .50025   .50025   .10020
                              LOWER LIMIT  480.00   499.75    499.95    49.975   49.975   4.9975   4.9975   .49975   .49975   .09980

DATE   TECH CO CYC  REP    CALIB    COST    PARAMETER  READINGS
8305     6  I  232   .3     .7                500   500.20    500.04    50.025   50.005   5.0020   5.0000   .50025   .50000   .09998

                    REPLACEMENT PARTS  K5-   I-E-K    -    - -     -    - -     -    - -     -    - -     -    - -     -    - -

9125    79  I  278   .0     .9                500    50010     50000     49994    50002    49994    50000    49980    50010    09980
                                             [redacted]
                    REPLACEMENT PARTS                  -    - -     -    - -     -    - -     -    - -     -    - -     -    - -

0021    79  I  050   .0     .9                500   500.00    500.00    50.001   50.009   4.9994   5.0010   .49990   .50015   .09980

                    REPLACEMENT PARTS  -    - -       -    - -     -    - -     -    - -     -    - -     -    - -     -    - -

0152    53  0  040   5.5    3.0               489   500.15    500.01    50.011   50.009   5.0001   5.0015   .49975   .50025   .09970

                    REPLACEMENT PARTS  GS-   8-L-K  GS-   9-L-K  GP-   5-A-A    -    - -     -    - -     -    - -     -    - -





       TOTAL REP TIME        5.8
       TOTAL CAL TIME        5.5
       TOTAL MAT COST         0
```

FIGURE 7. *Interval change history.*

this way we ensure that it meets its advertised specifications and is serviceable. Standardizing on test equipment has many advantages:

1. Operator familiarity with a single item.
2. Quantity discounts.
3. One set of spare parts.
4. More efficient calibration and maintenance.
5. Purchase of the best instrument for the job.

Previous vendor history records are consulted through the Family Summary Report to insure that calibration costs are minimized and reliability is optimized.

10. Family Summary Report

The Family Summary Report indicates by family:

1. Average calibration hours.
2. Average repair hours.
3. Average repair parts.
4. More efficient calibration and maintenance.
5. Average calibration interval.

With this type of information available, we can readily forecast the time required to perform a calibration on any instrument. We can isolate the instruments on which we are spending excessive amounts of time. We can compare relative performance of like instruments. For example, the report listed the following data on two equivalent models of differential voltmeters.

Mfg. & Model No.	*Cost*	*No. of Instr.*	*No. Calib.*	*Avg. Rep. Hrs/Cal.*	*Avg. Cal. Hrs/Cal.*	*Avg. Rel.*	*Avg. Cal. Interval*
Brand X	$1240	6	27	0.18	2.11	88	166
Brand Y	$1275	7	21	1.11	3.18	57	85

The Brand X instrument is more reliable, requires considerably less calibration and repair time, and can be calibrated half as often.

Thus, even though instruments might be equivalent in specification and purchase price, their actual history can reveal cost differences of great significance. This is the area we try to emphasize in our Standardization Committee meetings.

11. Conclusion

Although the 95 percent reliability statement of Military Handbook 52 is often criticized, it does serve a worthwhile purpose. Striving for this goal, we are presently increasing our instrument reliability, reducing our operating costs, and feel confident we are improving product reliability. The day is not too far off when mean time between failures will be specified on precision test equipment. Even some of the best-known instrument manufacturers sell an unreliable product. Metrology labs throughout the country, preferably through the auspices of NCSL, should band together to collect similar reliability data and should urge manufacturers to produce more reliable instruments.

NCSL 70

NEW U.S. AIR FORCE AUDIT PROGRAM

Lloyd W. Root

Department of the Air Force, Metrology Engineering Division, Drectorate of Metrology, Aerospace Guidance and Metrology Center (AFLC), Newark Air Force Station, Newark, Ohio 43055

This paper describes a unique quality assurance audit program used for testing worldwide Precision Measurement Equipment Laboratories (PMEL's). Conventional methods utilized during previous audits are examined briefly and disadvantages noted. The advent of highly sophisticated systems and test equipment has placed increased emphasis on the experience and skill level of the technicians who provide calibration support at PMEL's. Specific configuration of a unique package designed to evaluate this skill level is discussed in some detail and results obtained during the past year are presented.

Key words: Audit examinations; audit package; Precision Measurement Equipment Laboratories (PMEL); technician skills; U.S. Air Force.

1. Introduction

The United States Air Force operates a large number of Precision Measurement Equipment Laboratories (PMEL's) strategically located throughout the world. These are audited by five Air Materiel Area Laboratories (AMA Labs) located within the continental United States. Technical direction and management of the Air Force Calibration Program is the responsibility of the Air Force Logistics Command (AFLC) and has been delegated to the Aerospace Guidance and Metrology Center (AGMC) at Newark Air Force Station in Ohio. Each base PMEL is audited on an annual basis by its AMA with the latter being certified by AGMC. In general, examination is concentrated in five general areas—

1. *Environment:* temperature, humidity, dust, housekeeping.
2. *Software:* Technical Orders (T.O.'s),reference library.
3. *Reference standards:* traceable to NBS or other laboratories.
4. *Test equipment:* signal generators, 'scopes, multimeters, etc.
5. *Personnel:* adequacy of training, experience, and skill.

In addition, adequacy of facilities and administrative methods is thoroughly investigated.

2. Previous Audit Method

Past audits have utilized basic standards in the electrical and mechanical areas whose absolute values could easily be predicted by a laboratory technician to be within the tolerances allowed without actually measuring those values. This was true because the nominal values of the selected standards are known because of the model or part number. For example, a GR model 1482-L inductor has a nominal value of 100 mH, adjusted to be within 0.1 percent of exact value. Without making any measurements whatever, a lab technician could report the nominal value and be graded as acceptable if the tolerance allowed on his measurement were 0.1 percent. As another example, suppose he were asked to measure a high-quality gage block whose nominal value is known. He might report the exact nominal value (or even change it slightly to make the actual measurement more palatable), and if the allowed tolerance were ± 10 μin, he would pass with flying colors!

3. Proposed Revisions

Two possible solutions were proposed to avoid these situations. Allowable tolerances could be reduced or the standard item could be changed in value. Reduced tolerances were found to be unrealistic because of shipping shocks or even hidden damage not under control. Stability of some standards was found to be poor because of hysteresis effects caused by temperature excursions experienced in transit. A second solution, that of supplying a measurement problem which could not be "guesstimated," was also considered. For example, one surface of an optical flat could be refigured to produce a slight cylinder or sphere and the lab technician required to define the measured surface accurately. A standard resistor or capacitor could be "fudged" to have an actual value on the order of a few hundred ppm away from nominal. Unless the allowable tolerances were increased, however, the same obvious deviations might be attributed to shipping or local handling.

4. A New Approach

A unique approach to laboratory audits was envisioned as early as 1960. The number of possible problems has grown over the years from a half dozen to more than 20, about equally divided between electrical and mechanical areas. New devices are being developed so that completely different problems may be utilized during successive audits. Sources of supply for useful items include toy shops, surplus electronic outlets, "do-it-yourself" building supplies, and scientific houses.

Problems are designed to test the ability of the laboratory technicians to work together as a team in the solution of the test problems. Emphasis is placed on comprehension, original thinking, and measurement techniques rather than on resolution and accuracy to parts per million. The device being measured may be sensitive to its environment or to the pattern of the applied stimulus. Thus, test results may vary from one laboratory to another because the auditor may change the specified test parameters, resulting in many different answers to a particular problem—and all can be correct. Some problems may specify the choice of test equipment; others allow a very wide selection.

5. Audit Implementation

Problem layout and nominal parameters are sent to the audited laboratory at least one month in advance of the appearance of the auditor and actual test package so that they may be studied and measurement schemes prepared for the auditor's approval. One problem is designated as required, with an additional three of the remaining six to selected by the audited laboratory. Most problems may be solved in several different ways, but any scheme proposed must be acceptable to the auditor before being implemented. Assistance may be provided when required and, at the conclusion of the test, other schemes having equal or greater merit may be discussed. A valid error analysis must be included with each final answer produced.

All schemes, test data, compilation of results, and error analyses are reported in triplicate; one copy remains at the tested site, one is filed at the AMA, and one is sent to AGMC for analysis. When such analysis indicates lack of suitable test equipment, reference standards, or training, limited certification may be imposed or recommendations made for future augmentation of the laboratory capabilities.

To facilitate uniform reporting, a check list is used for each separate problem as follows:

Audit Package Checklist

NOTE: Minimum requirements—problem 2b plus a choice of three additional problems. Data sheets and measurement schemes are to be prepared in triplicate by audited laboratory.

Name of auditor/Symbol/Date ______________________________

PMEL/AMA Symbol, Building ______________________________

Problem number ______________

Work location illumination level, foot candles ______________

temperature limits, °C ______________

humidity limits, % RH ______________

Yes No

1. Was measurement scheme prepared in advance? ______________

2. Is it acceptable to auditor? (If not, on-spot OJT may be provided by auditor or alternate problem may be selected). ______________

3. Are current AFTO 108's affixed to the test equipment? ______________

4. Were model and serial numbers of equipment recorded ______________

5. Were model temperature/humidity recorded? ______________

6. If desk calculator, reference library, or special equipment were needed, were they available? (Explain with attachment, if necessary). ______________

7. If Ac ratio measurements were made, were proper corrections made for zero and unity balances? ______________

8. Were shielded cables used (if necessary)? ______________

9. On dc ratio measurements, were proper lead compensation corrections made or analyzed for possible error? ______________

10. Was effort wasted in attempting greater resolution of accuracy than required by the problem? ______________

11. Were loading errors considered? ______________

12. Was more than one method used to solve problem? ______________

General comments as to capability of audited personnel, attitude, cooperation, motivation, etc. (Use reverse side).

6. Audit Package Configuration

The actual package for the electrical audit is designed to test proficiency in the use of an Electrical Measurement Console (EMC) issued to all base laboratories. Two standard "mini-boxes" containing all components are housed in a small, foam-padded satchel. Figures 1, 2, and 3 show the method of packaging; figures 4 and 5 the component layout.

Many variations are possible for the oscillator circuit board depending upon the degree of sophistication desired. Two representative schematics are shown in figures 6 and 7.

Figure 1. *Portable audit package.*

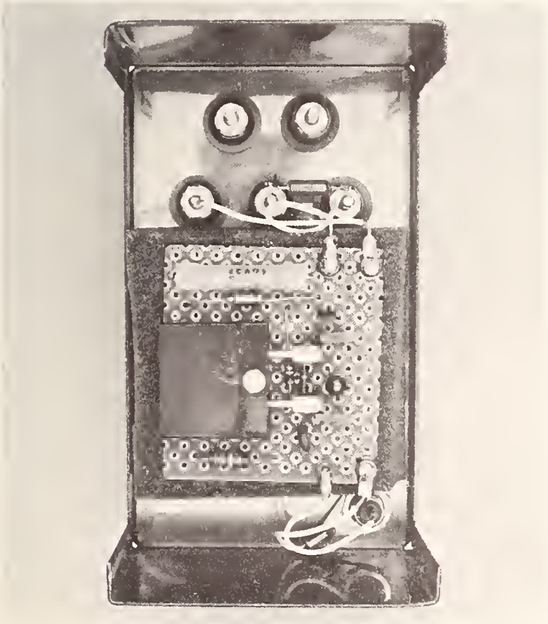


Figure 2. *Chassis layout "A" items.*

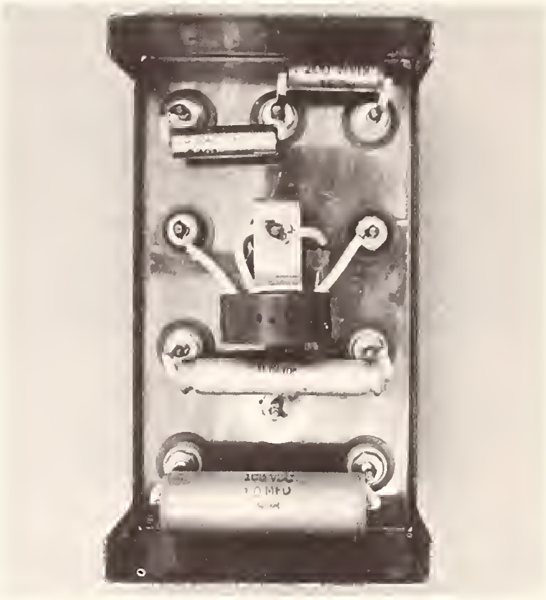


Figure 3. *Chassis layout "B" items.*

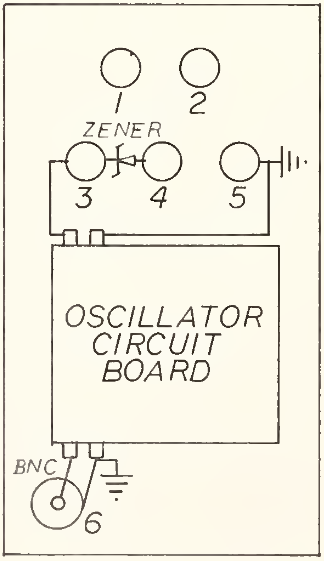


Figure 4. *Plan view "A" nominal values.*

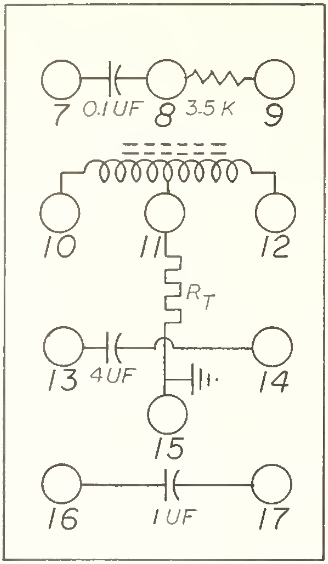


FIGURE 5. *Plan view "B" nominal values.*

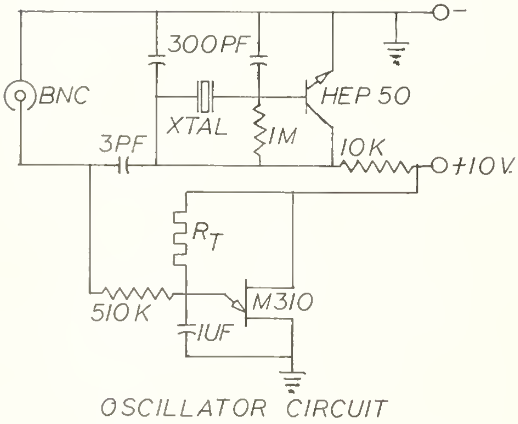
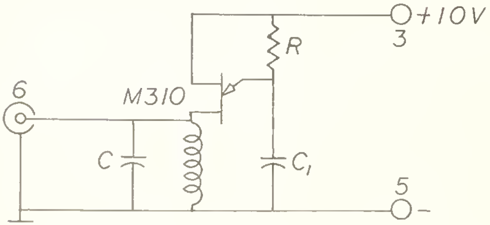


FIGURE 6. *Typical oscillator schematic diagram.*



S/N	C, PF	R, K-OHMS	C_1, UF
116A	180	9.97	.01
117A	932	4.86	.03
118A	330	10.09	.01

SPECIAL SERIES

FIGURE 7. *Special series oscillator schematic.*

7. Audit Problems (Instructions Accompanying Package)

1. *Caution.* Avoid rough or prolonged handling of the metal boxes—all internal components are temperature- and shock-sensitive to some degree. Some components can be damaged by application of excessive potentials or currents so that instruction should be followed exactly.

2. All serial numbers ending in "A" contain a complex signal source available at BNC connector, terminal #6, and a zener diode of nominal 6.8 Vdc breakdown between terminals #3(+) and #4(−). Note that terminals #5 is case ground.

a. ZENER DIODE PROBLEM. Avoid handling the metal boxes unnecessarily. Determine the voltage drop across terminals 3–4 when a specified current between 1 and 5 mA is made to flow through the diode in such a direction as to make terminal 3 positive. Using only components of the Electrical Measurement Console (EMC), devise a scheme for measurement.

Do not use a grounded current source and do not use terminal 5 for this test. Scheme must make it impossible to send a current through the diode or associated circuitry greater than 5 mA. Scheme must be approved by the auditor and all current and potential measurements must have an uncertainty less than 0.01 percent. Final report must detail the scheme used (schematic diagram) and include an error analysis to justify the 0.01 percent uncertainty. If the 0.01 percent uncertainty cannot be attained, a full explanation must be provided with a statement as to what uncertainty *can* be realized.

b. COMPLEX SIGNAL PROBLEM. Avoid unnecessary handling of the metal box. Apply 10 V dc to terminals 3(+) and 5(−) from a source which is current limited to 5 mA. Applied voltage must have a magnitude uncertainty less than 0.1 percent. A complex signal should now be found at BNC connector, terminal #6. No restrictions are placed on your choice of test equipment. Determine and record all parameters of the complex signal and document the method of test. Include an error analysis statement of estimated uncertainties.

3. All serial numbers ending in "B" contain the following:

a. Terminals 7–8, nominal 0.1 μF
b. Terminals 8–9, nominal 3500 Ω
c. Terminals 10–11–12, tapped toroidal inductor
d. Terminals 13–14, capacitor, greater than 1 μF
e. Terminals 16–17, nominal 1 μF
f. Terminals 11–15, thermistor, approximately 50 kΩ

Note that terminal #15 is case ground.

4. a. PHASE DEFECT PROBLEM. Using the Phase Standard, model 311, and the necessary ancillary equipment of your choice, drive terminals 7 and 9 with 10 V rms at 1 kHz and measure the phase angle of the output terminal 8 with reference to the input drive voltage. Now reverse the drive and again measure the output phase angle. It will be found that the sum of these two measured angles is slightly less than 90 degrees (if the experiment is correctly performed). This apparent "phase defect" is caused by an imperfect ca-

pacitor, i.e., one that has a dissipation factor greater than zero. From the phase angle "defect" noted, calculate the true dissipation factor of the capacitor, between terminals 7–8. Now, using the EMC Capacitance Bridge, model 707B, and AC Generator-Detector, model 861A, measure the same capacitor and compare results. Account for any disagreement in "D." Measure the resistance between terminals 8–9 and, using the measured capacitance between terminals 7–8, calculate the output phase angle relative to the input terminals 7–9 and account for any difference over the measured value obtained using the model 311.

b. CORE SATURATION PROBLEM. Using your choice of test equipment, devise a scheme for determining the maximum rms voltage that can be applied to the inductor terminals 10–12 before core saturation occurs. Express this maximum voltage (V, rms) as Kf where K is a constant (to be determined) and f is the applied frequency in hertz.

c. AC RATIO PROBLEM. Using only components of the EMC, devise a scheme to measure the turns ratio between terminals 11–12 compared to terminals 10–12. This should be done using a drive voltage and frequency as specified by the auditor. Determine also the phase angle between the voltage on terminals 11–12 as compared to the drive voltage on terminals 10–12.

d. THERMISTOR PROBLEM. Using the model 242 resistance-measuring system, make a two-terminal resistance measurement between terminals 8–15, using the minimum applied voltage needed to obtain a resistance measurement with a resolution of 0.1 percent. Note that terminal 15 is case grounded. Avoid handling the metal box unnecessarily. Record this measured value and the average room temperature near the metal box at the time. Note the excitation voltage applied to the system and calculate the voltage appearing across and the power dissipated in the unknown thermistor. Record all values.

Hint: It may be helpful to measure this resistor while it is protected from room temperature changes. To do so, form two 3-ft lengths of No. 22 AWG insulated copper wire (telephone wire) into a tightly twisted pair and guide it through the small hole in the right side of the carrying case so that the metal box (S/N XXX B) can be completely covered in its polyfoam-insulated container, with the cover closed during measurement. Connect the metal trim on the carrying case to ground to eliminate hand capacity effects. Now determine the voltage that must be applied to the test item to cause sufficient self-heating of the bead thermistor to change the measured resistance value by approximately 20 percent. Explain the result noted. Record all data.

e. CAPACITANCE AND DISSIPATION FACTOR PROBLEM. Using only the models 707B and 816A and any components found in S/N XXX B, devise a scheme to measure the capacitance and dissipation factor of the capacitor connected to terminals 13–14. Record all data used and have auditor check your results for accuracy. State expected accuracy to be obtained for both "C" and "D." The measurement is to be performed at 1 kHz, applying no more than 10 V rms to the 707B.

8. Deficiencies Observed—Action Taken

In a few cases, laboratory technicians had not attended Air Training Command school at Lowry Air Force Base in Colorado and thus were not thoroughly familiar with the Electrical Measurement Console. Certain areas of training had not been adequately covered so that many unusual field-measurement situations encountered could not be correctly diagnosed. With more than half of all reports received (80), the deficiencies can be noted as follows:

1. Temperatures not stated in degrees Celsius as requested.
2. Improper ANSI symbol usage.
3. Error analyses not understood.
4. Iron core saturation effects ignored.
5. Incorrect derivation of capacitance "D" factor.
6. Effects of loading on frequency and amplitude of complex signal generator not taken into account.
7. The terms "precision," "resolution," "accuracy," and "significant figure" not understood.
8. Lack of comprehension of signal source parameters.
9. Problems created by thermal or voltaic emfs, ground loops (common/normal mode) not recognized.
10. Need for independent measurement schemes for verification not appreciated.

Ignorance of the above areas can damage test equipment and reference standards and produce inaccurate or incomplete measurements. Corrective action has already been initiated. Controlled Multiple Address Letters (CMAL's) are sent out as required, the curriculum at Air Training Command is being modified to provide additional information in the above-noted areas, and technicians from the few PMEL's given limited certification are being given additional training at AGMC laboratories by Metrology Engineering Division Engineers.

9. Summary and Conclusions

The implementation of a new approach to metrology laboratory audits has reemphasized the importance of personnel in providing calibration support of aircraft and weapons systems. As Dr. J. L. Thomas once said, "You don't get six-dial measurements from a four-dial operator." The items described are sufficiently versatile so that completely different problems can be generated for subsequent tests. This can be accomplished either by interconnecting items differently or by actually changing readily available components.

A very high degree of interest and cooperation was observed at the audited laboratories and most were eager to solve all problems, rather than be limited to only four. The realizable advantages and goals may be stated:

1. Improves morale, stimulates original thinking.
2. Provides in-depth analysis.
3. Assists in yearly Posture Study.
4. Upgrades capabilities.
5. Allows augmentation of available reference material.
6. Enables meaningful revision of training programs.

NCSL 70

SESSION 5: NEW INTERNATIONAL DEVELOPMENTS

Chairman: C. E. White

General Radio Company, West Concord, Mass. 01781

NPL WORK ON THE DETERMINATION OF $2e/h$ BY THE AC JOSEPHSON EFFECT

B. W. Petley and K. Morris

Division of Quantum Metrology, National Physical Laboratory, Teddington, Middlesex, England

The a-c Josephson effect in superconductivity appears to be an exciting possibility for use as a quantum method of maintaining the volt as an SI unit, through the relations $2\ \mathrm{eV} = h\nu$. A potential-divider resistor was devised for precise comparison of a Wesson-cadmium cell with millivolt outputs from various solder-drop junctions excited at 36.8 GHz. The value found for $2\ e/h$ is $483.5941 \pm 0.0010\ \mathrm{MHz}/\mu\mathrm{V}_{69\mathrm{NPL}}$.

Key words: Inductive ratio divider; Josephson effect; NPL of UK; potential-divider resistor; quantum standard of voltage; solder-drop Josephson junctions; superconductivity.

1. Introduction

Part of the work of the Quantum Metrology Division at the NPL is devoted to measuring atomic constants and to deriving and maintaining the basic SI units. Already the units of length and time are based on quantum properties, and the ac Josephson effect in superconductivity [1, 2, 3][1] appears to be an exciting possibility for use as a quantum method of maintaining the volt. When microwaves of frequency ν are incident on the barrier between two weakly linked superconductors, supercurrent steps occur in the barrier-current-voltage characteristic which are separated by a potential difference V, given by $2\ \mathrm{eV} = h\nu$, where $h/2e$ is the superconducting magnetic flux quantum.

The initial objective of our work was the verification of the value obtained for $2\ e/h$ from the pioneering work [5, 6] at the University of Pennsylvania, to about the same level of precision. This paper describes some of the measurement techniques that have been employed in making the initial measurements.

2. The Basic Measurement Principle

As with most quantum units, the voltage available for measurement from the Josephson effect is much smaller than the maintained unit, being smaller by a factor of between 100 and 2000. The basic measurement problem, therefore, is that of comparing two very different potentials precisely. Further, although potentials of the order of a volt have been measurable to $0.2\ \mu\mathrm{V}$ for some time, there has not been nearly as much attention devoted towards measuring potentials at the millivolt level to parts in 10^7. It is preferable that, in the early stages at least, as many different methods as possible are explored by different groups of experimenters: agreement between two different methods will add considerably to the degree of confidence in either method.

Following the principles suggested by Dauphinee [7]. of minimizing the number of switches in the low-potential circuit, the comparison of the two potentials is achieved simply by using two resistors connected in series as in figure 1, and balancing the Josephson voltage across R_{ab} and the standard-cell emf by the voltage developed across R_{ac}. Unless the resistor ratio, microwave frequency, and supercurrent step number are particularly chosen, the current i_2 must be adjusted between

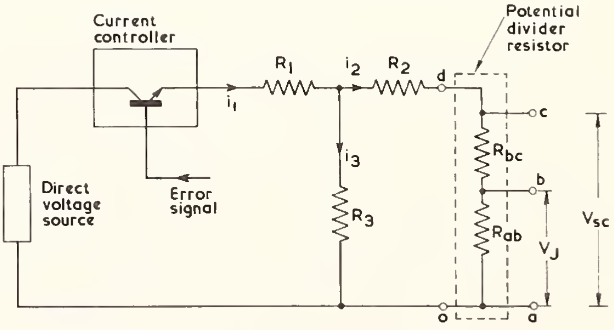


FIGURE 1. *Illustrating the principles of the potentiometer.*

---

[1] Figures in brackets indicate the literature references at the end of this paper.

the two balances; moreover the two currents must be known precisely in relation to one another. Considerations of the precision with which the resistance ratio could be measured led to the conclusion that the resistance R_{ac} should be about 500 Ω. which, at the time that measurements commenced, ruled out the current-comparator potentiometer [10] as the precisely variable current source. The basic methods of obtaining the variable current i_2 were either to maintain i_1 constant and vary R_2 and R_3, as in the Julie ([8, 9] inverted Kelvin-Varley-divider method used by the Pennsylvania group, [4, 5, 6] or to keep i_1 approximately constant and vary R_2, deriving a feedback error signal to the current controller such that the potential difference i_2R_2 exactly equals a standard-cell voltage. This error signal is readily available if the galvanometer-amplifier type of current controller is employed. The Tinsley-Stabaumatic potentiometer [11] which uses this principle was modified to suit our experiment, an important modification being the potential- divider resistor, *oabcd,* of figure 2. This resistor was located outside the potentiometer and was constructed at the NPL.

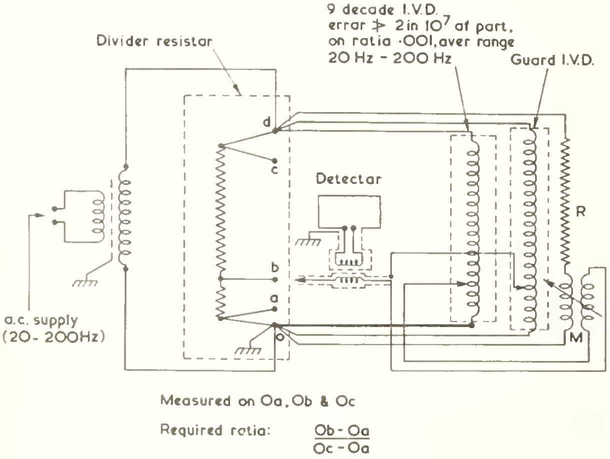


FIGURE 2. *Circuit arrangement used to calibrate the divider resistor.*

3. Potentiometry

The Josephson junction is a very broadband device [2] the frequency response extending from dc to the infrared, while the nonlinear behavior at the junction allows the mixing of any frequencies within this range A major problem in any experiment involving small potentials is always the elimination of potentials generated by pickup and ground loops. These are particularly difficult to overcome when more than one item of equipment is connected to the power lines. It was decided as a matter of principle to keep all leads and apparatus using alternating current more than 3 meters from the potentiometers and cryostat and to use only galvanometers and galvanometer amplifiers for detecting balance conditions.

3.1. The Voltage and Current Source

The voltage source in figure 1, and the source for the junction bias current, were both supplied by lead-acid batteries. These were charged overnight by electronic battery chargers to be at the beginning of their discharge plateau. During the day their emf was constant to a few millivolts.

3.2. Current Controllers and Galvanometer Amplifiers

There are two ways in which galvanometer amplifiers and associated current controllers may introduce alternating currents when used for sub-ppm precision measurements, even though they are screened from alternating magnetic fields. The first way arises if the galvanometer bulb is energized by an alternating current. The light falling on the photocells is modulated at the second-harmonic of the power frequency, thus introducing an alternating signal in the feedback loop which then appears on the current-controller output. This problem was avoided by energizing the galvanometer bulbs with direct current. The second way arises from any vibration of the galvanometer spot, for such vibration induces an alternating signal in the photocell output which again results in an alternating current at the output of the current controller. (The effect of the feedback loop is to increase the frequency response of the galvanometer to a few tens of hertz.) All galvanometer amplifiers were mounted on concrete blocks which were in good mechanical contact with the floor. Fortunately the site of our experiment was below ground level and known to be free from vibrations. The possibility of resonances from acoustic pickup effects was also checked.

3.3. The Potentiometer

The essence of this type of potentiometer is that a standard cell is used in the feedback loop of a servosystem. Since the gain of the system is about 2×10^4, the standard cell would supply current if the system was not supplying nearly the correct current throughout the balancing operation (which R_2 was switched). Three control standard cells were employed, being switched into operation in sequence as balance conditions were approached. The final balancing cell was thereby protected from any switching surges and current drain. The emf of this cell was merely required to be stable while the Josephson and main standard-cell voltages were intercompared. There was, in fact, a slow drift throughout the day as room temperature changes penetrated the heavy thermal lagging of the cell. This drift was useful since it meant that the positions of the switches varied from one set of balances to another and, by making measurements on different step-numbers, the whole of the potentiometer entered into the measurements.

The Stabaumatic potentiometer and its associated current controller are designed to supply up to 20 mA, and a good quality resistor was connected across *od* so that the combined resistance of it and the divider resistor was about 50 Ω. Possible nonlinearities in the current division between the two resistors were eliminated by an *in situ* ac calibration across the potential tappings, using a Guildline current-comparator potentiometer[10]. Corrections to the Stabaumatic-potentiometer dial readings were calculated and applied as part of a computer program for evaluating the $2e/h$ values. All switches in critical parts of the circuit, including the potentiometer dial switches, were rotated 20 times from zero to full scale before commencing measurements.

4. The Divider Resistor

This resistor was designed and constructed in the NPL and was measured by an ac measurement technique.

4.1. Design

Measurements were made over a range of supercurrent steps in the junction current-voltage characteristic and so the ratio of the divider was chosen to be 1,000 : 1. Techniques for measuring such ratios by an ac method [13] had recently become available in the NPL and it was expected that an overall measurement precision of better than a part in a million could be achieved on our ratio [14]. The inherent experimental difficulty of ensuring that the ac and dc values of the ratio were the same had already been solved by members of the NPL Electrical Science Division [15]. Our divider was designed and constructed by T. A. Deacon and M. John Swan respectively. The divider resistor was constructed from two types of Evanohm wire for the 500– and 0.5–Ω portions and thus behaved as two separate resistors as far as aging and temperature coefficient of the divider ratio were concerned. All current and potential connections were welded to the resistor, and the resistors were of bifilar construction, wound on a silicon glass laminate former, and mounted to be at least 5 cm from the brass container. The terminations were brought as close together as possible to reduce temperature differentials that might have an effect on dc.

Although most "dc" measurements are effectively made at frequencies between 0.01 and 0.5 Hz, the region between these frequencies and, say, 10 Hz is that in which changes due to Peltier and other effects are most likely to occur if the resistor is not sufficiently well designed. The design priority was given to ensuring that the ac and dc values were the same and to make the ratio independent of ac frequency, range 10 to 120 Hz. These objectives were satisfied in the completed divider.

4.2. Measurement

The equipment that was used for measuring the divider ratio is illustrated in figure 2. Both the divider resistor and the 9–decade inductive ratio divider were energized from the same transformer secondary winding and the voltage across the appropriate divider terminals was balanced against that developed by the inductive ratio divider. The resistance R and mutual inductor M were used to inject a small signal into the detector to balance the quadrature component.

The inductive divider transformer had an error of less than 2 parts in 10^7 of the output at the 0.001 tap over the frequency range 20 to 200 Hz [14]. The transformer used to isolate the detector was double-screened; the secondary screen and the detector were grounded. The primary screen was connected to the guard transformer divider. The guard voltage was set to better than a part in a million, although no effects were apparent when the guard voltage was offset by parts in 10^4.

The ratio of the divider was obtained from three measurements. In principle, of course, only two measurements are required but the grounding arrangements used for our initial work made it necessary to include the resistance of the current tail oa in the measurements of the divider ratio.

4.3. Performance

The divider ratio was measured over the frequency range 20 to 120 Hz, and no frequency-dependent variations of the ratio were observed. (If present, such effects would generally vary linearly and/or quadratically with frequency.) A change in the voltage applied to the divider from 1 V to 10 V did not change the ratio by as much as 2 parts in 10^7. In making the error assignments to the measured values of $2e/h$ it was considered that the divider ratio was known to a standard deviation of 0.5 ppm and that the ac value represented the dc value to 0.5 ppm.

The divider was put into service shortly after construction and hence aged initially by several ppm before it settled to a slower linear drift with time. Measurements of the divider ratio have been continued and the values obtained are within 0.5 ppm of the extrapolation of the curve fitted through the calibration points pertaining at the time of the $2e/h$ measurements.

5. Measurements

The apparatus, measurements, and errors have been described in greater detail elsewhere [16, 17].

5.1. The Junction

The solder-drop type of Josephson junction was used for the initial work, and so enabled the use of a normal liquid-helium storage dewar for the cryostat. This simplification had a number of advantages: for example, the thermal emf's in the dewar were very stable, and there were no liquid helium transfer problems since one filling lasted for over a week. Junctions have been transferred from one storage dewar to another over a period of six months and from one site to another.

The solder-drop type of junction is made by forming a drop of solder $\sim$ 1 mm diam, around a length of thinly oxidized niobium wire $\sim$ 0.15 mm diam. Two copper leads are then embedded in the solder-drop and these, together with the ends of the niobium wire, form a convenient four-terminal device. When the room-temperature resistance of the "dry-joint" formed between the solder and the niobium wire is about an ohm, the yield of junctions showing Josephson effects when the device is cooled to liquid helium temperature is, with practice, around 50 percent. It is, incidentally, rather harder to produce a "dry joint" of about 1–Ω resistance than it is to make a well-soldered joint.

In general, solder-drop junctions show characteristics of the weak-link type—that is, there is probably a very fine link of superconductor joining the niobium wire and the solder-drop. Such junctions are characterized by greater nonlinearities at the junction, although the supercurrent steps still appear at the appropriate potentials V, governed by $2eV = nh\nu$, where $h/2e$ is the superconducting magnetic flux quantum, n is an integer, and ν the applied microwave frequency. As a result of the non-linearities at the barrier in the weak-link type of junction, steps may also appear at values of n corresponding to the ratio of two integers, for example, for $n = 3/2, 5/2, 7/2$, etc. Such subharmonic steps are clearly visible in the solder-drop junction characteristic illustrated in figure 3. This characteristic was obtained with an X–X pen recorder.

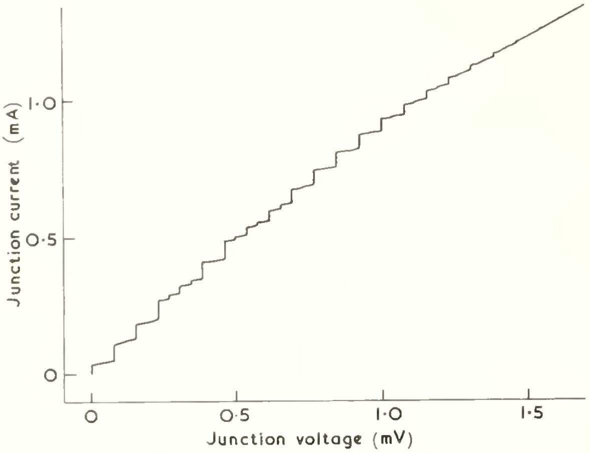


FIGURE 3. *Example of a solder-drop current-voltage characteristic when 36.8 GHz microwaves are incident on it.*
Note the subharmonic supercurrent steps.

5.2. Measurements

The measurements of $2e/h$ were made using a 36.8-GHz phase-locked klystron as the microwave source. Measurements were made at lock-points on either side of the reference-crystal harmonic, at different step numbers and using different solder-alloys for the construction of the junctions. The measuring sequence was as follows: Standard cell balance, junction balance, all currents reversed, followed by a second set of balances of the junction and standard-cell potentials. The temperature-controlled standard cells were calibrated by J. J. Denton against the NPL volts each day at the beginning and end of the $2e/h$ measurements.

5.3. Thermal Emf's

Thermal emf's are an important source of error in any dc measurement and are particularly so in $2e/h$ measurements, where the potentials are at the millivolt level. The procedure discussed above of reversing the currents was designed to eliminate the thermal emf's but it is, of course, rather reassuring if the procedure can be shown to eliminate them. Fortunately in this respect, during part of our experiment the thermal emf's increased to around 2 μV instead of the usual 100 nV (apparently resulting from a strain effect in the copper leads into the cryostat). It was found that the $2e/h$-values obtained with the high thermal emf were 0.8 ± 1.1 ppm greater than the low thermal values. The difference was not statistically significant but a standard deviation of 1 ppm was assigned to the elimination of the thermal emf's.

5.4. Ground Loop Effects

Ground loop effects are also a problem in the measurement of low dc potentials. These were avoided by ensuring that as far as possible, all low potential connections were copper to copper, and that the connections were oil immersed. The effects of ac pickup were reduced by operating all equipment within 3 m of the cryostat and potentiometer, from dc sources that were themselves well screened. After rearranging leads and modifying earthing arrangements while set on a supercurrent step, it was concluded that ground loop and pickup effects could not have affected the $2e/h$ values by as much as 0.5 ppm, and this was assigned as the possible error from these effects.

6. Results

Our results and discussion of the other sources of error have been discussed in detail in our Metrologia article [17] and this discussion is not repeated here. Figure 4 illustrates the values obtained for $2e/h$, with standard deviations, for solder-drop junctions constructed from different solder-alloys. Fitting a least squares line through the points indicates that the values for pure tin solders could be greater than those for pure lead solders by 3 ± 5 ppm. This difference is, of course, not statistically significant.

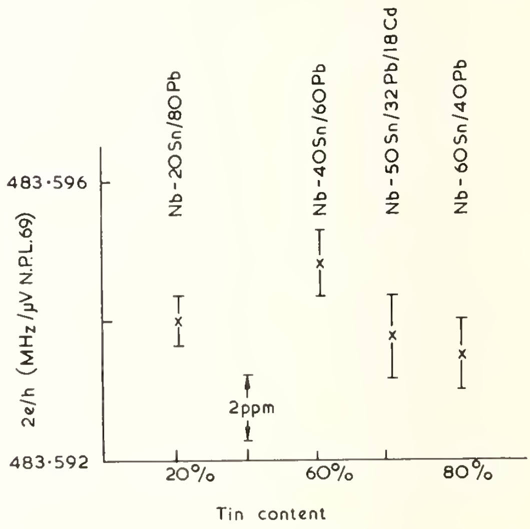


FIGURE 4. *The values obtained for* 2e/h *with solder-drop junctions using different solder alloys.*

The final value for $2e/h$ from these measurements is

483.5941 ± 0.0010 (2.2 in 10^6) MHz/$\mu V_{69\ \mathrm{NPL}}$.

The expression of our result in terms of the NBS volt cannot properly be made before the results of the 1970

BIPM International Volt comparisons are available. On the basis of the 1967 comparison, our values and those of the University of Pennsylvania [6, 18, 19] are unlikely to differ by more than about 0.5 ppm.

Already, the inadequacies of the Weston-cadmium cell as a method of maintaining the volt are becoming apparent in the Josephson effect. The precisions of the $2e/h$ measurements are well beyond the precision with which the volt is known absolutely [20] ($\backsim$ 2.7 ppm) and measurements are improving monthly. It appears likely that within a year or so sufficient agreement between National Laboratories may be achieved for the whole of the experimental error to be attributed to the maintenance of the volt by the Weston-cadmium cell. At this stage it will be possible to maintain the volt by the Josephson effect. Beyond that, there lies the possibility that the Josephson effect might ultimately lead to a redefinition of one of the SI units.

This work forms part of the research program of the National Physical Laboratory.

7. References

[1] Josephson, B. D., Phys. Letters **1**, 251 (1962); Rev. Mod. Phys. **36**, 216 (1964); Adv. in Phys. **14**, 419 (1965).

[2] Anderson, P. W., Progress in Low Temperature Physics, **5**, p. 1, Ed. C. J. Gorter (North Holland Publ. Co., Amsterdam, The Netherlands, 1967).

[3] Petley, B. W., Contemporary Phys. **10**, 139 (1969).

[4] Taylor, B. N., Parker, W. H., Langenberg, D. N., and Denenstein, A. D., Metrologia **3**, 89 (1967).

[5] Parker, W. H., Taylor, B. N., and Langenberg, D. N., Phys. Rev. Letters **18**, 287 (1967).

[6] Parker, W. H., Langenberg, D. N., Denenstein, A., and Taylor, B. N., Phys. Rev. **177**, 639 (1969).

[7] Dauphinee, T. M., IEEE International Convention Record (1965).

[8] Julie, L., IEEE Trans. Instr. Meas. **IM–16**, 187 (1967).

[9] Abramowitz, A., Rev. Sci. Instr. **38**, 898 (1967).

[10] MacMartin, M. P., and Kusters, N.L., IEEE Trans. Instr. Meas. **IM–17**, 263 (1968).

[11] Gall, M. H. W., Acta Imeko, **II**, UK–237, Ed. E. Nika and J. Scott (Hungarian Scientific Society for Measurement and Automation, 1967).

[12] Taylor, B. N., J. Appl. Phys. **39**, 2490 (1968).

[13] Hill, J. J., Proc. IEE **112**, 211 (1965).

[14] Deacon, T. A., Proc. IEE **117**, 634 (1970).

[15] Wilkins, F. J., and Swan, M. J., Proc. IEE **117**, 841 (1970).

[16] Petley, B. W., and Morris, K., Phys. Letters **29A**, 289 (1969).

[17] Petley, B. W., and Morris, K., Metrologia **6**, No. 2 (1970).

[18] Denenstein, A., Finnigan, T. F., Langenberg, D. N., Parker, W. H., and Taylor, B. N. (to be published 1970).

[19] Finnigan, T. F., Denenstein, A., and Langenberg, D. N., Phys. Rev. Letters **24**, 738 (1970).

[20] Taylor, B. N., Parker, W. H., and Langenberg, D. N., Rev. Mod. Phys. **41**, 375 (1969).

NCSL 70

THE IMPACT OF ADVANCED ELECTRONIC TECHNOLOGY ON MEASUREMENTS

Richard F. Clark

Radio and Electrical Engineering Division, National Research Council, Ottawa, Canada

Advances in electronic technology have made possible significant improvements in both accuracy and precision of measurements. Some comments will be made on the increase in accuracy through automatic application of data corrections (which were previously too difficult to be practicable) and the elimination of many "human" errors. Better precision coming from increased speed of measurement and improved control of the environment of the measurement will be discussed.

Key words: Attenuation measurement; automatic data correction; auxiliary receiver for microwave measurements; dual admittance Woods bridge; Engen microcalorimeter; rf coaxial impedance standards.

1. Introduction

Advances in electronic technology have made possible substantial improvement of both accuracy and precision through better control of the total environment of a measurement. In particular, reduction of human involvement and automatic application of corrections to data have increased accuracy, while shorter measurement times and automation of manually operated instruments have given us greater precision.

2. "Human" Errors

The experimenter's human characteristics have traditionally set limits on precision and accuracy of a measurement. In addition to basic defects in precision sensing, memory, physical stability, speed, and durability, his greatest asset—intelligence—makes him unable to perform reliably and consistently a simple task without frequent error. Now, there has begun a tremendous upsurge in the use of computers to replace man in the rapid performance of simple tasks.

The man in charge of a calibration can now have an unintelligent machine of incredible speed and great reliability to replace an intelligent technician. Doubtless, in the early stages of such a development, great effort is necessary on the part of the supervisor if he is to communicate with this unintelligent beast in its strange language. However, such extra effort will pay for itself in the insight gained into the calibration procedure. Perhaps a better and more basic measurement will result.

The whole aspect of standard calibration procedures can be improved by the sharing of computer programs by different laboratories. As programs are modified and become accepted by the different laboratories, many of our calibrations will be performed by a truly standardized procedure.

3. Data Corrections

One of the principal uses of computer involvement in a calibration laboratory is for the automatic application of data corrections. In January of 1950, D. Woods [1][1] gave a complete description of a dual-admittance bridge to be used for measurement of shunt capacitance from —50 to +50 pF and shunt conductance of 50 mmho or less in the frequency range 3 to 300 MHz. The excellent 0.1 percent accuracy of conductance measurement and 0.2 percent accuracy of complex admittance were made possible by painstaking care in assessment of all sources of error in the bridge. Many of the errors were made negligible by careful mechanical and electrical design and the use of external calibration standards. The considerable number of errors remaining were corrected for by the use of a prepared calculation table which guided the worker through the steps for the corrections. With the help of this table and an electric calculating machine, the results for a set of six measurements at one frequency could be obtained in two hours time.

This illustrates what was once a basic philosophy of a standards laboratory—time is not a major consideration. If you imagine the addition of automatic readout and computer application of corrections for the Woods bridge, you could further improve accuracy by performing more measurements using external standards with no need to improve the bridge itself. As is the case with the automatic measurement system described by Adam [2], the ultimate limitations on accuracy would be set by the repeatability of the bridge and the characteristics of the external standards and their connection to the bridge.

There is another factor to be considered in respect

---

[1] Figures in brackets indicate the literature references at the end of this paper.

to the use of automatic data corrections. A measurement technique which would be quite impractical and tedious for manual operation might be chosen because of its mechanical simplicity or the criterion of greater accuracy. An example of this is the technique for coaxial impedance measurement described by Jurkus [3]. This system has been used to calibrate coaxial terminations in 14-mm precision coaxial transmission line at about 100 frequencies per octave over the frequency range 1 to 8 GHz. It is a semiautomatic system using a fixed probe in the transmission line and makes full use of the computer for analysis of the data including corrections for source mismatch and loss in the reference air lines used as impedance standards.

4. Improved Precision

The time required to perform a measurement automatically is usually dramatically less than required for a manual one. Thus, statistical control of the measurement becomes a distinct possibility because large numbers of measurements may be performed within a reasonable time. Also, precision should improve, since the magnitude of certain parameters, especially those affected by temperature, will be more constant over a short period of time than over a long period.

The instrument makers, realizing that the human being is becoming less involved in the measurement process, are rapidly converting their instruments. The attention to and compensation for the defects of man are being replaced by a similar concern for the vagaries of the computer. Man, however, can benefit from some items such as programmable sources, meters with digital readout, or meters with an automatic zero adjustment. We have benefitted in our laboratory from an automatic zero adjustment on a thermistor bridge used to operate a thermistor mount for rf power measurement. This benefit arose in connection with the insertion loss measurement of a 20-dB fixed waveguide attenuator of the multihole directional coupler type and used as an interlaboratory transfer standard of attenuation at a frequency of 10 GHz.

As is sometimes the case in a standards laboratory, the stable microwave source and the precision microwave receiver which form part of the environment for our best attenuation measurements achieve, in part, their stability from their massive size. This size can make the insertion and removal of the attenuator difficult and time-consuming because of the severe requirements on alinement and positioning of the connecting flanges. Larson [4] has suggested modification of the attenuator so that the input and output parts are in line and have the same axis. This will reduce the required relative motion of the source and receiver, especially when a piece of waveguide having the same length as the attenuator is used to replace the attenuator and a differential insertion loss measurement is performed.

It is possible, however, to use a small auxiliary receiver as shown in figure 1. The auxiliary receiver is a thermistor mount and a tuner, and is light enough to be supported by the flange to which it is connected. The change in output power from the rf source required to maintain a level of 0.4 mW into the thermistor mount with the attenuator inserted or removed was measured by the precision receiver. The rf source output was reduced to zero and the power meter automatically zeroed by depressing a front panel switch immediately prior to each measurement. The standard deviation of the mean of 10 measurements on a 20–dB attenuator was 0.0003 dB, which is about an order better than we could obtain with an instrument having a manual zero, used in our air-conditioned laboratory at the level of 0.4 mW.

5. Role of the Standards Laboratory

Ultimately a computer-assisted measurement system will outperform a manual system to such an extent that the standards laboratories will be forced to participate fully in the revolution. For the present, the standards laboratory will be faced with the need for calibration of the standards which are used as references in the automatic system. The calibration accuracy probably need not be improved, but the range of the calibration will need to be increased as reliance placed on the instrument is shifted to the standards. I would like to end this paper with a few words about two particular rf standards which require calibration with the presently available accuracy but at many more frequencies so that the parameters of the standard are well known throughout its frequency range.

An ideal working or transfer standard for rf coaxial impedance measurement is the coaxial resistive termination. It is simple, rugged, stable, and covers a large frequency range. This is in contrast with quarter-wavelength coaxial air lines, which are very narrow

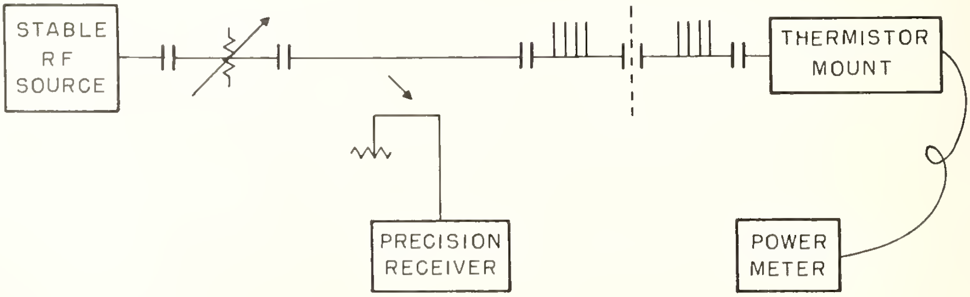


FIGURE 1. *Measurement of insertion loss with a thermistor mount and power meter combination used as an auxiliary receiver.*

band, and coaxial sliding loads in precision air lines, which tend to be expensive and somewhat limited in frequency coverage. The calibration technique of Jurkus [3], mentioned above, provides a sufficient number of calibration frequencies so that the calibrated coaxial termination may be used at any frequency from 1 to 8 GHz with the aid of linear interpolation of the data. For the "non-automated" who still measure impedance at one frequency with a slotted line having mechanical drive and X-Y recorder for readout, these calibrated terminations can provide a quick, accurate check of residual VSWR of the slotted line, again at the frequency of measurement.

The second rf standard which needs calibration at a great number of frequencies is the thermistor mount which is used as a transfer standard of power. The ideal calibration environment for accurate measurement, at several frequencies of the effective efficiency η of a thermistor mount, is the Engen microcalorimeter [5], since this calorimeter has a high-order sensitivity to $(1 - \eta)$ and a low-order sensitivity to mismatch error. We have used a calorimeter based on the Engen design to measure the effective efficiency of X-band and Ku-Band thermistor mounts at a sufficient number of calibration frequencies to permit linear interpolation (see fig. 2). The calibration time was lengthy, however, and we are currently constructing an X-band calorimeter of modified design with a view towards reduction of the time involved.

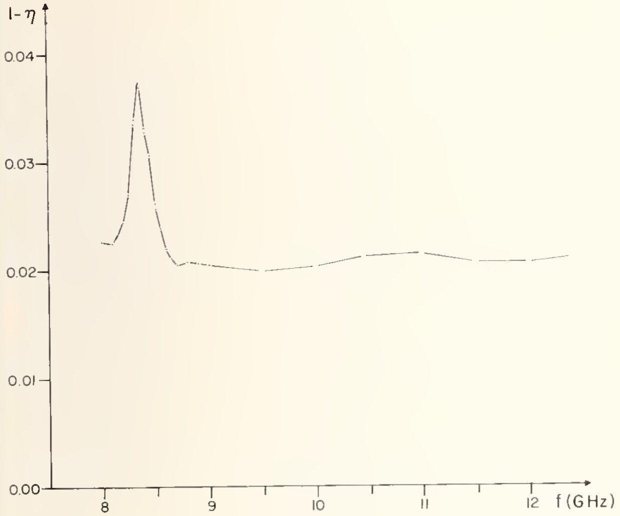
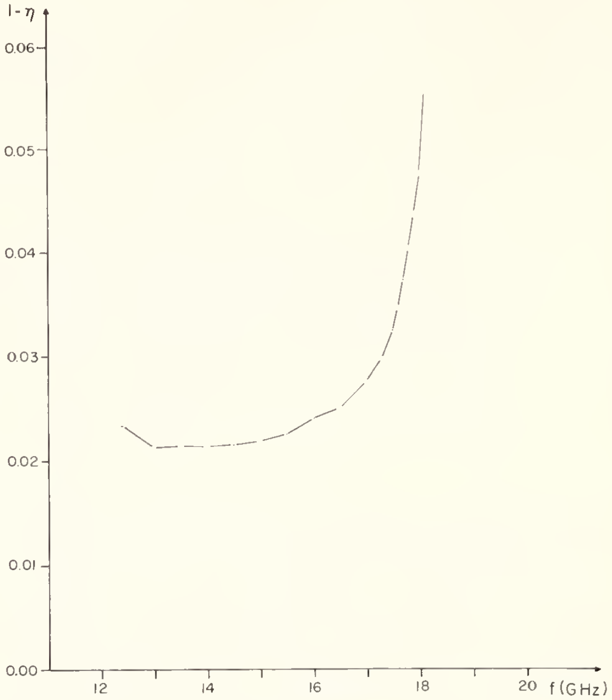


FIGURE 2. *Effective efficiency (η) of (a) an X-band waveguide thermistor mount; (b) a Ku-band waveguide thermistor mount.*



6. References

[1] Woods, D., A precision V. H. F. twin-T dual admittance bridge and associated standards (unpublished report, Ministry of Supply, London, England, Jan. 1950).

[2] Adam, Stephen F., A new precision automatic microwave measurement system, IEEE Trans, Instr. Mear. **IM–17**, 308–313 (Dec. 1968).

[3] Jurkus, Algirdas, A semi-automatic method for precision measurement of microwave impedance, IEEE Trans. Instr. Meas. **IM–18**, 283–389 (Dec. 1969).

[4] Larson, Wilbur, Inline waveguide attenuator, IEEE Trans. Microwave Theory Tech. **MTT–12**, 367–368 (May 1964).

[5] Engen, Glen F., A refined x-band microwave microcalorimeter, J. Res. Nat. Bur. Stand. (U.S.), **63C** (Eng. and Instr.), No. 3, 77–82 (July–Sept. 1959).

NCSL 70

DESIGN AND DEVELOPMENT THROUGH METROLOGY

Prem Prakash

National Physical Laboratory, New Delhi, India

The National Physical Laboratory of India, in implementing the 1956 Standards of Weights and Measures Act, adjusted and calibrated mass standards of 50 to 10^{-6} kg for 250 State Laboratories. Most of the 5000 balances needed by Inspectors were designed and fabricated by four commercial manufacturers in India, with specifications, technician training, and performance testing supplied by NPL. With this experience, two manufacturers designed and fabricated the higher precision balances for District-level laboratories. The technique is recommended to developing countries faced with similar projects.

Key words: Designing to specification; fabrication of balances; legal metrology; mass standards; NPL of India.

1. Legal Metrology in India

The Standards of Weights and Measures Act was passed in 1956 and thus, after many centuries, India once again had a uniform system of measurement throughout the country. The establishment of the standards of weights and measures was made the responsibility of the Central Government, whereas the enforcement of various provisions of the Law was made the responsibility of all the State governments.

To organize the enforcement machinery simultaneously in about 25 States and Union Territories was no simple matter, particularly because industry in the country was still in a developing stage. With proper planning and phasing of an implementation program, it became possible to procure most of the required equipment from local sources only.

At about this time, through a happy coincidence, the Weights and Measures Division of the National Physical Laboratory of India had been expanded in a big way by equipping it with a number of important measuring instruments and other important items of equipment. Most of these were obtained through the courtesy of the Technical Cooperation Mission of the United States of America under Agreement No. 26. The Laboratory was, therefore, in a position to take up all technical work relating to the implementation of the 1956 Act and was, in fact, associated from the beginning with the Central Ministry concerned and all the State departments.

The NPL's first assignment was to help in drafting the 1956 Act. The next important assignment was to work out the shapes and dimensions of various grades of standards (reference, secondary, and working), as well as commercial grades of new weights (requiring some four grades), length measures, and volume measures. One of the chief requirements for all the new weights and measures was that these should possess distinctly different shapes from all those already in use in the country. The third important assignment for the Laboratory was to recommend suitable limits of permissible errors for all categories of weights and measures, from reference standard grade down to the coarsest commercial grade. The fourth assignment was to prepare about two dozen demonstration sets of metric weights and measures, in accordance with the new shapes and dimensions, for exhibition in different States and Union Territories. This was done with a view to familiarizing the general public and the manufacturers with the new standards. Also manufacturers were given all necessary help to enable them to go ahead with the manufacture of the standards. All this work took a couple of years after the enactment of the new law.

Another important assignment for the Laboratory was to provide necessary training in high-precision tests and measurements to senior officers and to the Inspectors of Weights and Measures responsible for enforcement work in the States. This work is of a continuing nature and has been going on intermittently all these years. About 600 officers have already received this training.

2. Balances for the Enforcement Laboratories

The question of equipping the State Enforcement Laboratories was looked into along with other jobs. It was estimated that about 250 laboratories with about 1000 Inspectors of Weights and Measures would be required for effective enforcement of the Act. These laboratories were to be provided immediately with all necessary standards, measuring equipment, and balances for the verification of commercial-grade weights from 50 kg down to a milligram. It was decided that the weights would be manufactured by the India Government Mint. The assignment given to the Laboratory in connection with these standards was to adjust and calibrate them and to issue certificates for each item individually before they were supplied to the State departments.

Then came the question of providing some 5000 balances to these State laboratories. The possibility of importing these was ruled out, as this required a foreign exchange of about 25 million rupees. To make a quick start, however, it was considered necessary to import about 1000 balances. The purchase of the remaining balances was deferred with a view to trying to get these manufactured in our country. A committee, with the author of this paper as the convener, was set up in 1958 to look into the possibilities of getting the required type of balances made in India.

Taking all the relevant factors into consideration, the committee decided that a set of balances should consist of 50-kg, 5-kg, 200-g, and 2-g capacity balances. Broad specifications drawn up for these balances are given in table 1. Two types of balances were required:

(i) *Indoor-type balances,* to be permanently set up in the laboratories. All four balances in the set were required to be provided with the usual type of glass case.

Table 1

Capacity	Sensitivity Reciprocal	Approx. Beam Length	Work Load on each Balance (Nos. of Denom.)
	mg/div.		
50 kg	100	About 750 mm	3
5 kg	10	250–300 mm	4
200 g	1	150–200 mm	6
2 g	0.02	120–150 mm	11

(ii) *Portable balances*, for outdoor use. These should be easily dismantled and secured in their carrying cases. They should be sufficiently robust to remain undamaged even when the packages were transported over rough roads. They should be easily set up at camp laboratories. The 50-kg balance was not to be provided with the usual type of supporting pillar but with a sufficiently rigid foldable tripod stand for suspending the balance. No glass case was required for this balance.

After laying down these specifications, the project was entrusted to the author, to be tackled by the Laboratory in the manner considered best. Advantage was taken of earlier experience regarding Indian balances. The laboratory had had occasion to examine a few locally manufactured chemical balances some years earlier. (Small-scale production of such balances had been going on in the country from the beginning of this century.) On testing these balances it was found that, though these were all right for college purposes, they lacked many characteristics needed for precision work. Letters were then sent to the leading manufacturers telling them that the Laboratory would be able to suggest improvements in the quality of their balances provided they sent them to us for close and critical examination. Those manufacturers who responded to our offer did benefit by our advice, and their balances were subsequently considered superior to those of others. Our general finding was that, although the manufacturers had some of the finest craftsmen on their staffs, proper technical guidance was sometimes lacking.

The representatives of these manufacturers were trained in making good-quality knife edges and bearing planes for precision balances, as well as in carrying out various performance tests on these. They were asked to give complete tests to the balances before sending them to us. Based on our earlier experience with local balances we asked them to take special care with respect to

1. choice of proper material for the construction of knife edges and bearing planes; proper hardening of the knife edges where steel was used.
2. accurate lapping, correct positioning, and rigid mounting of the planes and knife-edges.
3. adequate rigidity of the beam, so that there was not much variation with load in the sensitivity of the balance.

The procedure planned was that the manufacturers were to fabricate sample balances to the best of their ability and submit the same to the Laboratory for critical examination. This would enable us to locate any defects. Necessary advice would then be given for the elimination of these defects in their subsequent attempts. This process would continue until their balances came up to the required standard.

Within a few months the manufacturers were able to work out details of their designs, fabricate the balances, and submit their first models for test. Detailed examination of these balances was carried out with a view to discovering any design or constructional defects, such as in overall workmanship, rigidity of the fixing arrangements for the planes and knife edges, and the proper positioning of these. The following tests were carried out:

1. Determination of sensitivity and period of swing under (i) no load, (ii) half load, and (iii) full load conditions.
2. Consistency of performance, i.e., the effect of releasing, arresting, and re-releasing the beam a number of times, and noting down the rest point. Some 20 observations were made in succession.
3. Accuracy of weighing. Rigidity of the beam, proper hardness, and accuracy of the lapping of the knife edges, etc., were inferred from the results of test.
4. Determination of the relative lengths of the arms.
5. Stability of rest point over a long period of time (at least two to three weeks) and under varying conditions of temperature.
6. Uniformity of the rider scale, if provided.

The results of this experiment were very encouraging, as some manufacturers were successful in the very first attempt to produce nearly the required quality of instrument. Representatives of the manufacturers were advised to be present during tests. They were given necessary instructions for further improving the performance of their balances. They then produced their second models, which were an improvement over the first ones. The whole process of testing and giving instructions to the manufacturers was repeated, and they were asked to prepare yet another model. This continued until they were able to produce the desired quality. Out of the six manufacturers who participated in the project, two gave up after making two or three unsuccessful attempts. Of the remaining four, three succeeded in producing the desired quality after making three or four attempts. This was within a year and a half of starting the project. The fourth manufacturer took somewhat longer, but he too qualified after making a few more attempts.

These four manufacturers met the entire demand anticipated for balances for the State enforcement laboratories within the next three years or so.

3. Higher Precision Balances

As the enforcement laboratories became more advanced in their work, they required more sophisticated items of equipment. They now required balances with higher accuracy and sensitivity which would be suitable for the periodical verification of working standard weights against the secondary standards. These balances were to be installed at the District-level laboratories. Taking into account the permissible errors on working standard weights, it was decided to have five balances in the set, with broad specifications as shown in table 2.

These specifications were sent to the four manufacturers who had been successful in producing balances for the use of Inspectors. They were asked if they were willing to follow the same old procedure for producing the more precise type of balance. Two manufacturers who possessed the experience of manufacturing a larger of number of balances than the other two, and had consequently gained more confidence, agreed to take up the development of these balances.

The same procedure was followed, and within one year these balances also were successfully produced by both manufacturers. Production is in full swing now, and some 60 sets have already been produced and supplied to different States.

Table 2

Capacity	Sensitivity Reciprocal	Minimum Scale Division	Approx. Beam Length	Approx. Width Across Pans	Approx. Clearance Above Pans
	mg/div.	*mm*	*mm*	*mm*	*mm*
20 kg	25	2	750	300	700
5 kg	7.5	1.5	350	175	325
1 kg	1.5	1.0	250	135	225
50 g	0.4	1.0	125	60	100
2 g	0.02	0.75	110	50	70

Within the next year or so, work in connection with balances of still higher precision will be undertaken. These balances, which will be installed at the State Headquarters Laboratories only, will be employed for the periodical verification of the secondary standard weights against the reference standards. Specifications for these balances will be considerably more rigid than those for the two types already produced. These balances will be required to be fitted with an optical lever system for increasing their sensitivity. The accuracy requirements, as well as the minimum requirements for the equality of arms, will also be prescribed. Making of these balances will be a somewhat tougher job. However, with the confidence the two manufacturers have now gained, they should be able to make these.

4. About the Method

The method which a research laboratory would have adopted in such a situation would be to put a large number of designers on the job, get the trial models made, and put these to practical tests. Depending on the results of tests, the designs might require further modification. After incorporating all the desired requirements in the finalized design, a prototype would be constructed to hand over to the industry. It was realized that, with the resources at our disposal, or for that matter at the disposal of any medium-sized laboratory, and to work simultaneously in many varied fields, it might not be possible to put a large team of designers and mechanics on any single project. It was estimated that if we adopted this method it would require at least five years to produce any tangible results.

Circumstances compelled us to think of an inexpensive method which would give the desired results within a short time, preferably a year or so, because the implementation program could not wait five years. The method followed by us as described above has certainly been efficacious. Essentially, the detailed design work is done by the manufacturers, with necessary guidance provided to them from time to time on the basis of tests and precise measurements on their product by the collaborating research institute. This method has proved its merits on two occasions already. It resulted in the saving of considerable foreign exchange and in establishing a flourishing balance industry in the country, and it has proved to be a promising technique for handling design projects. Together, the research institute and the industry have thus been able to achieve easily what each individually might have found quite difficult to tackle.

It is felt that this method, although employed out of necessity, can be used by developing countries with considerable benefit, by adapting it for any similar project. The advantages offered by this method are:

(1) It saves considerable time in the successful completion of a project for the following reasons:

(a) By use of the facilities of a number of manufacturers, a number of designers and precision mechanics much greater than even a big laboratory could afford to employ can be associated with the project.

(b) Involving a number of manufacturers in the same project creates a spirit of competition, and each manufacturer tries to achieve results more quickly than the others.

(2) It assures a good design for the product for the following reasons:

(a) The manufacturers' designers as well as mechanics who participate in the project can do the job better, because of association with the trade concerned, than can the general run of designers and mechanics.

(b) Since the design was not frozen by the research institute, each manufacturer uses his ingenuity to make his product better than that of his rivals.

3. It reduces cost very considerably:

(a) Instead of spending on the project, the research institute may even earn test fees by testing an item each time it is received from the manufacturers.

(b) Manufacturers will plan their design and fabrication work in the most economical manner by suitably fitting this work into the rest of their program. In this way they incur little extra expenditure.

FIGURES 1 and 2. *Two views of the NPL balance-testing section.*

NCSL 70

TELECOMMUNICATION MEASUREMENTS FOR AUTOMATIC PRODUCTION AND MAINTENANCE

Dr.-Ingr. H. Fleischer

Secretary General, Verband Deutscher Elektrotechniker, Frankfurt, W. Germany

Automatic recorders with uncertainties no greater than 0.1 dB up to 18 MHz are used in one channel of a microwave link to measure effective equivalence and noise level to provide production calibration control for filters and attenuators. Details of two German-made systems are described.

Key words: Automatic noise-level recorders; calibration of carrier-frequency filters; microwave transmission lines; Siemens-Halske AEG; Wandel & Goltermann.

The progress of developing techniques very often depends on communications. All prognoses for telecommunication expenditures, especially those of the Bell System, show the necessity for a very great number of links in the national, as well as in the international, field.

Beside the quantity of links, their quality must also be considered. It is known that each circuit able to be linked with other circuits for public use should hold special requirements elaborated by the International Consultative Committees (CCI) of the International Telecommunication Union. It may be that in the United States of America it will not be necessary to follow these requirements because only a small number of links will be connected with international lines. In Germany, however, we are in a quite different position. Our country is very small. Practically 100 percent of our traffic is automatically operated by the user. This is true also for international, and recently was inaugurated for intercontinental, service. We are surrounded by many other small countries. All the very heavy telecommunication traffic between these countries is switched automatically between countries and is normally considered as foreign exchange. Therefore, the quality of the circuits has to fulfill the CCI requirements. The measurements should be valid for microwave links as well as for carrier-frequency cables.

The very rapid increase in the number of lines subject to the necessary high quality controls is the reason for developing remotely controlled automatic measurement equipment for production and acceptance tests, as well as for maintenance. It would be impossible to get a sufficient staff to run the systems on any other basis.

The ever-increasing demands for quality of telecommunication-transmission systems require the use of high-precision measuring equipment. In addition to this, the measurements must be made in the most simple, exact, and time-saving manner, preferably automatically.

It seems unnecessary to mention the automatic noise-level recorder for checking the statistical values of noise in specific circuits. In the cable or microwave link of a multichannel carrier-frequency system, one channel is used as a measurement or control channel. Then it is possible to count and to print the median noise-level values for one hour, for one minute, or for 5 milliseconds. The measurement limits are between 100 and 100,000 pW. This equipment works together with a small computer to mark the values of out-of-tolerance limits and to indicate if the overall system is still usable.

On production and acceptance tests, the carrier-frequency filters take most of the testing time because each filter must be checked at many frequencies. The filters these days are mass produced with very high accuracy, about 0.1 dB at special frequency points.

There are two telecommunication measuring systems available in Germany. One is manufactured by Wandel & Goltermann, the other by Siemens. Both systems are especially designed for easy operation, remote control, programmability of all essential operating functions, and possible use as an automatic level-measurement system. Some years ago it was adequate to measure errors of 0.5 dB but the progress of carrier-frequency technology now requires measurement errors no greater than 0.1 dB at frequencies up to 12 or 18 MHz.

The assembly manufactured by Wandel & Goltermann is constructed principally for laboratories and includes a level generator. The generator and the level meter are synchronously tuned from a control oscillator, which allows decade-frequency settings in steps of 1 Hz between 200 Hz and 1,999,999 Hz. The absolute accuracy, according to the crystal, is 2×10^{-8} after one hour of service, and the transient time for varying the frequency is smaller than 100 μs. The generator output level can be selected in steps of 0.1 dB in the wide range of −69.9 to 9.9 dB, indicated as digital readout. This output level has a measurement error of 0.04 dB and, at special calibration points, about 0.01 dB.

The same accuracy applies also to the level measurement appliance. The manufacturer uses transformers for these precise steps, which are frequency-independent over a wide range. The required attenuation is determined exactly by the turns relationship of transformers and is not subject to aging. The transformers are connected together by electronic means.

With a program control unit, the set becomes suitable for high-precision level and attenuation measurements in development laboratories, construction plants, and test departments as well as for monitoring transmission systems in telecommunication technology. All essential adjustments on the individual instruments of the level-measuring set, and ultimately on the test object, can be remote controlled. The high measurement rate (approximately one measurement point per second) results in great time savings during prolonged measurement runs without affecting the high measurement accuracy offered by the set. Since it is only necessary to exchange program tapes in order to reprogram the measurement system for other measurement tasks, even small production lots and short measuring runs can be carried out economically.

It is possible, during the evaluation process, to compare the measured test results with tolerances given on the program tape. The test-point number, the classification of the sample, or a tolerance violation are directly indicated on the front panel and/or recorded by teleprinter, electric typewriter, or tape punch. On the tape, any 5– or 8–unit code can be used, with a maximum reading speed of 1000 characters per second. The reading time for an average program will be approximately 0.5 s.

The control of the various attenuators and the power-level calibration are made automatically with the aid of the control unit. The power level available at the output terminals, therefore, is always referred to the selected output-impedance value. The operation is really simplified, since the calibration occurs automatically during the measurement process. The automatic measuring system can be matched to a variety of measurement tasks with the aid of further accessories. To illustrate the test speed, an acceptance test of a group filter can be carried out in about 2 min. The program can be stopped after any time interval.

The other manufacturer, Siemens, has chosen a system with a great number of special appliances which can be combined with a large number of measuring sets according to the tasks. The main appliances are still the generator, the level measuring set, the switching device, the attenuator, and all the different sets for remote control and display, available either by typing in any form or by showing on a screen. The accuracy is as good as the equipment mentioned first.

Special efforts were made for the switching device, which is able to connect the appropriate units with the different devices either manually or automatically up to a frequency of 2 MHz, with coaxial impedances of 75 or 100 Ω and with symmetrical impedances of 15 or 600 Ω. In the range up to 100 MHz only the 150–Ω impedance is used. The system is constructed using new techniques for precision and for easy operation.

Another most important part of the Siemens assembly is the variable attenuator, of a really high accuracy, which combines a rather large number of single elements. These are specially designed resistors on glass carriers, constructed by a new technology, which do not change their values in time, space, or with frequency. The steps used in the attenuator are also 0.1 dB, but each element is calibrated to a maximum 0.003–dB error. You should note that this is not a calibration in a laboratory but is valid in the production stage. The set can be used for many purposes—in the very early stage of newly developed equipment, to survey the outcome of production, to register the relevant statistical endurance, and also in the field of research.

In the near future the enlargement of the national telecommunication systems will be aided also by a rapidly increasing number of data-exchange lines with wider bands and with increased transmission requirements. Last but not least, we are standing at the beginning of the Picturephone era. This will bring us larger networks with still wider bandwidths.

The German postal service, PTT, like that of other nations, was confronted with these problems and with the lack of staffs trained for this job. It was therefore necessary to develop an automatic system and to measure all the different lines from only a few measurement centers. This system is named "Automatische Messwert-Ubertragung," meaning automatic transmission of measured values. It operates in the following manner. A code number must be given to each line or channel—not to the whole transmission link—in order to select this specific channel by remotely controlled automatic switches, separated from the normal switches in automatic exchanges. Remotely controlled, highly precise measurements are possible in the field of noise level, effective equivalence, frequency response, group delay, effective attenuation of termination circuits, and instability of amplifiers by measuring the return loss. All these measurements are remotely controlled, so that it is not necessary to have a person at the far end of the line. The remote control unit and the line selector will not be discussed here, but examples of the measurement principles will be mentioned.

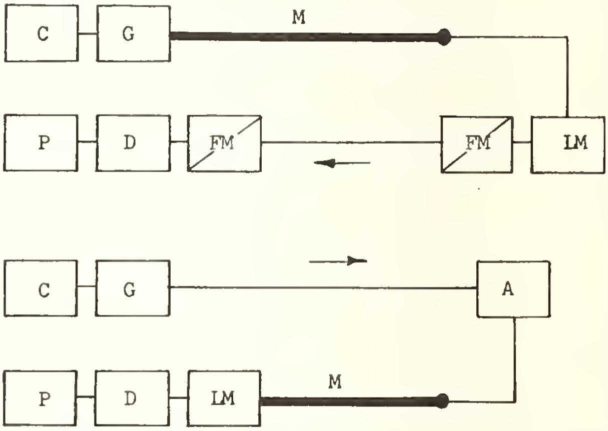


FIGURE 1. *Measurement of effective equivalence.*
C=control unit; R=resistor (600–Ω); G=generator; M=branch to be measured; LM= level meter; FM= frequency modulation and demodulation; D=decoder; P=printer/display; A=automatically controlled amplifier.

As shown in figure 1, the measurement for the effective equivalence is done first for the transmitting direction. The generator is switched to the near end and the level measurement equipment to the far end. The results are coded and transmitted by frequency-modulated signals via the second (receiving) end of the line.

The measurement of the effective equivalence of the receiving side of the line also is done by control at the near end. Instead of the level measurement equipment, an amplifier with automatic gain control will be switched to the far end of the transmitting line. This amplifier transmits all controlled signals to the far end of the receiving branch so that this side can be measured. The level meter is then switched to the far end of the receiving branch so that this side can be measured. The level meter is then switched to the near (receiving) end of the line.

For the noise level measurement (fig. 2), the transmitting near end is switched to a resistor (600 Ω) and the far end of the transmitting branch is connected to the level measurement equipment. The values are transmitted, as before, over the receiving branch and are displayed in the same way. To measure the noise level on the receiving branch, the far end of this branch is switched to the balance resistor (600 Ω), and the level is measured at the near end. The transmitting branch is used only for remote control.

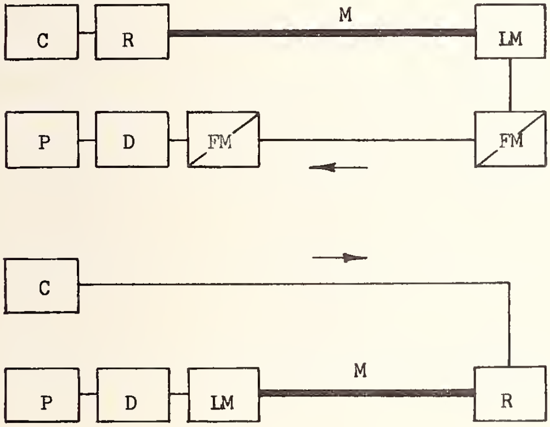


FIGURE 2. *Measurement of noise level.*
C=control unit; R=resistor (600–Ω); G=generator; M=branch to be measured; LM= level meter; FM= frequency modulation and demodulation; D=decoder; P=printer/display; A=automatically controlled amplifier.

The high precision necessary for reliable measurements makes it necessary to incorporate in the program a surveillance of the automatic controlled amplifier. This is done (fig. 3) in the following way. The generator at the near end works to the amplifier at the far end. The far-end level measuring equipment is connected directly to the output of the amplifier and transmits the results in the usual manner to the control unit. This check of the accuracy of the controlled amplifiers becomes even more important when a line to be measured does not end at the measuring center but must be switched to the measuring center through one or two other lines.

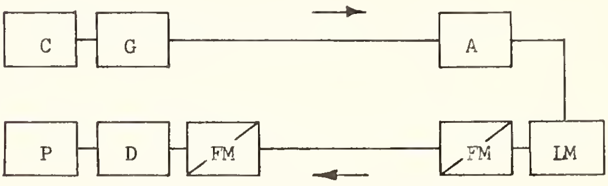


FIGURE 3. *Calibration control*
C=control unit; R=resistor (600–Ω); G=generator; M=branch to be measured; LM= level meter; FM= frequency modulation and demodulation; D=decoder; P=printer/display; A=automatically controlled amplifier.

All this equipment could be constructed only according to the new electronic technologies, which permit equipment to be small, light, reliable, and precise. The special design of transformer or resistor attenuators, together with automatic calibration and comparison allows remote control of the whole measurement procedure in production tests as well as in acceptance tests. Hours of highly qualified staff members are saved for further development work. Hours of production are saved to supply the telecommunication companies with the necessary appliances and components for the extension of networks to serve the progress of economics.

Automatic maintenance enables the companies to install wideband transmission lines necessary for data exchange with the necessary reliability for this special purpose. Economical and technical progress are dependent, to a very great extent, on good communications and better data exchange.

NCSL 70

PRESENT STATUS OF ELECTRICAL STANDARDS AND THEIR TRACEABILITY IN JAPAN

M. Kanno

Standards Division, Electrotechnical Laboratory, Tokyo, Japan

The national electrical standards for Japan described herein are established and maintained in the Electrotechnical Laboratory. Dissemination is by two public agencies. Committees on traceability and on measuring techniques are active in the Institute of Electrical Engineers.

Key words: Absolute measurements; basic electrical standards; quantum electric standards; radio-frequency standards.

1. Introduction

The requirement for better standards and their traeceability to the national standards has been emphasized in Japan. This is most significant in electrical standards. The national electrical standards (and those for photometry, acoustics, and ionizing radiation) were established and are maintained in the Electrotechnical Laboratory (ETL), in this country. Research on the standards has been continued in ETL.

The electrical standards are supplied throughout Japan by two major public agencies and their branches. Many activities have been continuously supporting the flow of the standards. Committees on traceability and measuring techniques have been actively operating in the Institute of Electrical Engineers of Japan. A government committee has been established to improve the connection between national standards laboratories and industry. Improvement in international contacts regarding this problem is desired, and establishment of an organization similar to the NCSL is being considered.

2. Electrical Standards in the ETL

2.1. Basic Electrical Standards

(1) *Resistance and voltage:* Standard values of resistance and voltage are maintained by 10 resistors and 21 cells. They have been checked by regular international comparisons. Measuring accuracy of 0.01 ppm has been obtained. From experience gained with extensive testing of many standard cells, criteria for selection of standard cells for the bank of 21 cells were established.

(2) *Capacitance:* A standard value has been determined absolutely by a cross capacitor with an uncertainty of 1 ppm. An improved cross capacitor is now completed. Good results were obtained in international comparisons of 0.1–μF and 10–pF capacitors. The excellent stability of the 0.1–μF capacitor at ETL was recognized. Fused-quartz capacitors, and improved fused-quartz tubular capacitors have also been used.

(3) *Ac–dc comparison:* Electrostatic and thermal comparators have been tested. Differences of ac–dc response have been measured with accuracy better than 25 ppm at 4 kHz, and 40 ppm at 20 kHz. Extension of frequency range is being tried. Preparation for the planned international comparison has almost been completed.

(4) *Automatic measuring system for standard cells:* The system has been completed to monitor the standard cells. It is composed of a scanner, digital-voltmeter and a programmer, and can compare 200 cells with a resolution of 0.1 μV. Presently, data are treated in a separate computer but a complete on-line system is planned. Extension of the system to other standards is also under consideration.

2.2. Absolute Measurements

(1) *Determination of capacitance by cross capacitor:* Cross capacitor No. 2 has been completed. An accuracy of 10^{-7} has been verified by tests. The capacitor is shown in figure 1.

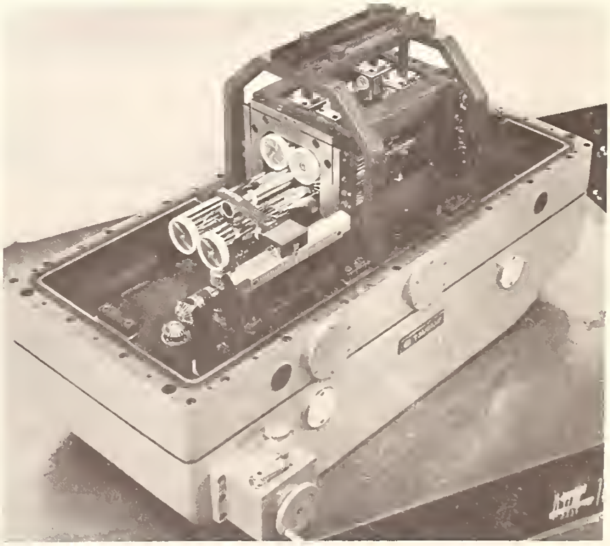


FIGURE 1. *Improved horizontal cross capacitor (No. 2).*

(2) *Evaluation of resistance by capacitance and frequency:* Based on the capacitance standard, such measurements are being prepared, using an improved quadrature bridge.

(3) *Evaluation of voltage by an electrostatic balance:* A method of measuring force produced by an incremental energy change in a movable capacitance electrode system has been studied. A balance, with the electrode system and a measuring system for high voltage are being constructed.

2.3. Quantum Electric Standards

(1) *Measurement of p':* The value of p' (gyromagnetic coefficient of the proton) has been determined with an accuracy of ±4 ppm. The free precessional frequency of a proton in water, in a calculable magnetic field produced by a single layer air-core solenoid, is measured. A new system for a quantum standard of current has been planned this year. In this method a new device called the Magnetically Isolated Calculable Solenoid (MICS) will be used. The MICS has a very wide constant and calculable magnetic field which is not affected by ambient field variations. If this method goes well, a quantum standard of current without the need for a non-magnetic environment can be expected.

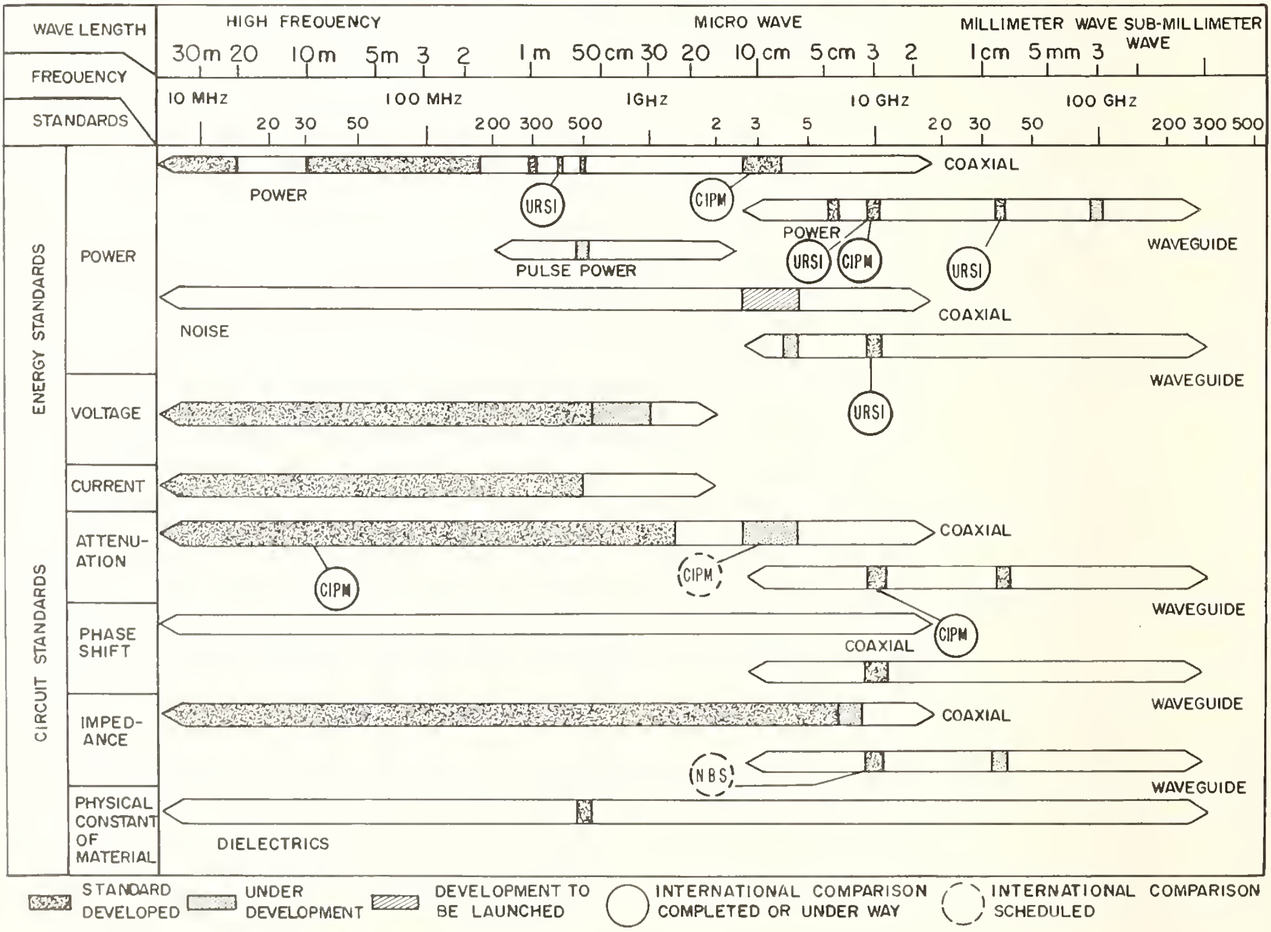
(2) *Stark voltmeter:* A quantum standard of voltage by determining the Stark separation coefficient of particles has been studied. An accuracy of ±30 ppm was obtained in 1969, by measuring the spectrum (20 GHz) of *s*-trioxane ($C_3H_6O_3$). The spectrum of methyl cyanide (CH_3CN^{15}) at 36 GHz is also being investigated in an effort to obtain higher accuracy.

(3) *Ac Josephson voltage standard:* Research on a pure quantum standard of voltage, using the Josephson effect in a junction of two superconductors, was started in 1969. It now is in the primary stage of study on how to make the tunnel junction.

2.4. Radiofrequency Standards

Research and development concerning rf measurements and standards was started at ETL in 1952. Since then a great deal of effort has been expended towards basic research and development of the national standards for, and the measurements of, various fundamental quantities in the radio spectrum. These high-frequency, microwave, and millimeter-wave standards and measurements include such items as power, voltage, current,

TABLE I. RADIO FREQUENCY STANDARDS IN JAPAN 1970



noise, attenuation, phase shift, and impedance. Their present status is shown in table 1.

Since 1959, ETL has made many efforts towards the achievement of agreement among the standards of different nations. We have actively participated in the intercomparisons of such standards as 10-GHz waveguide power, 400-MHz coaxial power, 35-GHz millimeter-wave power, 10-GHz noise temperature, 3-GHz coaxial power, and rf attenuation at three different frequencies.

3. Traceability of Electrical Standards in Japan

In Japan the traceability route is split in two, mainly for historical reasons. The dc and low-frequency standards are distributed by the Japan Electric Meters Inspection Corporation (JEMIC), and the radiofrequency standards by the Japan Machinery and Metals Inspection Institute (JMI), as shown in figure 2, where it is compared to that of USA.

The standards are compared through their rural branches to standards of other organizations as maintained in their own central standards laboratories. Measuring instruments of the organizations also are calibrated at their standards laboratories. However, many instruments are brought to the corporations directly from smaller companies.

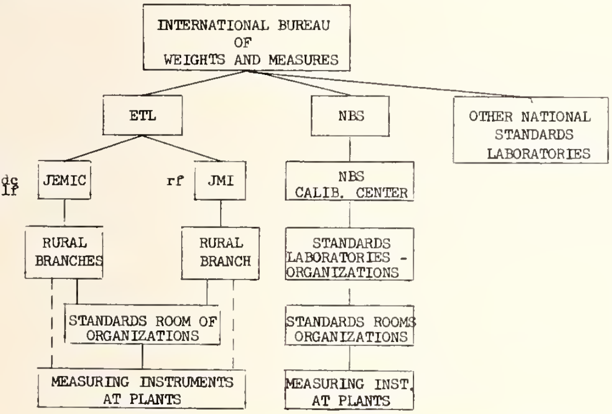


FIGURE 2. *Traceability of electrical standards in Japan and the United States*

3.1 Japan Electric Meters Inspection Corporation (JEMIC)

The JEMIC is a public corporation established in 1965. The activities of the JEMIC are regulated by law. That is to say, the function of the Corporation consists of three main activities, namely (1) type-approval test and individual inspection of watt-hour meters, (2) calibration services for electrical standards and measuring instruments, (3) research and investigations for electrical measurements.

The calibration services for electrical standards and measuring instruments were transferred from ETL to JEMIC. At present, ETL does not perform direct calibration services at dc and in the low-frequency region, but JEMIC supplies the standards as maintained by ETL to all the industries and the government offices in Japan. Moreover, ETL maintains only basic standards such as standard resistors, standard cells, standard capacitors, and ac-dc transfer standards. So, the JEMIC develops some practical standards independently, such as standard inductors, ratio sets, shunts, voltboxes, instrument transformers, inductive voltage dividers, standard watt-hour meters, etc.

At present, JEMIC has 1300 personnel. Of these, about 120 are employed on standards work both for its own use and calibration services. JEMIC covers the whole service area in Japan through fifteen branch laboratories located all over the country. The JEMIC calibrated 8700 articles by request in 1969.

3.2. Japan Machinery and Metals Inspection Institute (JMI)

The JMI is a nonprofit public agency founded in 1957, subsequent to the Export Inspection Law. The Department of Calibration of Electronic Measuring Instruments was established in 1963, as one of the agencies to transfer the national standards of ETL to official and private organization users.

The main business of JMI is (1) calibration of standards and measuring instruments in the radiofrequency ranges, and their adjustment and repair, (2) general inspection of machinery, metals, electrical and electronic products, particularly inspection of equipment for export, (3) safety tests by CSA and UL, and spurious-radiation tests by FCC rules.

The JMI has 550 persons and a branch in Osaka. Research for better calibration has been continued. Main instruments for calibration are signal generators, hf ammeters, power and impedance meters, Q meters, distortion-factor meters, wow-flutter meters, electrical standards and indicating meters.

4. Committees

4.1 Traceability Committee

In March 1968, the Institute of Electrical Engineers of Japan set up the Traceability Committee to investigate, to discuss, and to solve the problem of traceability. The members of this committee are the metrology scientists and engineers of ETL, of public standards laboratories, and of the users and makers of electrical and electronic measuring instruments. The major activities of this committee are as follows:

(1) Disseminating the research data concerning legal standards and international comparisons.

(2) Informing committee members about the work and the standards-supply systems of the national and public standards laboratories.

(3) Collecting and disseminating information about standards systems in other countries,

(4) Investigation of standards-maintenance systems of the industries,

(5) Investigation of the conditions of standards-laboratory rooms,

(6) Standardization of the calibration methods of electrical and electronic standards and instruments.

(7) Presentation of new instruments.

This committee meets regularly every month.

4.2. Precision Electromagnetic Measurements Committee

This committee was established in April 1967, in the Institute of Electrical Engineers of Japan, to exchange novel techniques for precision measurements among people of ETL, agencies of inspection, and professors and engineers from the measuring-instrument industry.

Topics concerned with research and development basic to applications, and covering the range from dc to laser frequencies, are presented and discussed. The committee meets monthly as a rule.

4.3. Governmental Committee on Standards and Measurements

This committee was established in February of 1969. Members include people from the Ministry of International Trade and Industry, standards laboratories, inspection agencies, institutes, universities, manufacturing and other industries, and measuring-instrument makers. Seven branch committees for electricity, illumination, units, temperature, ionizing radiation, length, and standard materials have been established. Activities and objectives of the committee are:

(1) Presentation of information from national and international conferences and committees on standards,

(2) Exchange of information on national standards laboratories and inspection agencies, and discussion of means to improve their operation,

(3) Collection of requests from industry to the laboratories and the agencies,

(4) Discussion of future general traceability systems.

The necessity for securing good traceability and for improving measuring techniques in the industry have been pointed out. For this purpose, establishment of a new organization similar to the NCSL in the USA is being considered.

5. Conclusion

The importance of favorable supply and effective application of standards have been recognized in the industry of Japan. Some activities have been established and operated for this purpose. However, such a trend is seen to appear in many countries. They may have common problems to be solved. International contact is very necessary and effective even if domestic conditions are different. Methods of traceability as well as the standards themselves must be international to realize their full value.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1971 O—405-321

Latest developments in the subject area of this publication, as well as in other areas where the National Bureau of Standards is active, are reported in the NBS Technical News Bulletin. See following page.

HOW TO KEEP ABREAST OF NBS ACTIVITIES

Your purchase of this publication indicates an interest in the research, development, technology, or service activities of the National Bureau of Standards.

The best source of current awareness in your specific area, as well as in other NBS programs of possible interest, is the TECHNICAL NEWS BULLETIN, a monthly magazine designed for engineers, chemists, physicists, research and product development managers, librarians, and company executives.

If you do not now receive the TECHNICAL NEWS BULLETIN and would like to subscribe, and/or to review some recent issues, please fill out and return the form below.

(cut here)

Mail to: Office of Technical Information and Publications
National Bureau of Standards
Washington, D. C. 20234

Name ______________________________

Affiliation ______________________________

Address ______________________________

City ____________________ State __________ Zip __________

☐ Please send complimentary past issues of the Technical News Bulletin.

☐ Please enter my 1–yr subscription. Enclosed is my check or money order for \$3.00 (additional \$1.00 for foreign mailing).
Check is made payable to: SUPERINTENDENT OF DOCUMENTS.

SP 335

U.S. DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20230

OFFICIAL BUSINESS