NBSIR 75-935

The National Measurement System for Electricity

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Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

Issued September 1978

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PREFACE

The National Measurement System for Electricity is that system of people, organizations, standards, apparatus, and software which performs the function of providing quantitative information on materials, manufactured items, and processes through the measurement of their physical properties or parameters. This report is one of a series of similar reports produced by the Institute for Basic Standards (IBS) of the National Bureau of Standards to provide a complete description of that system, of which IBS is the foundation. The format of this report is common to the series and was chosen to provide uniformity and completeness.

The authors would like to express their appreciation to their many colleagues who supplied information and perceptions for inclusion in this study. Special appreciation goes to those who arranged or hosted visits at private and government organizations for the authors and others of the Division staff. We would like to also acknowledge the work of Denise Prather, who assisted in the production of the final draft. Finally we are most indebted for the efforts of Sylvia Ramboz, who was responsible for the production of the manuscripts for two interim reports as well as this document; and for her comments, suggestions, and encouragement.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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June 1976

EXECUTIVE SUMMARY

Electrical measurements are of critical importance due to the universal use of electricity as the primary means for the transmission and control of energy and data. The National Measurement System for Electricity is that set of laboratories, organizations, documents and people which make possible and are responsible for all electrical measurements made in the U.S. at all levels of accuracy. This document summarizes the results of a four-year study of that system.

The structure of the system may be conceived as having a number of components, each serving a particular sector of society and each having distinct characteristics reflecting differing requirements. Two major components exist: the industrial electronics component and the electric power industry component. There are a number of minor parts in each.

Electrical measurements in the system's industrial electronics component are used to ensure quality and reliability of materials and manufactured products, to provide for interchangeability of components and parts, and to control meanufacturing processes.

This component can also be further subdivided into two general areas: the measurement-intensive industry segment and the general industry segment. Measurement-intensive industry and its measurement system are characterized by high technology and the need for a very high degree of product reliability. Included in this portion of the defense, communication, computer, and electronic component industries. Measurement accuracy within this segment is ensured by a hierarchical laboratory system in each organization. Test equipment used for quality and process control is calibrated periodically using precision instruments which are in turn calibrated by comparison with primary standards in the corporate standards are then periodically calibrated at the National Bureau of Standards or intercompared regularly with standards which have been so calibrated. This system, which in large organizations can have a complex hierarchy of laboratories, is primarily the result of the quality control requirements of DoD, GSA, and NASA procurement contracts, the reouirements of regulatory agencies such as EPA and OSHA and logistics constraints.

In the general industry segment of the system, quality control requirements are usually less stringent than in the high technology segment; accuracies are generally lower; and the manufacturing processes are less affected by absolute accuracy of measurements. Thus, organizations in this portion of the system are inclined to buy calibration and repair services from instrumentation manufacturers, large corporate laboratories in the aerospace industry, or companies specializing in calibration and repair work. As previously noted, each of these generally maintains a rigid, well-defined measurement support system.

There appears to be a number of problems and shortcomings in the industrial electronics component of the system. Among the most important are a lack of standards (written and artifact) for the support of dynamic, high-speed electrical measuring instruments and automated test systems; the non-availability in certain areas of procedures and test techniques of guaranteed reliability; a potential future shortage of competent measurement personnel; a failure on the part of some people in the system to perceive that calibration is not always a sufficient condition for assurance of measurement quality; and an inherent rigidity in the government contractural requirements which stifles innovative approaches to measurement problems.

The electric power industry segment of the National Measurement System for Electricity can also be divided into two parts: operational and research for improved electric power transmission and distribution. Electrical measurements play an important role in the day-to-day operation of the nation's electric power systems. They are used to control the generation and transmission of electricity, to provide a basis for equitable exchange (energy metering), and for testing machinery and equipment supplied to the power companies.

Measurement support for both of these areas is generally provided by the measurement laboratories of power companies and those of the electrical equipment manufacturers. In the energy metering area, many of the state and local public utility commissions which regulate the power companies require acceptance testing of watthour meters as well as retesting of older meters. NBS calibration of physical standards and electrical apparatus, both at NBS and in the power companies' and manufacturers' laboratories, ensures the overall integrity of the system.

Most of the industry - both utilities and manufacturers - is adequately equipped to measure traditional quantities such as current and voltage at levels up to 15 kilovolts. Fewer companies, especially in the utility sector, have capabilities above 100 kilovolts. At extra-high voltage (EHV) and ultra-high voltage (UHV), the utility companies, with rare exceptions, have little measurement and calibration capability. Such capability, however, does exist with the manufacturers of large electrical equipment. With respect to nontraditional quantities, such as transient high voltages and currents, measurement capability is generally available only with the large equipment manufacturers.

The quality and consistency of electric power system-related measurements, including traceability to NBS-maintained standards, follow the above pattern of measurement capability. Whenever the calibrations are relatively simple and inexpensive, and if there is also regulatory incentive to do adequate work, the system is in excellent condition. A good example is watthour meter calibrations. But for higher voltage, and especially for non-conventional measurements where the calibrations are difficult to perform and reliable methods are not always readily available, the system has deficiences. Included in this category and EHV and UHV steady-state measurements, and transient measurements in general.

Electricity will become the predominant form of energy in use before the end of the century. Consequently, a large research and development effort funded by the Energy Research and Development Administration and the Electric Power Research Institute is being directed at ways to increase the transmission capability and efficiency of the country's electric power systems. New high voltage and electrical-related measurements are required as transmission technology advances. Examples of new technologies include cryogenic transmission systems, UHV overhead lines, compressed-gas insulated substations, and high-voltage direct-current transmission systems. Each is a relatively measurement-intensive, emerging-technology area. While some older types of measurement methodologies can be adapted for these new areas, generally they cannot and some significant deficiencies now exist including measurements for accelerated aging tests of electrical insulation, and traceability to national standards for impulse measurements.

Two important additional components of the National Measurement System for Electricity are associated with the scientific community and consumer electronics. Measurements made in laboratories not under DoD or NASA contract are generally supported by local instrumentation shops. In contrast with the usual practice in the industrial electronics component, periodic recalibration is unusual - calibration is generally performed only before and after a crucial experiment, or as part of a special maintenance effort. Measurements in support of consumer electronics, such as TV, stereo systems, citizen band and amateur radio, auto electronics, and general electrical work are usually of low accuracy. Consequently, manufacturers' claims of test equipment accuracy are accepted until malfunction occurs. This portion of the system has few, if any, serious measurement problems.

In summary, the Electricity Division of NBS provides the basis for that uniform system of electrical measurement in the U.S. which permits equity in trade, interchangeability of components, the transmission and distribution of electric power, a means of maintenance for electronic equipment, the ability to control the quality of production, and the general advance of science and technology. This is achieved by developing improved means for realizing, maintaining, and disseminating the basic electrical units; by calibrating electrical standards, instruments, and systems for industry, government, and the academic community; by developing new instrumentation and measurement methods; by obtaining basic data and determining fundamental constants related to the electrical units; by ensuring that electrical measurements carried out in the U.S. are consistent with those made in other countries; and by providing advisory and consultative services.

1. INTRODUCTION

The National Electrical Measurement System began to assume its present form around the beginning of this century. At that time the uses of electricity were limited to the easy transmission and use of energy in manufacturing and transportation and for lighting and primitive means of communication (telephone and telegraph). The establishment in 1901 of the National Bureau of Standards led to the foundation of a uniform system of electrical measurement where none had existed before; a foundation which permitted and expedited the development of electrotechnology which has made our present way of life possible. Since then the measurement system has continuously grown in magnitude and scope along with the industries it supports [1].

Today the system pervades every aspect of modern life. The electric power industry is the largest in the United States [2]. The electronics industry is one of the larger industries as well, and its products make possible the inexpensive production of goods and services throughout the rest of industry. Our present level of electrotechnology is only possible because a uniform system of electrical measurement exists. This system provides scientists, electrical engineers, and quality control engineers with a common language and thereby minimizes the need for trial-and-error approaches to design by permitting the existance of necessary data bases and allowing the meaningful communication of technical information in quantified detail. It is also true that the level of sophistication and general quality of all electrical-electronic products as well as many others are predicated, among other factors, on the state of the measurement system. The stability with time of the units of measure, the compatibility of measurements throughout the system, and the effectiveness with which new requirements are anticipated and dealt with are key factors which establish bounds on the level and rate of advance of technology. The system permits interchangeability, at affordable cost, of parts with very high levels of precision, a vital part of modern manufacturing technology.

The study of the National Electrical Measurement System, the results of which are summarized in this report, is intended to provide a complete picture of the system at the present time, and to forecast its future posture, needs, and shortcomings, The present intensive study is also to provide a data base for program planning within the National Bureau of Standards, a data base which will be expanded over the years as the result of a continuous surveillance of the system. The study was carried out primarily in two parts. Technical data were gathered as the result of visits to companies, correspondence with colleagues, interviews with visitors to the NBS, and interactions with fellow members of standards committees by Electricity Division personnel. Economic data were gleaned primarily from the literature. Because of the nature of the Electrical Measurement System, separate studies were not conducted on each measurement area. Rather, the system was observed as consisting of two unique sets of users, the electric power industry and the electronics industry. The term "electronics industry" as used here refers not only to the manufacturers of electronic components, modules, instruments, and systems, but to the users of these as well. Each of these will be further subdivided as the report progresses. Since the system is so large and pervasive, no attempt was made to define its size exactly. Recurring structural features make sampling an effective means of viewing the system.

As a result of the study, it was determined that:

(a) the system is adequately equipped and manned to support most measurements of a static nature;

(b) although most new instruments are designed and specified for use under computer control, there is virtually no capability in the system as a whole to support dynamic measurements; i.e., measurements in which time is a factor;

(c) there are expected to be increasing pressures from government regulatory agencies and from industrial firms engaged in international commerce for the establishment of a system for accrediting standards, calibration, and testing laboratories of various types;

(d) future sophisticated instrumentation, if not designed for computer control, will contain small control and logic units called microprocessore, creating a need for methods of verification of measurement implementation software;

(e) there exists a need, whose urgency is being determined, for improved measurements of electrical conductivity for application to non-destructive materials testing;

(f) because of the energy crisis, there is a need for new measurement methodologies for the support of energy-related research, especially in the areas of electric power;

(g) there is a lack of capability within the electric power industry to perform ultra-high voltage measurements;

(h) the exchange of technical information takes place in the system at an unacceptably low level.

It must be noted that consideration in this study was not given to those electrical measurements associated with the processing of semiconductor materials. Such measurements are addressed in depth by the impact study of the Electronic Technology Division of NBS.

2. STRUCTURE OF THE ELECTRICAL MEASUREMENT SYSTEM

2.1 Conceptual System

The system provides the capability for measurement of electrical quantities shown in table 1 below in the frequency range between dc and 1 MHz.

Table 1. Electrical quantities and units

Quantity	Units
Capacitance (C)	Farad
Current (I)	Ampere
Charge (Q)	Coulomb
Potential Difference (E)	Volt
Inductance (L)	Henry
AC-DC difference, voltage	(Unitless)
AC-DC difference, current	(Unitless)
AC-DC difference, resistance	(Unitless)
Power	Watt
Energy	Watthour or Joule
Ratio, resistive	(Unitless)
Ratio, dc voltage	(Unitless)
Ratio, ac voltage	(Unitless)
Ratio, current	(Unitless)

The above are measured in terms of the so-called legal units, those embodied in physical standards maintained by the National Bureau of Standards or defined by them as a function of physical constants. These units are - to the degree practical - compatible with the SI (Système International) units.

The Système International de'Unites provides the internationally accepted theoretical basis for the metric units of measure. In it, seven base units - the metre, the kilogram, the second, the kelvin, the mole, the candela, and the ampere - are regarded as being dimensionally independent and all other units stem from them, either through known physical relationships or defining equations [1]. In practice a set of four independent equations is available to define the six basic electrical quantities given at the top of table 1 with their symbols. They are $E=IR$ (Ohm's Law); $Q=It$ (t is time); $C=Q/E$; and $L=E/\frac{dI}{dt}$. These can serve to define only four of these quantities. The system is completed by requiring the unit of electrical energy to be equal to the unit of mechanical energy and devising electromechanical experiments - absolute experiments - involving force and length (whose product is energy) and corresponding electrical quantities to realize in practice two of the electrical units.

Absolute experiments are very complex and time-consuming, require the most meticulous approach, and involve the design and construction of special apparatus. Moreover, in the case of the ampere and volt, the uncertainties of the results are very large by comparison with those attainable using either artifacts, such as standard resistors or capacitors, or physical phenomena (e.g., the Josephson effect) to carry forth defined units. It is for these reasons our system of legal units exists. Figure 1 shows in detail the derivation of assigned values for the legal electrical units. In the past, absolute experiments have been performed to realize the ampere by comparing the force between current-carrying coils of known geometry to that exerted by the earth's gravitational field on a known mass. This was done most recently at NBS in 1967 using a Pellat-type electrodynomometer. The result was the determination that the ratio of the NBS ampere (derived from the legal units) to the SI ampere equals 1.0000105 with a probable error of 7 parts in a million.

These results as well as those of four other experiments formed the basis for an eleven part per million adjustment in 1969 to the value of the ampere as derived from the units maintained in Sevres by the Bureau International des Poids et Mesures - the International Bureau of Weights and Measures, which by the treaty of the Metre maintains electrical and physical units to promote international measurement uniformity. In consequence of this adjustment and drifts in the U.S. volt measured with respect to the BIPM volt, the U.S. legal volt was changed by 8.4 parts in a million on January 1, 1969. U.S. laboratories were informed of this change and advised to make the appropriate adjustments to the assigned values of their standard cell emfs through correspondence and technical publications in the media.

The ohm has in the past been determined in absolute measure using a specially constructed coil system of known geometry. The mutual inductance of such a system may be determined from its geometry and dimensions using electromagnetic theory. A commutated dc method may then be used to obtain the value of a resistance as a linear function of the mutual inductance (length) and the rate of commutation (time). The resulting overall uncertainty of the last experiment of this type performed at NBS in 1948-1949 was 10 parts per million [2] - rather large especially when compared to the precision with which resistance standards may be intercompared (~0.01 ppm) and their drift rates relative to one another (~0.05 ppm/year). More recently, it has been determined using a calculable cross capacitor. This device is based upon the theorem of Thompson and Lampard which describes geometric conditions for the construction of a device whose capacitance is a known function of the displacement of a moveable electrode and hence can be calculated if the displacement can be measured. A quadrature bridge is then used to effect a calibration of resistance in terms of capacitance. This experiment thus establishes both the farad and the ohm in absolute measure. This is a much more accurate experiment than either the previously-described ohm determination or the ampere determination, having an uncertainty of 0.06 ppm [3].

The volt may also be obtained in absolute measure. Experiments are now underway at NBS and in the national laboratories of several other countries. The NBS experiment involves the measurement of the dc voltage applied to concentric cylindrical capacitors in terms of the electrostatic force generated between them as a function of their relative displacement and the charge in capacitance resulting from the displacement. The target accuracies of these experiments is of the order of 1-3 ppm. When completed, these determinations will not only provide the difference between the maintained and SI units of voltages, but when coupled with the results of the Farad-Ohm determination, will constitute an indirect determination of the SI ampere for comparison with previous directly-obtained values.

The legal units are maintained at NBS in the form of assigned values to groups of artifact standards. The legal farad is embodied in a group of ten, very stable, fused-silica capacitors [4]. The mean capacitance of the group has been assigned from absolute capacitance determinations. The legal ohm is the mean 4-terminal resistance of a group of Thomas-type standard resistors immersed in oil at 25°C under a power dissipation of 0.01 watts. This value is slightly inconsistent with the results of absolute experiments and will be adjusted after further work. It is not anticipated that this adjustment will be as large as one part per million.

The ampere, however, cannot be conveniently maintained using a physical standard. Instead, the absolute measurements of resistance and current are used to derive an absolute volt from which a legal unit of voltage may be assigned. Until 1972, the volt was maintained via a group of saturated standard cells in a temperature-controlled enclosure. Since July 1, 1972, use has been made of the ac Josephson effect to maintain the legal unit. The ac Josephson effect is a superconducting, pair-tunneling phenomenon - the discovery of which has permitted the construction of a linear frequency-to-voltage converter whose proportionality constant is invariant with respect to time and other factors at the part in 10^9 level [5]. Figure 1 depicts the derivation of the basic electrical units. It does not show an experiment for the direct absolute determination of the volt presently underway. Table 2 gives characteristics of the artifacts embodying the legal units. Appendix B contains a description of both the primary electrical standards and the working standards used to provide for the dissemination of the electrical units.

The other quantities listed in Table 1 are derivable at various levels of accuracy over their ranges. Accuracies of calibrations of standards in each of these areas are more than adequate to meet most static measurement requirements except the following:

(a) Capacitance between 30 kHz and 1 MHz, needed to support measurements resulting from increasing carrier frequencies in communications systems.

(b) AC voltage from 0.1 Hz to 100 Hz at millivolt levels and below for the support of vibration measurements aboard helicopters.

(c) DC conductivity measurements in ferrous and nonferrous metals for the support of nondestructive testing of airframes and other structures.

The standards and capabilities mentioned to this point apply only to static measurements, i.e., those measurements for which the time of measurement is not a constraint. The advent of integrated circuits and the resulting enormous increase in complexity of electronics has resulted in requirements for many more measurements in industry to ensure the quality of products and for maintenance purposes. Manual measurement methods are totally inadequate to the demand. Fortunately this same new technology has provided the system with the tools needed to perform measurements at very high speeds - fast settling instrumentation to convert analog electrical parameters to encoded digital signals, high-speed data handling equipment for routing digital and analog signals, and readily available inexpensive digital computers to control experiments, collect data, direct it

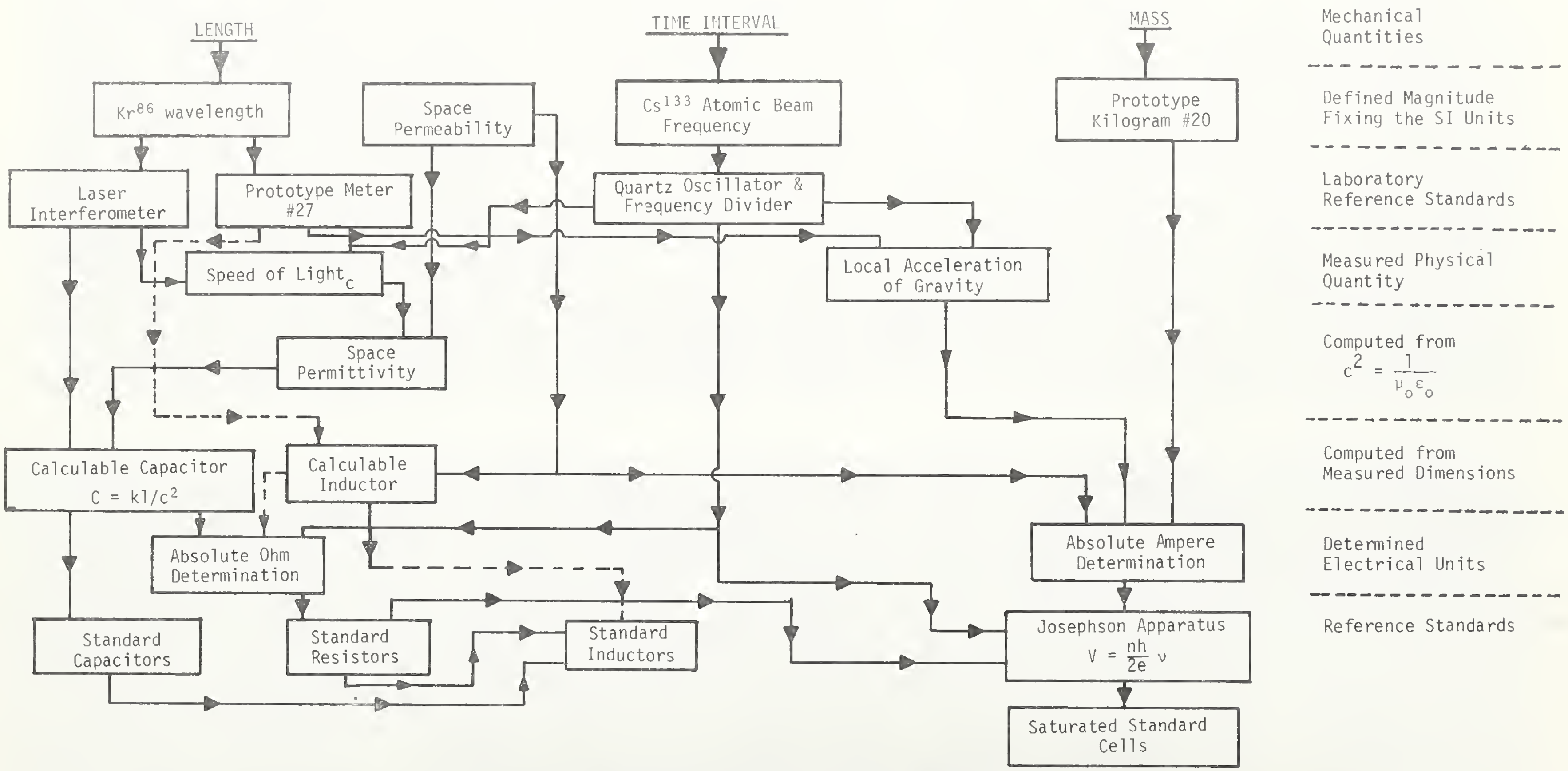


Figure 1. The derivation of the electrical units

Table 2. Characteristics of the basic legal units.

Unit	Artifact	Nominal Value	Maintenance Accuracy	Absolute Accuracy
Ohm	Thomas-type resistor	1 ohm	0.08 ppm	.06 ppm
Volt	Josephson apparatus	10 mV	0.1 ppm	7.8 ppm
Farad	Fused-silica capacitor	10 pF	0.4 ppm	0.034 ppm
Henry	Maxwell-Wein bridge	--	200 ppm	200 ppm

[a]Maintenance accuracy is that with which a perfect standard of equal magnitude could be calibrated.

[b]Absolute accuracy is the accuracy with which the difference between the SI and legal units has been reported.

to storage devices, and perform the mathematical manipulations necessary to put it in useful form.

Unfortunately, standards to provide a basis of accuracy for these high-speed or dynamic measurements simply do not exist. There is no common, well-defined terminology for describing the performance of these modern measurement tools, nor are there accepted test methods or artifact standards for verifying their accuracy under use conditions. There is no reliable way of precisely determining the trade-off between speed of measurement and accuracy. Presently, dynamic measurements are supported through the rapid measurement of static standards, a practice which does nothing to verify the capability to measure the rapidly-varying parameters characteristic of modern electronics. Other time-related properties of the measurement instrumentation such as the rate at which they should sample, the frequency of the measurements made, or delay times after switching are determined on a trial-and-error basis. Such standards as do exist are the intracompany standards of each of the instrumentation and module companies and, while they serve to achieve a degree of uniformity within each company's product line, are not directly relatible on an intercompany basis and certainly not available to the customers of the companies. In fact, such standards are considered proprietary in that they seriously affect product development in one of the most competitive marketplaces in existance.

This lack of standards and measurement verification capability results in undue costliness of measurement equipment, in hardware, testing and design costs, and in unfulfilled measurement capabilities. Undue cost accrues as the result of overspecification of components and modules at design time. In addition, validation procedures must be developed by trial-and-error techniques where adquuate standards do not exist.

A program for the development of standards and test techniques to support the dynamic measurement of electrical parameters has recently been initiated within the NBS. It is visualized that the hardware and written standards developed in this program will be made available to manufacturers and users of electronic measurement equipment in the form of calibration services, measurement assurance programs, and publications. As such they will provide the basis needed for uniform and compatible dynamic measurements throughout the country in the same way that existing standards now do for manually-made measurements.

2.2 Basic Technical Infrastructure

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

There are basically two major international standardizing organizations impacting the Electrical Measurement System. The International Electrotechnical Commission (IEC) is concerned with the production of standards, terminology, and specifications in support of electrotechnology. It has approximately 75 technical committees to perform this function. A list of those technical committees most affecting the system is given in table 3. In this country, a delegate to each committee of interest is appointed by the chairman of the national committee. The delegate, in the case of each proposed standard, attempts to develop a consensus U.S. position by getting technical support from interested parties in industry and government. The work of the IEC is very important to U.S. foreign trade activities. If standards which are essentially incompatible with common American practice are developed, they could be used against the U.S. in restraint of trade. More importantly, standards developed overseas tend to be restrictive in two other ways. In many cases, methodology is stressed rather than performance. This tends to inhibit technological advancement in some product areas. Furthermore, the level of technology reflected in some standards is low by comparison to that in the U.S. These two factors can readily couple to close foreign markets to U.S. manufacturers.

Table 3. IEC committees affecting the Electrical Measurement System

Committee	Title
1	Terminology
3	Graphical Symbols
13	Measuring Instruments
25	Quantities and Units, and their Letter Symbols
38	Instrument Transformers
42	High Voltage Testing Techniques
45	Nuclear Instrumentation
50	Environmental Testing
56	Reliability and Maintainability
62	Electrical Equipment in Medical Practice
66	Electronic Measuring Equipment

The International Organization for Legal Metrology (OIML) is a recently-formed group concerned with legal aspects of metrology, such as weights and measures. Within OIML is a pilot secretariat, Secretariat 13, for the measurement of electric and magnetic quantities which is concerned with the provision of traceability for those kinds of measurements presently legally required. Secretariat 13 is held by the U.S. and has the subcommittees listed in table 4.

Within the U.S., there are a wide variety of legal and regulatory standards which impact the Electrical Measurement System. In the electronics world, traceability requirements for suppliers are made mandatory through contract by the federal government's largest consumers: the Department of Defense, the Department of Transportation, and the National Aeronautics and Space Administration. The Department of Energy requires that all contractors running installations for them have a stylized quality control system, and they provide for the servicing of those systems through their laboratory in Albuquerque, NM, run by the Sandia Corporation.

Table 4. OIML Pilot Secretariat 13

Measurement of Electric and Magnetic Quantities

Subcommittee	Title
13.1	International Compatibility of Primary Etalons
13.2	Power Meters (wattmeters)
13.3	Energy Meters for Direct Connection
13.4	Energy Meters Designed to be Used With Measurement Transformers
13.5	Measurement Transformers
13.6	Indicating Instruments for Voltage, Current and Frequency
13.7	Recording Instruments for Voltage, Current and Frequency

The Department of Defense contractually requires of its suppliers compliance with military specifications MIL-Q-9859A, Quality Program Requirements; MIL-I-45208A, Inspection System Requirements; and MIL-C-45662A, Calibration System Requirements. By doing so, it forces manufacturers to set up calibration and quality control systems which require periodic calibration of all measurement equipment, traceability to national standards in the case of all such calibrations, complete documentation of the calibration system including test procedures and traceability, and any instrument undergoing calibration to be tested using standards at least four times more accurate than it is. NASA has a similar but more rigid set of regulations - NPC 200-1A, Quality Assurance Provisions for Space Contractors. The Department of Transportation requires traceability in its highway safety test programs by specifying compliance with provisions of the Society of Automotive Engineers' Standard J211b.

Of great potential impact are new and forthcoming requirements of the Occupational Safety and Health Administration (OSHA). That organization has proposed that all industrial electronic and electrical equipment comply with certain minimum safety standards. Furthermore, it is proposed that all devices be tested for compliance in certified testing laboratories and that tests must be conducted in a laboratory not belonging to the manufacturer of the item being tested. At present these proposals are being appealed by industrial groups.

The electric power industry subset of the measurement system is also affected by the mandatory safety requirements of the Occupational Safety and Health Administration. Safety testing will be required of apparatus used in work environments. Once again it is likely that all testing will be done by accredited laboratories.

At present, the Food and Drug Administration fosters safety standardization in the manufacture of medical devices and instrumentation by sponsoring and promoting the generation and adoption of standards with the voluntary cooperation of industrial concerns, medical experts, and their own experts. Recently (May 1976) enacted and signed into law is The Medical Device Safety Amendment to the Food, Drug and Cosmetic Act, which will set up control mechanisms for medical instrumentation administered by the Food and Drug Administration. These mechanisms will range from having to obtain approval before marketing to simply having to register products in such a way as to enable an effective recall process in the event defects are found. In addition, manufacturers will be subject to a number of standards called Good Manufacturing Practices. These Good Manufacturing Practices, about to be promulgated, will require the existance of formal quality control procedures (in many cases where none exist now) and, in some areas of critical application, the establishment of formal calibration support systems with measurements required to be accurate in terms of national standards. This will result in the creation of new standards laboratories and perhaps in recognition of new types of measurement applications.

The bulk of the regulations affecting the electric power industry come from state utility regulatory commissions. These commissions have broad powers in regulating the operations of electric utility companies. They approve rates and siting of power plants and major transmission lines; to some extent they have a jurisdiction over the quality of electric power service--occasionally they prescribe tolerances for the supply voltage; they regulate the accuracy of watthour meters and the quality control systems which have been set up to test both newly-acquired and previously-installed meters.

There are a large number of voluntary standards organizations impacting the Electrical Measurement System. The majority are listed in table 5. Those organizations whose titles are starred have the greatest impact since they produce standards which have affect on the higher accuracy measurement processes, instruments, and artifact standards which support the system. NBS personnel participate in the activities of a number of committees sponsored by each of these organizations.

Table 5. Voluntary standards sponsoring organizations

Aerospace Industries Association
American Home Lighting Institute
*American National Standards Institute
American Society for Quality Control
American Society for Testing and Materials
American Welding Society
Association of American Battery Manufacturers
Association of Edison Illuminating Companies
Audio Engineering Society
*Edison Electric Institute
Electric Apparatus Service Association
*Electronic Industries Association
*Institute of Electrical and Electronic Engineers
Institute of High Fidelity
Institute of Printed Circuits
*Instrument Society of America
National Association of Relay Manufacturers
*National Electrical Manufacturers Association
Radio Technical Commission for Aeronautics
Resistance Welder Manufacturers Association
*Scientific Apparatus Manufacturers Association
Society of Automotive Engineers
Underwriters Laboratories
Variable Resistive Components Institute

*Organizations having major impact

2.2.1.2 Survey of Documentary Standards

A survey on documentary standards affecting the electrical measurement system was performed. Consideration of documentary standards in the electrical area shows that the documents may be divided into six categories: safety specifications and testing methods, terminology, dimensional requirements for compatibility, testing methods to determine electrical properties, performance parameter specifications and testing, and reliability assurance procedures. It is apparent that all except dimensional requirements involve or affect electrical measurements in some fashion. Since there was no evident valid means of ranking or quantifying these various effects, and since any document directly concerning etalons (artifact standards), measurement apparatus, and instrumentation would be more likely to have a large impact on the measurement system, those documents were considered separately.

Investigation of documents sanctioned by the International Electrotechnical Commission showed that, of the population of 759 standards and supplements, 45 referred directly to etalons, instrumentation, and precision measuring equipment. Most of these specify moderate accuracy instrumentation. Of the remainder, perhaps ten percent deal with terminology and symbols and another ten percent with dimensional specifications. As has been pointed out, the remainder have a bearing on the segment of the system dealing with the testing of export products for compliance with these standards to assure acceptance abroad. And, although a third or more of the remaining documents refer to radio frequency measurements above 1 MHz and therefore outside the scope of this study, measurements at those frequencies require a degree of low frequency measurement support [6].

A similar investigation of standards issued by the American National Standards Institute and having bearing on electricity and electronics, revealed that, of 944 standards, supplements, and handbooks issued, 20 provided definitions, specifications of performance, and test and verification methodology for standards, instrumentation, and precision measurement apparatus. Terminology is largely concentrated in C42.100, the Institute of Electrical and Electronic Engineers (IEEE) Standard Dictionary of Electrical Terms. About ten percent of the documents in this study specify dimensions for compatibility. The remainder specify or outline tests or measurements of various electrical parameters. The standards sanctioned by this institute are perhaps the most universally accepted in this country. A very high percentage of them have been adopted directly from the work of other groups such as the IEEE, the National Electrical Manufacturers Association, and the American Society for Testing and Materials [6]. mary standards

Generally speaking, IEEE standards dealing directly with measurement apparatus, instrumentation, and etalons have been adopted by the American National Standards Institute and, hence, are covered above. Standards and recommended practices produced by the Instrument Society of America deal primarily with the application of instrumentation to industrial processes and with the use and measurement of transducers. There are 18 such procedures involving electronic instrumentation. Standards produced by the Electronic Industries Association deal primarily with electrical testing of components and with electronics in the manufacturing process.

The Edison Electric Institute, the Association of Edison Illuminating Companies, and the National Electrical Manufacturers Association have contributed to standards for electric power systems, either through sponsorship of, or participation in, ANSI committees. In the measurements field three standards are very prominent: ANSI C12 (watthour meters, electricity metering; committee is chaired and co-sponsored by NBS); ANSI C57.13 (instrument transformers); ANSI C93.2 (coupling capacitor voltage transformers) [7]. The IEEE is a very important contributor to the measurement and test standards for electric power systems through the Power System Instrumentation and Measurements (PSIM) Committee and its subcommittees and working groups. This committee is responsible for about 10 standards, most of which have been adopted by ANSI.

There are two areas in which the standards reviewed have little or no impact. The first is the area of the dynamic measurement of electrical processes in which timing is a significant factor. With the increasing use in this country of computer-driven measurement equipment, standardization of terminology and specification of valid timing test methods are necessary to relieve the chaos which presently exists in the marketplace for that type of equipment [6]. (See also Appendix C.)

Methodology for testing the measurement system is not well documented as such. Although documentation of tests on certain types of instruments is available, techniques for the verification of the measurements are not documented. No mention is made in published standards of the type of system-output sampling that is employed in many of the Measurement Assurance Programs being carried out by the NBS.

The importance of these voluntary standards is reflected by the support given to their generation by industry and the government. Most standards committees meet at least biannually and the meetings are generally well attended even though the participants are from various parts of the country. And, although the use of these standards in this country is on a voluntary basis, their generation gives a solid technical base for U.S. input for international standards work, the results of which may carry the force of law in other countries. Heavy and successful U.S. activity in that area is needed to enhance our export trade posture.

2.2.2 Instrumentation System

2.2.2.1 Measurement Tools and Techniques

Practical (end use) measurements in the Electrical Measurement System are supported by a hierarchical structure resembling an inverted pyramid with the National Bureau of

Standards as its base. At NBS, the legal electrical units, which have been determined in terms of the theoretical (SI) units, are maintained and disseminated to the standards and calibration laboratories of the community. (See Appendix E for a list of NBS primary and working electrical standards.) The units are transferred there from standards to a class of instrumentation commonly known as test equipment. It is this test equipment which provides the means for the calibration and maintenance of virtually all electronic and electrical equipment in the country, regardless of its nature.

A few basic types of standards, used in corporate standards and calibration laboratories and supported by NBS, are used to tie the units embodied in test equipment to the legal units. Table 6 lists these basic standards. Standards are arranged in descending order of performance capabilities where more than one are listed. Approximate accuracy capabilities are expressed in parts per million (0.0001%) in parentheses.

In parallel with the hierarchical organization mentioned above, there are similar technical chains of measurement traceability from NBS standards to the end uses. Examples of these are to be seen in figures 2 and 3 which depict the traceability of applied voltage measurements in the electronics industry and applied energy measurements in the electric power area, respectively.

The dissemination of electrical units is generally accomplished in one of two fashions. In the traditional calibration method, the standard to be calibrated is taken to the laboratory in which the standard used to calibrate it is kept. It is then calibrated, and returned. Although this approach has the merit of being easily managed and is generally adequate in most situations, it has a number of technical flaws. The standard is not calibrated in the environment in which it will be used. Hence possible environmental effects tend to be overlooked. The same holds for the electrical conditions of use. Checks are not made on the veracity of the measurement made in the use of the standard; and no assessment of the stability of the standard during the physical transfer is generally made. Alternatively, the units may be disseminated by using suitably tested transport devices to sample the quality of measurements being made in the measurement chain. This latter

Table 6. Basic units and industrial standards

Unit of	Starting Level	Standards
DC voltage	1.02 V	Saturated standard cell enclosures (0.5)[†]; solid state reference devices (5), unsaturated standard cells (50)
DC resistance	10^{n*} ohm	Primary standard resistors (0.1-1); Rosa-type and other intermediate standard resistors (1-15); resistance transfer boxes and precision decade resistors (10-250); resistive shunts (50)
DC resistance ratio	1/1	Hamon devices (0.02); precision resistive dividers (0.05); standard volt boxes (5); potentiometers (10)
Capacitance	10 pF	Fused-silica dielectric capacitors (0.4); gas dielectric capacitors - 3-terminal (3-100); gas dielectric capacitors - 2-terminal (50-1,000)
Inductance	100 mH	Air core standard inductors (200-2,000)
AC voltage ratio	N/A	Inductive voltage dividers (0.1); instrument transformers (100-300); high voltage transformers (100-3,000)
AC-DC voltage difference	N/A	Multijunction thermal voltage converters (5-10); Hermach-type thermal voltage converters (5-100)
Power	N/A	Wattmeters (100-10,000)
Energy	N/A	Watthour meters (200-1,000)
AC current ratio	N/A	Current transformers (100-300)

[†]Numbers in parentheses are approximate uncertainties in ppm.

*n can be any whole number between -4 and 14.

Auxiliary Calibration Equipment	Standards	Location	Uncertainty (ppm)	Notes
Potentiometer	Standard Cell 1 volt	Primary Stds. Lab.	$\pm$ 1.5	Uncertainty assigned by NBS
Method A (Volt box Potentiometer)	Standard Cell or Zener Diode 1 volt	Calibration Lab.	$\pm$ 2.0-10	Working Standard
or				
Method B (Power supply Kelvin Varley Divider)	DC Voltmeter Calibrator 0-1000 volts dc	Calibration Lab.	$\pm$ 10-100	Accuracy depends upon method and calibration characteristics
	Digital Voltmeter 0-1000 volts dc	Calibration Lab.	$\pm$ 40-500	Accuracy depends on calibrator accuracy and DVM characteristics
	Source in Guidance Unit (END ITEM MEASUREMENT)	Production Line	$\pm$ 160-1000	

Figure 2. Traceability of voltage measurements

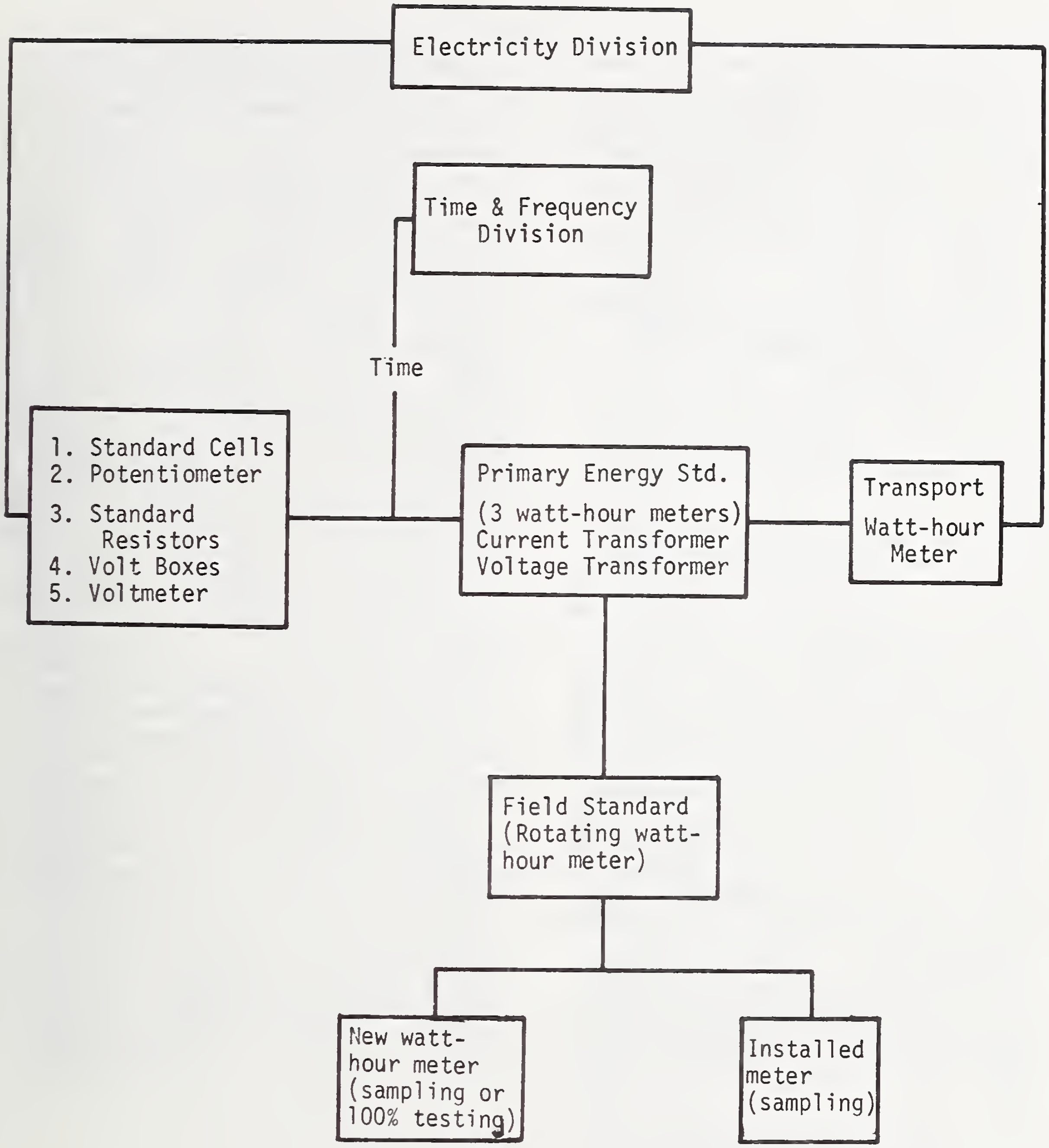


Figure 3. Traceability of energy measurements

method is somewhat more complicated in terms of data analysis and management and more costly in labor, but gives a more realistic picture of system performance. This approach is now being used more and more for dissemination purposes, especially where high accuracy is desired for the dissemination of the basic units between primary laboratories, or in cases where a suspicion exists that a measurement process is in trouble.

Technical information is disseminated throughout the system in the following ways:

(a) written calibration procedures,

(b) manufacturers' instruction manuals and user newsletters,

(c) informal contacts between colleagues,

(d) technical papers published in the open literature, and

(e) voluntary standards (previously discussed).

Most information is probably disseminated through the use of published procedures. Most government quality control contractual requirements demand the establishment of a library of written procedures covering everything from data handling to instrument calibration. Such procedures are exchanged throughout the segment of industry supporting the government through GIDEP, the Government Industry Data Exchange Program. Participation in this data-bank program is now mandatory for Defense Department contractual suppliers. Procedures must be submitted at a given rate by each participant for inclusion in a giant data bank. The bank is accessible to all participants. (GIDEP is not confined to calibration information. Other aspects include reliability data, instrumentation applications, etc.)

Many manufacturers include calibration instructions as well as application instructions in the user manuals supplied with instrumentation. This is probably the second major source of technical information in the system. The others seem to be less significant.

2.2.2.2 The Electronic and Electrical Instrumentation Industry

The instrumentation industry [8,9] is the only source of those measurement tools which provide the foundation for the quality of all manufactured products and, in some cases, provide the enabling means of their manufacture. Instruments are manufactured to measure every electrical parameter with accuracies ranging from those to be found in standards laboratories (parts per million) to five percent for analog panel meters. Their use with transducers enables the measurement of other physical parameters, such as temperature, strain, force, pressure, resistance, etc., as well. Instruments can be as simple as the dwell-tachometer used to tune an automobile or as complicated as a system for the checkout of inertial navigators, employing dozens of separate pieces of test equipment, capable of 0.005% accuracy in some cases and completely under the control of a computer.

Measurement instrumentation and control equipment enable the large volume, high quality, and low cost mass production which has made our high standard of living possible. The ready availability of digital computers as well as of reliable, accurate instrumentation capable of being computer-driven has led to the increasing use of electronic process control systems in areas such as the petrochemical industry to replace existing pneumatic, hydraulic, or manual systems. Electronic systems have the virtue of being able to respond much more rapidly - nearly instantaneously - to process changes than mechanical systems and offer greater flexibility in that process modifications may be readily brought about through software rather than hardware changes. In addition, the use of digital logic makes availabile a capability for decision-making of a complex nature.

Electrical measurements are necessary to the maintenance of this type of electronic equipment as well as all others of a durable nature.

A representative list of electronic instruments used for calibration, maintenance, testing, and analysis is given in table 7. Table 8 is a list of the major manufacturers of basic standards and primary calibration equipment in common use in standards laboratories in the U.S. It is not exhaustive.

Table 7. List of common instruments

Acoustic noise generators
Admittance meters
Ammeters
Amplifiers (over 30 types)
Analog-to-digital converters
Audio frequency analyzers
Audio mixers
Audio test oscillators
Automotive test systems
Bridges (17 types)
Calibrators (current, voltage, oscilloscope)
Current sources
Data recorders
Decade boxes (capacitance, resistance)
Digital comparators
Digital filters
Digital-to-analog converters
Digital voltmeters
Distortion analyzers
Electronic integrators
Electronic micrometers
Electrostatic voltmeters
Fluxmeters
Function generators
Harmonic analyzers
Hysteresis plotters
Interferometers
Instrument transformers
Multitester meters
Operational power supplies
Oscilloscopes
Peak power meters
Potentiometers
Reflectometers
Sampling voltmeters
Tachometers
Telemetry modulators
Vibration meters
Voltage-to-frequency converters
Volt ratio boxes
Watthour meters
Wattmeters

Table 8. List of electrical standards manufacturers

Beckman Instruments, Inc.
James G. Biddle Co.
Electro Scientific Industries
Engelhard Industries
Eppley Laboratories
General Electric Company
GenRad
Guildline Instruments Ltd.
Hewlett-Packard Company
John Fluke Manufacturing Company
Julie Research Laboratories
Keithley Instruments
Knopp Inc.
Leeds and Northrup Company
Penn Airborne Products
Sangamo Electric Company
Tittex
Victoreen
Western Electric Company, Inc.
Yokagawa Electric Works

Test equipment and instrumentation manufacturers constitute a much larger segment of industry (SIC Codes 3811, 3821, 3822, and 3825). Total estimated sales in these categories for 1976, according to the Domestic and International Business Administration, U.S. Department of Commerce, were in excess of $7.7 billion [10]. Domestic customers included every segment of industry using high technology.

Electrical measuring instruments shipments were estimated to value $2.1 billion in 1975 and are expected to increase to $2.4 billion in 1976 [10]. Test instrumentation accounts for 60 percent of the output of this SIC (3825). Low accuracy meters, used in panels and switchboards, and portable meters constitute 28 percent, and watthour and other integrating meters make up the remainder. The test equipment industry is a high technology industry which is noted for rapid exploitation of technological advances. Some manufacturers spend as much as ten percent of their annual sales on research and development [9].

The growing semiconductor market, increases in the complexity of components, and their growing application to consumer products has generated an expanding market for automatic test equipment for production line quality testing and adjustment. Automatic test equipment is increasingly being used by semiconductor device users as well as manufacturers. Digital instruments are rapidly replacing analog equipment due to substantial cost reductions and the minimization of reading error.

The instrumentation market is expected to expand over the next few years as manufacturers are spurred by the need to conserve energy and costs and reduce pollution.

In the category of Engineering and Scientific Instruments (3811), navigational and guidance instruments, and automatic pilots for ships, aircraft, and space vehicles comprised nearly one half of the industrial output. Thirty percent was composed of laboratory instruments and equipment. The remainder was composed of engineering apparatus for meteorological, hydrological, geological, civil, and mechanical engineering purposes. Production of measurement and control instrumentation was expected to reach $2.8 billion in 1976 [10]. The process control portion of this industry is the portion to be considered part of the electrical instrumentation industry. There is a high degree of activity in this area spurred by manufacturers' demands for processes which are more economical or efficient and which have reduced energy consumption and environmental impact.

Exports of all instrumentation are presently at the $60.1 million level [10], having risen sharply over the last two years. Although the U.S. holds a strong lead in the most advanced instrumention, foreign competition is increasing. The recent increase in exports is expected to moderate somewhat in the future and imports are expected to increase slightly [9].

2.2.3 Reference Data

Some reference data, i.e., physical constants and other similar data, are generated in the NBS and the academic portion of the measurement system and used primarily by research scientists seeking to test and improve physical theory. Examples of such data are measured values for γ_p, the gyromagnetic ratio of the proton, and e/h, the ratio of electronic charge to Planck's constant [5, 11], both obtained experimentally at NBS. Recent accurate measurements of the speed of light have made more accurate determinations of the absolute ohm possible [3,11].

Although their use throughout the bulk of the measurement system is limited, their determination has a fundamental impact on the values of the basic maintained electrical units and as a source of improved methodology for monitoring the stability of those units. Furthermore, much work has been done at NBS to supply least-squares adjusted values for the fundamental physical constants [12]. These values, internationally sanctioned by CODATA, the Committee on Data for Science and Technology of the International Council of Scientific Unions, tie together all of the remote branches of physics and are universally used by theoretical and research physicists. Data of this type are disseminated by publication in the scientific literature.

A more widely used type of reference data is that of electrical performance characteristics used by all design engineers. This type of data is disseminated by publication in various engineering and scientific handbooks, prepared by technical institutions and private corporations, such as those given in table 9.

Data in these handbooks range from conductivity of wire, breakdown characteristics ("volt-time curves") for sphere gaps, and Kerr electro-optical coefficients to recommended circuits for various applications. The most universal of them are obtained as the result of experiments done in national laboratories such as NBS, and in universities. Others, such as transistor performance characteristics, are published by semiconductor device manufacturers. All are essential to the efficient functioning of the design engineer and the experimentalist. It is apparent that if these data were not generally available, each new advance in technology and each design of a new circuit would come only after a long period of trial and error, measurement and experimentation.

2.2.4 Reference Materials

The direct role of reference materials in the Electrical Measurement System is limited to two areas: those of eddy-current measurements of the conductivity of non-ferrous metals and measurements of resistivity of silicon used in the semiconductor industry. The eddy-current technique is widely used in the aircraft industry and its metals suppliers as a non-destructive means of determining the heat treat of alloys, notably those of aluminum and titanium. Such measurements are commonly made using eddy-current conductivity meters which actually measure the change of inpedence of a probe, driven at a certain frequency, caused by its coupling with a conducting material. Such meters are calibrated using small standard samples (coupons) of metals manufactured either by Boeing Aircraft Corporation or the manufacturers of the meters. The conductivity of the coupons is generally determined in terms of the legal unit of resistance using dc measurement methods performed on rather large samples of materials which are then cut up.

However, dc measurements thus made are of the average conductivity through the entire metal piece and in one direction only. Eddy-current measurements are localized in a small

Table 9. Sample sources of reference data for engineers

Source	Publisher
Reference Data for Radio Engineers	International Telephone and Telegraph Corporation, New York, NY
Handbook of Chemistry and Physics	Chemical Rubber Publishing Co., Cleveland, OH
The Semiconductor Data Book	Motorola Semiconductor Products, Phoenix, AZ
Formulas for Computing Capacitance and Inductance, NBS Circular 594	National Bureau of Standards, Washington, DC
American Institute of Physics Handbook	American Institute of Physics, New York, NY
Digital Logic Handbook	Digital Equipment Corp., Maynard, MA
The Transistor and Diode Data Book	Texas Instruments, Dallas, TX

volume in contact with the probe and usually limited to a shallow depth. Because of the structure of most metal samples, (grain orientation, impurities, local strain, etc.) the local conductivity can vary widely and intercomparisons of eddy-current meters and conductivity coupons have revealed some rather large discrepancies in measurements being made. Accordingly, NBS has been approached by a number of aircraft companies to establish material standards in order to eliminate these discrepancies and to remove the confusion which exists in this area. In 1977, NBS held a workshop in this area to identify the problems associated with these measurements and identify other areas where standards are needed. Plans have been made and work is underway to establish national standards of conductivity in the range between 1% and 100% of the conductivity of copper. Based upon this work, eddy-current conductivity standards or coupons of various metals will be made available through the Standard Reference Materials Program.

Standard reference samples of silicon are available through the Standard Reference Materials Program to support the measurement of the resistivity of semiconductor materials. This SRM results from work done by the NBS Electronic Technology Division and will be reported in that Division's impact report.

2.2.5 Science and People

Electrical metrology involves the direct application of principles of physics and electrical engineering to the solution of measurement problems. The role of physics is most evident in basic metrology work; the development of instrumentation and the assembly of sophisticated instruments into measurement systems. The major contribution of the measurement system to its undergirding science and technology is to provide a common means of communication, a universal technical language without which the transfer of knowledge and technology within the system would be impossible. Without such data transfer, the advanced technological society we find in the United States would not be possible.

There is heavy involvement of professional societies in the Electrical Measurement System. They provide a means of informal and formal communication of knowledge throughout the system through their meetings and publications. The following is a list of these societies:

1. Institute of Electrical and Electronic Engineers; Group on Instrumentation and Measurement
2. Instrument Society of America; Metrology Division
3. Precision Measurements Association
4. National Conference of Standards Laboratories
5. American Society for Quality Control
6. American Society for Testing and Materials
7. American Physical Society
8. IEEE Groups on

    a. Automatic Control
    b. Biomedical Engineering
    c. Circuits & Systems
    d. Communications
    e. Industrial Electronics and Control Instrumentation
    f. Reliability and Maintainability

9. IEEE Power Engineering Society

The first four of these are groups dealing directly with electrical metrology and its applications. Their members produce document standards, engage in measurement activities, such as round-robins, and, most importantly, communicate and encourage communications by means of meetings, colloquia, conferences, seminars, and producing various publications. The remaining are more peripherally involved in that their activities are supported by the system and they provide the system with backup technology and information.

The major electrical metrology publications commonly used in the U.S. are:

Metrologia
IEEE Transactions on Instrumentation and Measurement
IEEE Transactions on Power Apparatus and Systems
Measurements and Data
Instrumentation Technology
Review of Scientific Instruments

All feature technical papers on metrology in various application areas or sectors of the measurement system. More specific, detailed information on specific calibration problems is disseminated through documented calibration procedures as discussed previously.

Measurements people generally fall into one of five categories: physicist, electronic engineer, electrical engineer, statistician, or electronic technician. Those in the first four receive their professional training in universities and colleges. Electronics technicians generally receive their education as the result of military service and occasionally through correspondence or technical schools. All can improve or augment their background through the many seminars and short courses in metrology and electronics offered around the country. The field of metrology is fortunate in having a very high degree of dedication on the part of its workers.

2.3 Realized Measurement Capability

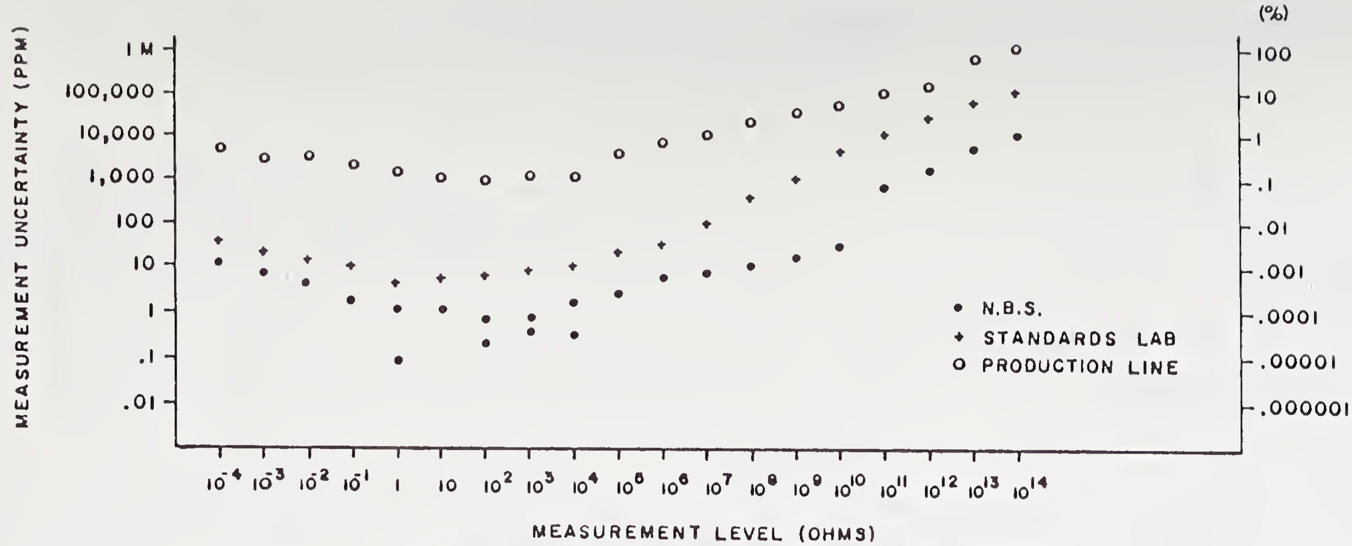
The graphs on the following two pages represent measurement accuracies available throughout the measurement system. It must be understood that they represent an oversimplification of an extremely complex interacting set of parameters. For example, the question of a specified time frame in which a measurement is made has been ignored. Environmental and power line effects have been likewise ignored. The fact that a good metrologist can coax performance far in excess of manufacturers' specifications from measurement instrumentation, given appropriate resources or complete freedom of choice regarding methodology, is not represented. In essence, the graphs represent a compilation of manufacturers' specifications and known behavior traits of populations of standards in common usage. In the interest of brevity, ac quantities have been shown at one frequency, 1000 Hz in the case of capacitance and inductance, 60 Hz in the case of energy and current ratio, and 10 kHz in the case of rms ac voltage.

The instrumentation available is adequate for the fulfillment of static measurement needs at the present time in most cases. Recent evidence, however, indicates the possible existance of a hitherto unsuspected loss of measurement accuracy as a result of high accuracy electronic instruments having been physically transported, either to be calibrated or for use elsewhere. The problem is presently being investigated.

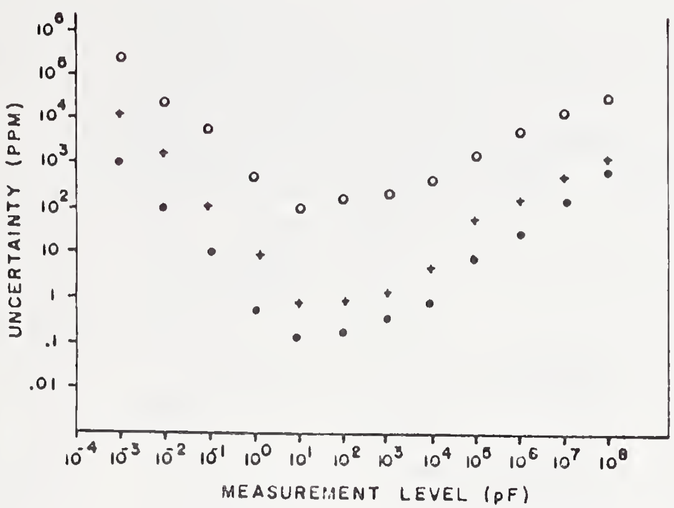
Another problem area, whose importance is emphasized in light of present economic conditions, is the cost of maintaining an instrument in calibration. Many new instruments are being designed with self-checking features to permit extension of calibration intervals or the elimination of periodic calibrations. A method of testing the verity of self-test features is desperately needed.

More and more measurements are being made by automatic test systems; assemblies of off-the-shelf commercial instruments, customized apparatus, and interconnecting circuitry, all controlled by computer. Generally such systems have some self-test capability which provides a functional check and perhaps a limited calibration using an internal standard as a reference. The self-test capability must be periodically augmented by calibrations. Usually this is accomplished by removing critical pieces of apparatus to a remote laboratory for individual calibrations which are assumed valid when the system is reassembled. Rarely are systems calibrated as systems, despite the fact that, because of temperature, interface, and electrical grounding and shielding problems, they tend to be somewhat more than the sum of their parts. The major restraining factors of systems calibration seem to be lack of acceptance of the approach by military and other government inspectors and the nonavailability of hardware specifically designed for the purpose. There does at present seem to be a growing awareness of the advantages of this methodology.

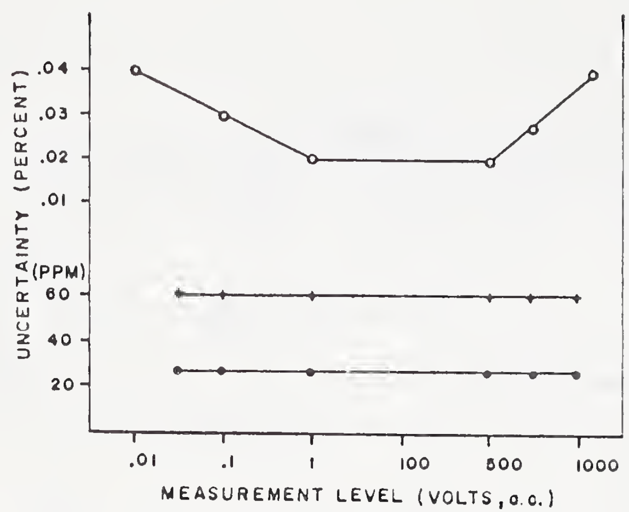
There are a few areas in which present measurement technology has fallen behind requirements. There is a problem, previously discussed, regarding the use of samples of nonferrous metals as conductivity standards for nondestructive testing purposes. Another area is that of ac voltage measurements throughout the audio frequency range. Improved measurements in this area are needed to support modern ac voltage measurement equipment. A third area is that of the measurement of impedance (capacitance) in the frequency range between 10 kHZ and 100 kHz.



TYPICAL UNCERTAINTIES IN RESISTANCE MEASUREMENTS



TYPICAL UNCERTAINTY IN CAPACITANCE MEASUREMENTS



TYPICAL ACCURACY FOR rms VOLTAGE MEASUREMENTS (AT 10 kHz)

FIGURE 4a. UNCERTAINTIES OF MEASUREMENTS

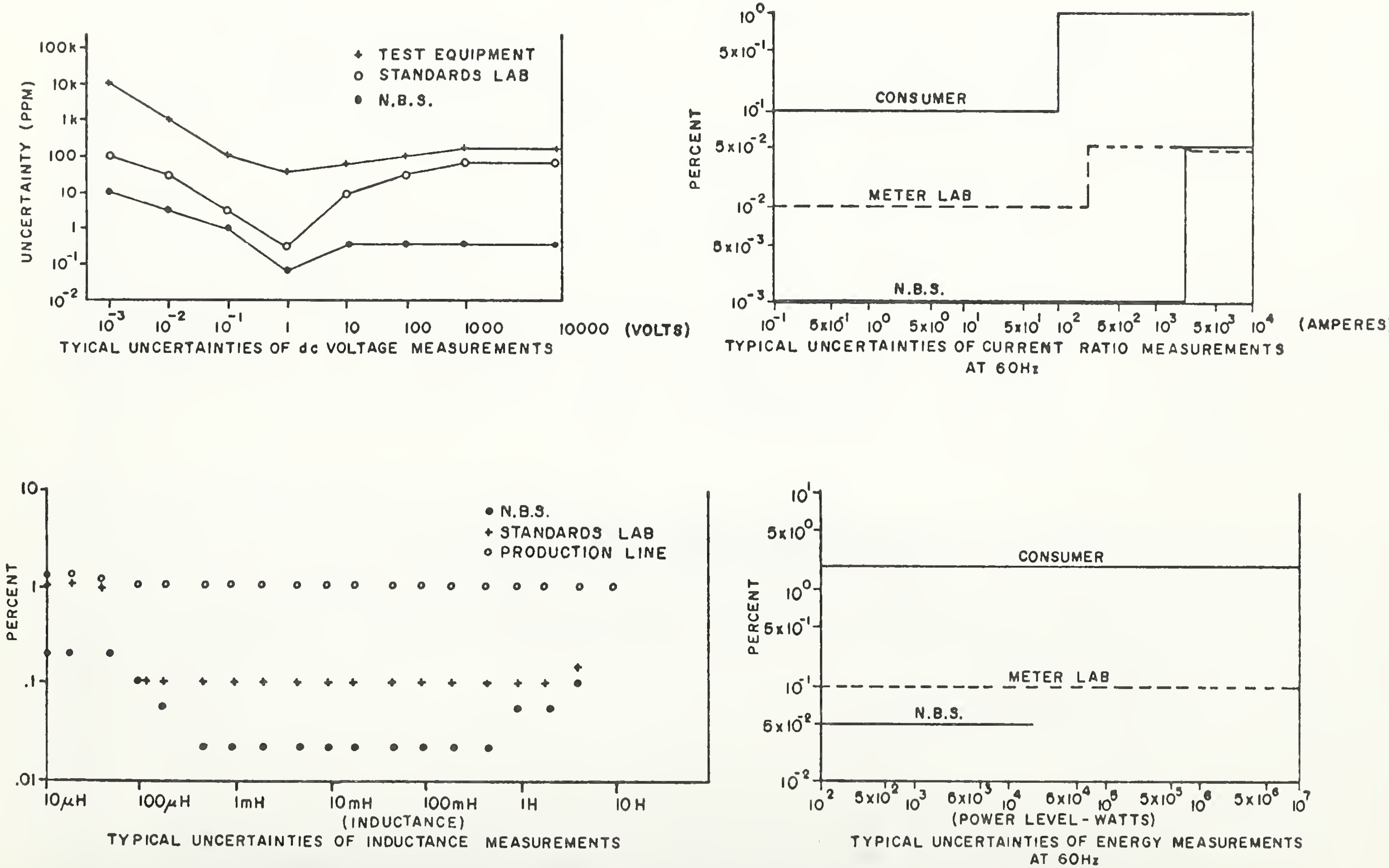


FIGURE 4b. UNCERTAINTIES OF MEASUREMENTS

The communications industry is in a trend toward increasing carrier frequencies into this range and have requested calibration data there.

The energy crisis has created some high voltage measurement problem areas. Because of the limited supplies of petroleum, electric energy will comprise an increasingly larger share of all energy consumed. Efforts are underway, sponsored by the Department of Energy and the Electric Power Research Institute, to develop more efficient and safer ways to transmit electric power. These efforts require new or improved methods and standards for measurements of impedance, ratio, voltage, and current at voltages as high as 1.2 million volts. They are needed for the evaluation of dielectric losses in insulators at cryogenic temperatures under high voltage conditions, for measurement of electric fields caused by ultra-high voltage transmission lines (to test biological effects), and for the measurement of high voltage transient signals to test their effects on lines, measurement apparatus, switchgear, etc.

As noted, the entire section thus far has concerned only static measurements, measurements in which time is not a critical factor. However, the timing of a measurement is increasingly important for two reasons. Because of the ever-increasing complexity of electronic modules, components, instruments, and systems, more and more testing is required for quality control purposes. As testing is the factor which limits the production rate of electronic goods, increasing emphasis is being placed on "thruput".

Secondly modern electronic circuitry is more usefully characterized in terms of transient responses to changing input conditions. This leads naturally to the need to measure rapidly varying parameters, to be concerned with wave shapes as well as integrated energy content. This can only be done by "sampling" or measurements at high speed.

In order to increase the speed at which measurements are made, a whole new world of automatic testing has evolved. Analog-to-digital converters with microsecond measurement times are computer-controlled and switched in systems which permit thorough testing of complicated circuits in relatively short time.

Along with this evoluation has come a degree of chaos. The conclusions of a recently-held workshop on "Critical Electrical Measurement Needs and Standards for Modern Electronic Instrumentation" [13] are:

(a) There is a need to introduce time as a measurement parameter as a result of requirements of automatic test and control systems.

(b) A host of new parameters have resulted from the application of automated systems to the production line, parameters for the measurement of which there are no standards, techniques, or even a common terminology.

(c) A need for a new or higher accuracy measurement has resulted from recent work at the leading edge of measurement technology in electronics.

From these, a number of critical, specific areas needing immediate attention were indicated. Among them were:

(1) capacitor and resistor characterization under pulsed conditions;

(2) dynamic performance characterization for modern signal conditioning and data conversion devices, such as aperature times of sample-hold amplifiers, resolution-time product for analog comparators, jitter error of digital-to-analog converters, etc.;

(3) characterization of settling times for precision sources and measurement devices, for example digital voltmeters and programmable power supplies;

(4) transport standards for system performance validation to be used as a basis for Measurement Assurance Programs;

(5) effects of dynamic loading on sources;

(6) prediction of long-term performance of components and devices from short-term behavior, for example, relating output noise and device reliability;

(7) improved transportable dc standards based upon solid state technology which would be immune to short-circuit or loading damage, not materially effected by temperature fluctuation, and perhaps at more useful levels of voltage, current, or resistance than are present standards;

(8) measurement of dielectric hysterisis in capacitors and other components; and

(9) generation of nonsinusoidal, high crest factor precision signals for true rms calibrations.

The workshop was attended by 24 participants who represented a variety of industrial and government organizations. The abstract, preface, and list of participants from the final report of the workshop (published as NBS Technical Note 865) are appended [Appendix C].

2.4 Dissemination and Enforcement Network

2.4.1 Central Standards Authorities

The Bureau International des Poids et Mesures (BIPM) is the supranational authority of the electrical measurements world. In its laboratories are housed artifacts embodying international standards of voltage and resistance. At three-year intervals, BIPM undertakes the intercomparison of transportable standards of voltage and resistance from the major national laboratories of the world and its own international standards. The published results of these intercomparisons are generally accepted as quantifying the differences among the units of the participating countries. BIPM also sponsors international exchanges, such as a present round-robin intercomparison of transportable capacitance standards. Such devices are measured at various national laboratories and the results submitted to BIPM. At the conclusion of the experiment the results are published.

The Consultative Committee on Electricity, to which the Chief of the Electricity Division, NBS, is a delegate, advises and recommends courses of action to BIPM in matters dealing with electrocal metrology.

The National Bureau of Standards is the delegated legal authority for electrical measurements in the United States. Public Law 617, 81st Congress (21 July 1950), states in Section 12:

> "It shall be the duty of the Secretary of Commerce to establish the values of the primary electric and photometric units in absolute measure, and the legal values for those units shall be those represented by, or derived from national reference standards maintained by the Department of Commerce."

Most nations with modern technological capabilities have organizations performing the function of maintaining legal electrical units. Aside from minimizing the effects of discrepancies between legal electrical units on export trade, the major interaction between these laboratories and the Electrical Measurement System is to provide an international redundancy in the realization of the absolute electrical units. Parallel experiments, perhaps with differing approaches and performed under different roofs, offer the best opportunity to eliminate the effects of unidentifiable systematic errors from experimental results. Since adjustments to units are made as the result of these experiments, redundancy in them is of great importance.

2.4.2 State and Local Offices of Weights and Measures

The Electrical Measurement System only interacts with the weights and measures field to the extent of providing the basis for design and maintenance of any electronic equipment used in that field.

2.4.3 Standards and Testing Laboratories and Services

Three kinds of laboratories provide measurement services to the Electrical Measurement System. Standards laboratories are those laboratories which can provide for the calibration of electrical standards with accuracies within an order of magnitude of those offered by NBS. They may well be, and usually are, capable of providing calibration services for nearly any type of instrument over any range of parameters and at any accuracy level up to those of the basic standards. A calibration laboratory, on the other hand, calibrates and repairs test equipment and production-line equipment of more moderate accuracy. The third type of laboratory is a testing laboratory. Although it may offer services similar to the other two, it is characterized by facilities for environmental, safety, and performance testing.

The first two types can be either the basic measurement laboratory of a large corporation, the service repair department of an instrument manufacturer, or a small private company dealing only in those services mentioned. Standards laboratories tend to be of the first two varieties, whereas calibration laboratories tend to be of the third.

Within the electric power industry one can make a distinction between the utility and manufacturing sectors. The major utility companies each operate a kind of laboratory which can be characterized as a mixture of the standards and calibrating laboratory with some functions of a testing laboratory. With respect to accuracy, the most demanding requirement is for watthour meter and instrument transformer calibration. For these functions the laboratory maintains high quality standards, with accuracies within an order of magnitude of those of NBS standards. The same laboratory usually also calibrates and repairs test instruments for the company. Finally, the laboratory may have jurisdiction over the acceptance tests of all incoming and in-service watthour meters and instrument transformers. The latter is a function of a testing laboratory.

Within the manufacturing sector, the typical laboratory can be classified as a testing facility employed in quality control and performance testing of a company's products. This laboratory may obtain standards services from a standards laboratory elsewhere within the company, may occasionally ask for NBS help, or may rely on traceability through the supplier of the measuring instruments.

Appendix D contains a list, drawn from the sources indicated, of standards and calibration laboratories whose services are available to extra-company organizations. It is not exhaustive. The 138 laboratories listed, along with others of their kind and the major military and corporate laboratories supplying services only within their own and subcontracting organizations, provide the traceability skeleton supporting the body of electrical measurements in this country.

Of federal laboratories other than NBS, apparently only three offer electrical calibration services on a fee basis. They are:

(a) U.S. Army Electronics Command, Ft. Monmouth, NJ
(b) Naval Air Rework Facility, Norfolk, VA
(c) Navy Eastern Standards Laboratory, Washington, DC

Other military and NASA laboratories will generally provide a contractor with services if they are not elsewhere available, or if it is to the advantage of the government.

All the above-mentioned and those included in the referenced appendix are laboratories having services available to outside organizations on a fee basis. No mention has been made to this point of the remaining group, namely, those laboratories which provide services only internally, to their own organization. Of the 222 standards laboratories listed in *A Directory of Standards Laboratories* [14], 164 have dc and low frequency capability, and only 65 choose to make that service available to outside firms or organizations.

An analysis was made in 1973 of NBS calibration clientele for the purpose of determining, among other things, the general magnitude of the Electrical Measurement System. A representative sample of clients' names was classified by primary SIC code by Dun and Bradstreet. The resulting list of code numbers was filtered to remove obvious measurement-void categories. Dun and Bradstreet's data base, which contains information on over 3 million U.S. companies, was then searched to provide information on all companies in the relevant group with numbers of employees in excess of 25. Information was provided on 12,865 companies. Even though this figure is not an accurate count of measurement-intensive organizations due to the way the individual SIC code numbers are assigned, it is a good protrayal of the extensiveness of the measurement system. In fact, the figure is on the low side because companies engaged in routine measurements without rigid traceability requirements are not included. Efforts to sample this grey area of the system have been minimal due to financial constraints.

For companies not having rigid traceability requirements, the measurement system may flow through the company via the electronic maintenance shop or the outside organization which performs this function for them. Many of the laboratories in Appendix C also perform repair functions.

For organizations which must maintain traceability because of contractual or legal requirements, the flow of electrical units through the system becomes more stylized. The flow of the electrical units through such an organization is depicted in figure 5. The corporate or primary laboratory may receive its units from NBS or from any outside laboratory. It is repsonsible for the most accurate standards in the organization.

The actual organizational relationship of these various components varies from corporation to corporation. An extremely large corporation, such as Boeing Aircraft, may have a corporate standards laboratory which serves as a single tie between NBS and all of its calibration laboratories. Other large companies such as Honeywell and IBM have a standards laboratory at each location and many such laboratories have standards calibrated by NBS. Other corporations such as 3M and General Electric do not make the use of any particular structure mandatory. Each operating division is autonomous and may pursue its quality assurance program quite independently.

In smaller organizations the standards and calibration facilities are usually combined. Occasionally even the maintenance shop is in the same organization, if not in the same room. These basic elements are always present, however, even if not structurally distinct. Take the case, for example, of a small company employing about 800 persons, which is concerned with the manufacture of temperature and air speed transducers and allied instrumentation. They have need of extremely accurate resistance standards because of their temperature work. However, their dc voltage requirements are not as stringent. They have their resistance standards calibrated at NBS, but their corporate voltage standard is a digital voltmeter calibrator which is calibrated for them periodically by another company in the area.

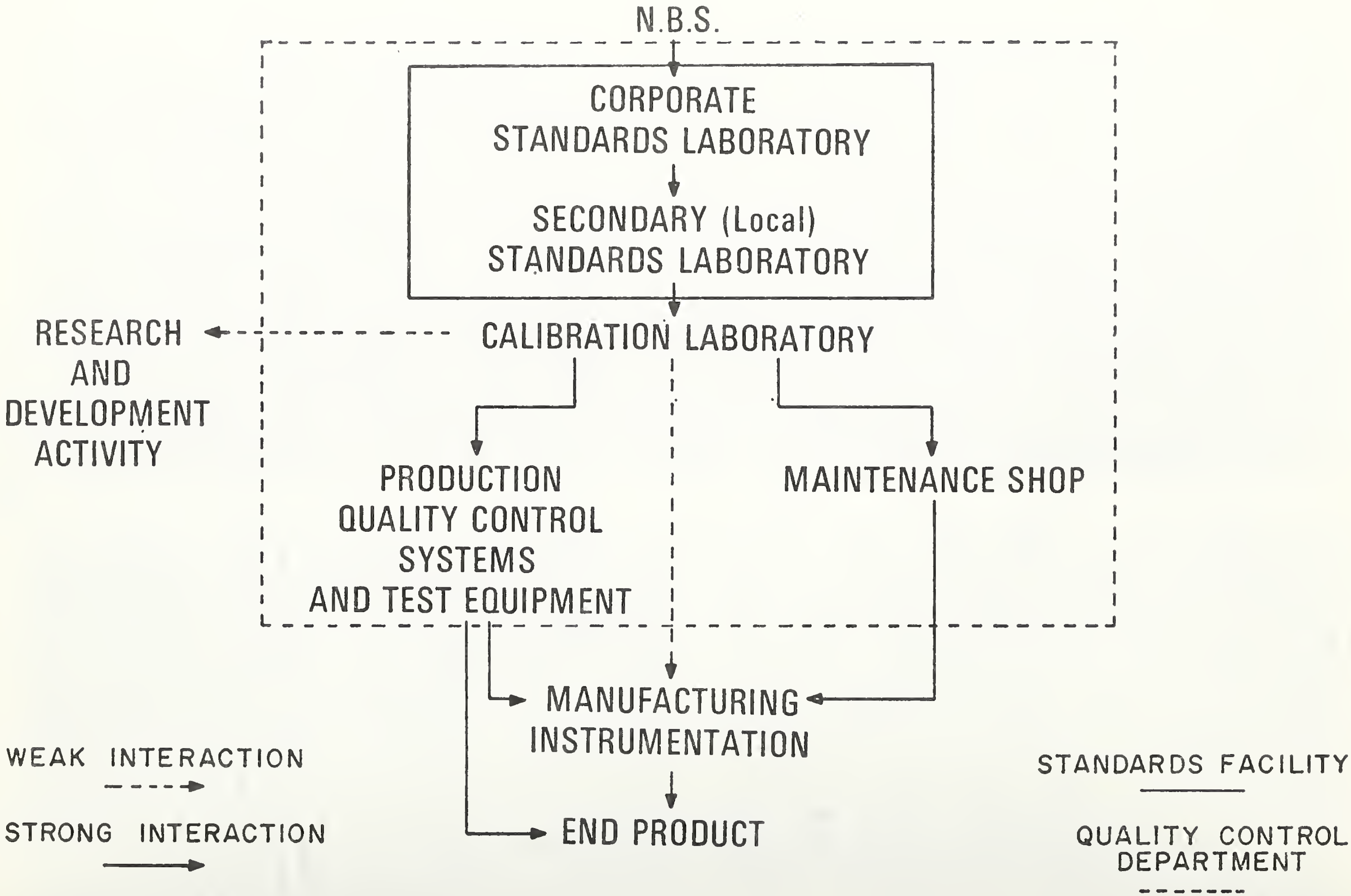


Figure 5. Typical corporate support structure

Representative organizational charts for two large corporations and the U.S. Air Force are to be found in Appendix E.

The specific structure of any given part of the measurement system is a function of the technical requirements of the end product, the legal obligations of the organization, the financial resources available, and the standards, apparatus, and test equipment available to meet the ultimate measurement requirements.

2.4.4 Regulatory Agencies

Table 10 gives the titles of regulatory agencies and agency categories impacting the Electrical Measurement System.

Table 10. Regulatory agencies and agency categories

Federal Government

1. Nuclear Regulatory Commission
2. Environmental Protection Agency
3. Federal Aviation Administration
4. Food and Drug Administration
5. National Highway Traffic Safety Administration
6. Occupational Safety and Health Administration

State Governments

State Public Utility Commission

The Nuclear Regulatory Commission (NRC) has the function of being Federal watchdog over radioactive materials in this country for both security and safety purposes. They have issued regulations which compel the formation of quality assurance programs in nuclear power plants and fuel reprocessing facilities. Regulation 10CFR50, "Licensing of Production and Utilization Facilities" has an Appendix B entitled "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants." This Appendix and corresponding Regulatory Guides call for periodic calibration of all measuring equipment. The result of such regulations is the establishment of standards and calibration laboratories at all nuclear use and processing sites to ensure the quality of measurements at such sites.

The Commission is presently in the process of revising these regulations to improve their clarity. The National Bureau of Standards is anticipated to be called upon to provide technical assistance in this activity.

The Environmental Protection Agency (EPA) has an indirect effect on the Electrical Measurement System. The instrumentation, which is required by the agency and by industry to monitor pollution, is used mostly for analytical and accoustic measurements. Sales of such instruments are increasing at a rapid rate, sparked by large increases in federal and private research and development in this area [9]. This equipment is basically electronic in nature and, as such, requires maintenance, if not electrical calibration.

The Federal Aviation Administration (FAA) is responsible for all air travel safety in the U.S. It regulates the communications and navigation equipment used in the air travel system. A measurement laboratory facility is maintained in Atlantic City, NJ, which supports a network of navigation aids such as radar systems, landing systems, and beacons at airports throughout the country, in addition to a test facility for avionics on the Atlantic City site. In addition, the FAA is now in the process of implementing a program for the periodic recall and calibration of all test equipment in its system. This new calibration structure may be ultimately supported by the standards laboratory of the FAA maintenance and repair depot in Oklahoma City.

The Food and Drug Administration, as was pointed out previously, is expanding into the regulation of medical devices. Aside from the proposed regulatory program for new products described in Sec. 2.2.1.1, they are involved in a program to ensure safety through the proper level of application of voltage to x-ray tubes. It was found as a result that the voltage dividers used for measurement of cathode voltages were poorly calibrated at best and improper x-ray dosages resulted. Bureau of Radiological Health support resulted in the establishment of a calibration service for such dividers at NBS.

The National Highway Traffic Safety Administration is responsible for enforcement of the application of safety standards to automobiles. The group monitors the whole field of automobile safety testing. Use is made of Society of Autmotive Engineers' specifications to detail methods to be followed in the testing and to prescribe requirements for quality assurance. Periodic test and calibration of measurement instrumentation using standards traceable to NBS are features of SAE Standard J21b. Manufacturers are required to abide by its provisions.

The Occupational Safety and Health Administration generates job-related safety regulations. Its major impact on the Electrical

Measurement System is its requirement that certain devices be safety-tested in accredited laboratories. That requirement is expected to be the forerunner of many future requirements for laboratory accreditation programs. None of the methodologies yet proposed embodies a valid scheme to ensure the proper behavior of standards, instruments, and systems on a continuous basis, either through careful monitoring or any other means. A real need exists for a technically-valid scheme for accreditation.

State Public Utility Commissions, in addition to regulating the rates charged consumers of electric power, regulate the system by which energy transfer is monitored to determine total user costs.

Watthour measurements are used to quantify energy distributed within the power system for metering purposes. The electric power companies are generally required by the Public Utility Regulatory Commisions in individual states to supply users with watthour meters accurate to within 2%. Refunds are required for overcharges if the meter regulation is found to be in error -- faster than nominal -- by more than 2%. While power companies are entitled to recompense from users should the meter err in their favor, they generally do not bill such users because of the bad publicity which could result. Because of this situation, power companies typically calibrate new watthour meters with an uncertainty of 0.1-0.2 %. Measurements at this relatively high level of accuracy also permit new meters to be inspected using sampling techniques, thus avoiding the large amount of work required to inspect 100% of the incoming lot. Because this practice is common in the power industry, meter manufacturers must also use strict measurement tolerances.

Installed meters are generally recalibrated throughout the industry. However, there is no industry-wide established interval between calibrations. This interval ranges generally from five to fifteen years and in most instances is done on a sampling basis with 100% recalibration only being performed on the basis of poor results from an initial group of tests. These measurements are made with the same uncertainty as are those on new meters.

Of all quasi-regulatory activities, procurement regulations governing suppliers of the Department of Defense and the National Aeronautics and Space Administration have the greatest impact on the measurement system. The present hierarchical system of laboratories, accuracy needs at the primary standards level, and the generation of use of detailed calibration procedures all stem from the enforced application of MIL-C-45662a, MIL-Q-9859a, MIL-I-45208a, and the equivalent NASA regulations, all detailed previously.

2.5 Direct Measurement Transactions Matrix

2.5.1 Analysis of Suppliers and Users

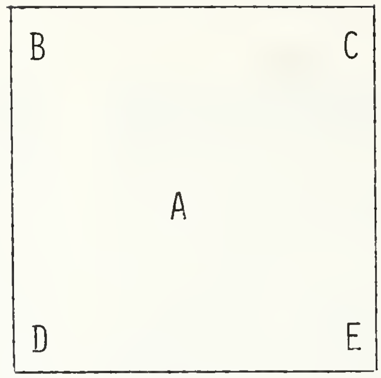
The organizational input-output matrix in Figure 6 is a portrayal of the present magnitude and importance of measurement transactions among various segments of the economic system. Each entry in the array gives the magnitude, role of changes, import, adequacy, and type of transaction according to the code in Figure 7. An "X" as a particular entry indicates that the transaction was excluded from the study for some reason. Entries of "0", "X", or "?" require no further information for that transaction. It must be remarked that the matrix is only a qualitative portrayal. The uncertainties in each ranking factor are high (±2) as it is difficult to quantify relationships such as quantity or volume in the context of various sizes and technical contents of industries. The general approach taken was that a measurement capability could not cease to exist, since in that sense, the "Importance" entry would be 4 by any rational consideration for each transaction. In addition, those industries which require measurements, instrumentation, and standards closest to the state-of-the-art" naturally are more familiar to the authors and received more attention during the course of the study as they are the most likely source of measurement problems.

2.5.2 Highlights re Major Users

Although virtually every segment of manufacturing depends to some extent on the ability to make electrical measurements, major users of the measurement system have a very stringent need for an accurate measurement capability. These are the aerospace industry, the calibration and repair industry, civilian agencies of the Federal government, electronic component manufacturers, computer manufacturers, the Department of Defense, the instrumentation industry, the power industry, and research institutes. It should be understood that technical measurement problems to be found in this system are generally not unique to a specific segment of industry in the SIC sense. Rather they are generally associated with a broad class of activity such as instrument maintenance or quality control of electronic products and accordingly are not belabored in this section. Pressing problems which are industry-peculiar are mentioned.

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR Electrical Quantities — USERS / SUPPLIERS	Knowledge Community 1	International Metrology Organizations 2	Documentary Stds. Organizations 3	Instrumentation Industry SIC 38 4	NBS 5	Other US National Standards Authorities 6	State and Local Office of Weights & Measures 7	Standards & Testing Laboratories & Services 8	Federal Regulatory Agencies 9	DoD except Standards & Cal. Labs. (Under 8 above) 10	Civilian Federal Government Agencies 11	State & Local Government Agencies 12	Industrial Trade Association 13	Agriculture, Fishing Mining SIC Div. A&B 14	Construction Div. C 15	Food, Tobacco, Textile, Apparel, etc. SIC #5 20-26;31 16	Chemical Petroleum, Rubber, Plastics etc. SIC 28-30, 32 17	Metal Products SIC 33-34, 391 18	Non-Electrical Machines SIC 35 19	Electrical & Electronic Equipment SIC 36 20	Transportation Equip. SIC 37 21	Transportation & Public Utilities SIC Div. E 22	Trade, Insurance, Finance, Banking, etc. SIC Div. F-H & J,#27 23	Health Services SIC 84 24	General Public 25
1 Knowledge Community	2 3 1 3 ADE	2 2 1 2 ADE	2 1 1 2 A,D	3 3 1 2A,D-F	4 4 1 2 ADE	3 3 2 3 E	X	3 3 1 2 D	X	X	X	X	X	X	X	X	2 2 1 2 D	2 2 1 2 D	2 2 1 2 D	2 2 1 2 D	2 2 1 2 D	2 2 1 2 D	X	X	X
2 International Metrology Organizations	2 2 1 2 A,D	3 2 2 2 ABD	1 2 1 2 AD	3 2 1 2A,D-F	4 3 2 2ABDE	3 3 2 3 E	X	3 2 1 2 AD	X			X								3 3 1 2 A	3 3 1 2 A	3 3 1 2 A			
3 Documentary Stds. Organizations	2 3 1 2 D	2 3 1 2 D	3 3 2 3 DF	2 3 1 2 D	2 1 1 2 DE	X	X	2 2 1 2 ED	2 2 1 2 D	2 2 1 2 D	2 2 1 2 D	X	2 2 1 2 E				2 2 1 2 D	2 2 1 2 D	2 2 1 2 D	2 3 1 2 D	2 3 1 2 D	2 3 1 2 D		2 2 2 2 D	
4 Instrumentation Industry SIC 38	2 3 1 2 BCD	3 1 1 2 CD	2 4 1 2 D	4 4 2 3 B-E	3 4 2 3 CE	3 2 1 2 BCD	3 1 1 2 BCD	3 4 1 2 BCD	3 3 1 2 BCD	3 4 3 3 BCD	3 3 1 2 BCD	3 1 1 2 BCD	2 3 1 2 AE	X	X	X	2 4 2 3 BCD	3 3 1 3 BCD	3 3 1 3 BCD	3 4 3 3 BCD	3 4 3 2 BCD	3 4 2 2 BCD	2 1 1 3 BC	3 3 2 3 BCD	1 1 1 3 C
5 NBS	3 3 1 3 ABD	3 3 1 2 A-E	2 3 1 3 AD	4 4 3 3 A-E	4 4 1 3 A-E	2 2 1 2 A-D		3 4 3 2 A-E	3 3 2 3 BD	2 2 2 2 DB	3 3 1 2 B	3 2 1 2 B	1 2 1 2 D				3 1 1 2 B	3 1 2 2 B		3 3 1 2 BD	3 4 1 2 B-E	3 4 1 1 BD		3 2 1 2 BD	
6 Other US National Standards Authorities	X	3 3 2 3 CE	X	2 1 1 2 E		X		2 1 1 2 E	1 3 1 3 ACD	X	X	X	1 1 1 2 ACD				2 2 2 3 ACD		2 2 2 3 ACD	3 3 2 3 ACD	3 3 2 3 ACD	2 3 2 3 ACD		3 3 2 3 ACD	
7 State and Local Office of Weights & Measures	X	X	X	2 1 1 2 E			X	2 1 1 2 E				X													
8 Standards & Testing Laboratories & Services	3 3 1 2 BDE	1 1 1 2 DE	2 3 1 2 D	3 4 3 2 DE	2 3 2 2 E	3 1 1 2 B	1 1 1 2 B	3 4 1 2 B-E	3 3 1 3 BD	3 4 3 3 BDE	3 3 1 2 BD	3 1 1 2 BD	X	X	X	X	3 4 3 2 BD	3 3 1 2 BD	3 2 2 2 BD	3 4 3 2 BD	3 4 3 2 BD	3 4 1 2 BD		3 2 1 3 BD	
9 Federal Regulatory Agencies	2 1 1 3 E	X	2 2 1 3 D	3 3 1 3 EF	2 2 2 3 E	3 2 1 3 E		3 3 1 3 E	1 1 1 3 DE	3 2 1 3 F	3 2 1 3 F	3 1 1 3 F	2 2 1 2 E	X	X	X	3 3 1 3 F	3 2 1 3 F	3 3 1 3 F	3 4 1 3 F	3 3 1 3 F	3 3 1 3 F		3 3 2 3 F	
10 DoD except Standards & Cal. Labs. (Under 8 above)	2 2 1 2 DF		2 2 1 2 DE	3 4 3 2 EF	2 2 2 2 EF	X		3 3 3 2 E	X	3 4 2 2 C-F		X	2 2 1 2 EF				3 3 1 2 F	3 3 1 2 F	3 3 1 2 F	3 4 1 3 EF	3 4 1 3 EF			3 2 1 3 F	
11 Civilian Federal Government Agencies	2 1 1 2 D		1 2 1 2 DF	2 1 1 2 E	2 1 2 2 E	X		3 2 1 2 E	2 1 1 2 B		1 2 1 2 B						3 2 1 2 EF	3 2 1 2 EF	3 2 1 2 EF	3 3 1 2 EF	3 3 1 2 EF	3 2 1 2 EF		3 2 1 2 D	
12 State & Local Government Agencies	X	X	X	2 2 1 2 E	2 1 1 2 E	X	X	3 2 1 2 E	X	X	X	2 2 1 2 B-D	X	X	X	X	X	X	X	X	X	X	X	X	X
13 Industrial Trade Associations	X		3 4 1 2 E	3 4 1 2 E	2 3 1 2 E	1 1 1 2 E		3 2 1 2 E	X			X	2 2 2 2 D-F				1 2 2 3 DE	1 2 2 3 DE	1 2 2 3 DE	1 2 2 3 DE	1 2 2 3 DE	1 2 2 3 DE			
14 Agriculture, Fishing Mining SIC Div. A&B	X			X				X				X		X	X	X	X	X	X	X	X	X	X	X	X
15 Construction Div. C	X			X				X				X		X	X	X	X	X	X	X	X	X	X	X	X
16 Food, Tobacco, Textile, Apparel, etc. SIC #5 20-26;31	X			X				X				X		X	X	X	X	X	X	X	X	X	X	X	X
17 Chemical, Petroleum, Rubber, Plastics etc. SIC 28-30, 32			2 1 1 2 D	3 1 1 2 E	2 1 1 2 E	2 2 2 3 E		2 2 1 2 E		3 3 1 2 A	3 2 1 2 A	X	1 2 2 3 E	X	X	X	2 3 1 3 B-E	X	X	X	X	X	X	X	X
18 Metal Products SIC 33-34, 391			2 1 1 2 D	3 1 1 2 E	2 2 2 2 DE			2 2 2 2 E		3 3 1 2 A	3 2 1 2 A	X	1 2 2 3 E	X	X	X	X	2 2 2 2 B-E	X	X	X	X	X	X	X
19 Non-Electrical Machines SIC 35			2 1 1 2 D	3 1 1 2 E		2 3 2 3 E		2 1 1 2 E		3 3 1 2 A	3 2 1 2 A	X	1 2 2 3 E	X	X	X	X	X	X	X	X	X	X	X	X
20 Electrical & Electronic Equipment SIC 36	3 3 1 2 D	2 3 2 3 DE	2 2 1 2 D	3 4 1 2 E	2 3 1 2 E	2 3 2 3 E		3 4 1 2 DE		3 4 1 2 A	2 3 1 2 D	X	1 2 2 3 E	X	X	X	3 3 1 2 A	3 3 1 2 A	X	4 4 2 3 A-E	3 2 1 2 AD	X	X	X	X
21 Transportation Equip. SIC 37	3 4 1 2 D	2 3 2 3 DE	2 3 1 2 D	3 4 1 2 E	2 4 1 2 E	3 3 2 3 E		3 4 1 2 E		2 3 1 2 A-D	2 3 1 2 D	X	1 2 2 3 E	X	X	X	2 2 1 2 ADE	2 2 1 2 ADE	2 1 1 2 ADE	3 4 1 2 ADE	2 2 2 3AB-D	2 2 1 2 AF	X	X	X
22 Transportation & Public Utilities SIC Div. E	2 2 1 2 D	2 3 2 3 DE	3 3 1 2 D	2 3 1 2 E	2 4 1 3 E	2 3 2 3 E		2 3 1 2 E			2 3 3 2 A-D	X	1 2 2 3 E	X	X	X	X	X	X	X	X	3 3 1 3 BE	X	X	3 4 1 3 A
23 Trade, Insurance, Finance, Banking etc. SIC Div. F-H & J,#27	X											X		X	X	X	X	X	X	X	X	X	X	X	X
24 Health Services SIC 84	X		2 2 1 2 E	3 2 2 2 E	2 1 1 2 E	3 3 2 3 E		3 1 3 2 E		3 2 1 3 A	3 2 1 2 B	X		X	X	X	X	X	X	X	X	X	X	3 1 2 3 B-E	X
25 General Public	X			1 1 1 3 E								X		X	X	X	X	X	X	X	X	X	X	X	2 1 1 3 BC

Figure 6. MATRIX



A. Volume or quantity of transaction

0 - Trivial (other entries not needed)
1 - Minor
2 - Moderate
3 - Above average
4 - Major
X - Excluded from study

B. Importance

1. Convenience; not essential
2. Economically important
3. Legally required; no alternative source
4. Absolutely essential

C. Adequacy of Transaction

1. Under control
2. Marginally adequate
3. Deficient, but useful
4. Out of control; totally inadequate

D. Rate of change of transactions

1. Declining volume (negative)
2. Stable (0)
3. Growing (+)
4. Explosive growth (very +)

E. Type of transaction

A. End use measurement data (specifications, etc)
B. Other measurement services (calibrations, etc.)
C. Measurement instrumentation and software
D. Measurement "How to" information
E. Measurement requirements information
F. Legal performance specifications

Figure 7. Code for transaction matrix

Aerospace (SIC Codes 3721, 3724, 3728, 3761, 3764, 3769, and 3662). The aerospace industry is that segment of manufacturing which produces space vehicles and aircraft and their supporting electronics systems for both military and civilian applications. It is a high technology industry (engineers and scientists employed, 161,000) which makes extensive use of electronics in the develop ment and manufacture of its products, and especially, for their weapons and guidance systems. The industry is a large one, with estimated sales of products and services in 1974 of $20.9 billion of aircraft and parts, $9.6 billion of electronic systems support equipment, and $5.8 billion of guided missiles and space vehicles [9]. Estimated total sales (1976) are $35.7 billion with an estimated electronics content in excess of $20 billion. The estimated exports value of aerospace equipment for 1976 is $7.6 billion, the third consecutive year that this industry's exports have exceeded $7 billion. This industry embodies 2,107 establishments and employs about 928,000 workers [10].

The primary impact of this industry is upon our national defense. Slightly over ten percent of the aircraft produced were sold to the Department of Defense as were all guided missiles. These products are vital to the national security. Important secondary benefits have come from this source. Consumer electronic products have been revolutionized by such spin-offs from the aerospace industry as monolithic large-scale integrated circuits whose low cost, reliability, and small size per unit function have permitted the production of quartz crystal watches, pocket calculators, and miniature radio sets at exceedingly low cost.

An increasing portion of the output of the electronic systems component (SIC Code 3662) of this industry is being consumed by civilian-oriented commercial and industrial firms. This is due to the need in industry to make more use of digital data transmission, automated process and quality control, and telecommunications to offset rising labor costs and lower profit margins. Such areas as satellite communications systems, data networks, land-mobile radio communications, and interactive, broadband cable communications systems contribute heavily to this increase.

The electronic systems component is an area in which exports are expected to rise sharply, 23%, from 1975 to 1976. This is largely due to increased consumption in the developing nations and, particularly, the oil-producing nations of the Middle East. These countries, particularly Iran, Saudi Arabia, and Indonesia, are attempting to develop their industrial bases in the avionics, industrial, electronics, and communications areas, in addition to increasing their military sophistication [10]. Exports in this area are expected to increase for the next five years.

Electrical measurements in the aerospace industry are used to characterize electronic circuitry of all types, both for the assurance of quality and compatibility in manufacture and for maintenance while in service. Accuracy requirements for so-called end measurements are quite high (as high as 10 ppm, in some cases) due to the sophistication and precision of guidance and weapons systems. Since nearly all companies in this category are contractors or subcontractors to the Department of Defense or to the National Aeronautics and Space Administration, the industry is subject to the provisions of the regulations used by these government agencies to assure quality in the systems and vehicles procured. The concepts there outlined are instrumental in making the accuracies required of an individual corporate calibration support structure quite high.

Measurement problems faced by the aerospace industry are as follows:

(a) to reduce the cost of quality control efforts in the face of a slightly deflated market while adhearing to DoD and NASA requirements and regulations [10,13,15]; and

(b) measurement problems inherent in the use and support of automatic test equipment, such as those resulting from failure to calibrate under use conditions (e.g., making dynamic use of A-D converters which have been calibrated statically) [15,16].

Calibration and repair of test equipment (SIC Code 7393). There is a small industry in the U.S. having to do solely with the calibration and repair of instruments, test equipment, and standards. Most companies involved in this activity are quite small, having annual incomes of less than $500,000 and employing less than 25 people. These companies supply calibration and repair services to a variety of industries, such as small component manufacturers, transducer makers, small electronic job shops, and other companies whose calibration needs are so modest that the establishment of an internal capability would be unduly costly. (Such service is provided also on a fee basis by the corporate standards laboratories of many large corporations. See Appendix D.)

Equipment used by such companies ranges from state-of-the-art standards and calibration equipment to older test equipment of relatively poor accuracy. This results in a wide range of capabilities being available, from the state-of-the-art to meter accuracies, that is, three to five percent. In most cases the capability is equal to the job performed. Problems related to electrical measurements in this industry seem to be logistical in nature. Lack of facilities for training, poor communications of technical data, increasing costs of publications, and an increasing shortage of experienced technicians are a few examples.

Civilian agencies of the Federal government (SIC Div. 1). Those civilian agencies which have or support (as opposed to require) an electrical measurements capability are as follows: Federal Aviation Administration, Bureau of Reclamation, Energy Research and Development Administration, National Aeronautics and Space Administration, Tennessee Valley Authority, and National Oceanic and Atmospheric Administration. FAA activity was covered in Sec. 2.4.4. The Bureau of Reclamation operates Hoover Dam and leases power generated thereby to five regional power companies. The organization has a standards laboratory that supports all of the maintenance and power monitoring equipment on the site.

The Department of Energy (DOE) has a contracted primary standards laboratory in Albuquerque, NM, run by the Sandia Corporation, which is responsible for supporting and assuring quality of measurements and contractural compliance with calibration requiremnts at each of the DOE field sites. The National Aeronautics and Space Administration (NASA) maintains a large number of standards laboratories, one at each of its major centers and tracking facilities. NASA has an extremely large test equipment inventory which is used to support space electronics, its computer network, communications equipment, tracking systems, and aircraft. Many of these laboratoies are staffed by contractors but the agency owns all of the equipment.

The Tennessee Valley Authority laboratory at Chickamauga Dam, TN, supports the power monitoring equipment and electronic maintenance areas at that facility. The National Oceanic and Atmospheric Administration supports the test and measuring equipment it uses in its investigation of undersea and atmospheric phenomena by maintaining a standards and calibration facility at the Navy Yard Annex in Washington, DC.

The social impacts of these agencies are wide-ranging. The Department of Energy plays an ever more important role in the search for means of alleviating our energy shortage. Since it is a highly technical endeavor, the use of measuring apparatus is heavy, and electrical measurements, especially those at high voltages, are of prime importance. NASA is concerned not only with space ventures but also with air transportation problems. Technical spin-offs of its programs have resulted in the creation of whole new technologies such as integrated circuit technology.

Electronic components (SIC Code 367). The industry employs about 359,000 people in about 2,500 establishments. The industry's gross sales were $10 billion in calendar year 1975, and are projected to exceed $11 billion in 1976 [10]. Exports in this field are at the $1 billion mark and increasing rapidly; up 23% from 1974 to 1975. It produces such components of electronic equipment as resistors, capacitors, inductors, diodes, transistors, integrated circuits, tubes, and rheostats. By doing so, the industry provides versatility and cost effectiveness for every electronics-intensive industry such as those involving the production of automotive electronics, communications equipment, instrumentation and process control equipment, etc.

Measurements are vital to this industry for both product quality control and development of new products. The biggest measurement problems faced here are those concerned with the proper calibration of very high-speed component testers. Such equipment is used to test large numbers of resistors, capacitors, or other components at a high rate of test. Even more importantly, complex integrated circuits must be thoroughly tested in a short time frame. The time taken per measurement is generally much shorter than the time per measurement allowed in the calibration process, and for that reason the calibration data may not be valid when the tester is used on the production line.

There are a few problems having to do with the state-of-the-art in measurements. For example, solid-state device manufacturers are generally convinced that some of the voltage reference devices they produce have stabilities in the sub part-per-million (ppm) range over the short-term and long-term (a few weeks) may be as stable as 1 or 2 ppm. Few, if any, of these same manufacturers, however, have a measurement capability adequate to determine this. Such capability would mean a cost savings to industry as a whole because if these devices are indeed capable of such stabilities, more accurate instruments could be built and instruments being built at present accuracies would require less frequent calibrations and possibly less maintenance. Even if the reference devices were not found to be as stable, an improved measurement capability would result in the ability to determine their stability with fewer measurements taken over a shorter time span. Manufactured devices could thus be much more easily categorized and sorted. Similar problems exist in the scaling processes for other units such as resistors.

Computer manufacturers (SIC Code 3573). Sales of the computer industry were $10.4 billion for 1975 and are estimated to increase to $12.1 billion in 1976 [10]. This rapidly growing industry (current growth rate is about 14% per year) is estimated to have 179,000 employees. Its output products, computers, large and small, and peripheral equipment, are being used more and more throughout our society. They are used as accounting machines, problem solvers, process controllers, navigation aids, machinery controllers, and in nearly every other situation where decisions must be made and action taken on the basis of numerical data. The advent and continuing improvement of the minicomputer, a small, inexpensive, and reliable computer, and the microprocessor, a computer on a chip, have made the tremendous power and capability of the computer available to virtually every segment of industry. Small scale processes are being automated at a very rapid rate, thus providing some offset to the ever-rising cost of labor in this country.

Since most computers are electronic, electrical measurements play an important role in their manufacture. Each component that is received is checked to its specification at most companies. Testing is done at each stage of the assembly of such a device. The equipment used for all such testing must be maintained and calibrated and most large computer companies have corporate standards and calibration laboratories to perform this function. Electrical measurement problems in the computer industry are related to the use and support of the automatic test sets which perform the quality assurance function. Some problems result from applying static calibration data to dynamic testing situations. A particular problem of great current interest results from the giant number of measurements required to test a digital circuit to an adequate degree. Even if it is solved, however, there will be increasing need, as semiconductor components become faster responding and more complex, to make measurements of both digital signal response and dielectric properties of components at higher speeds and with greater reliability. The state of technology is pushing the few standards which do exist in this area. Another problem area is the measurement of impedances, especially inductors, in the frequency range between 10 kHz and 1 MHz.

The Department of Defense. The Department of Defense is very heavily involved with electronics in communications, weapons, guidance, and navigational systems. The Department will have spent $2.6 billion for research, development, testing, and evaluation of such equipment and $1.61 billion for the procurement of electronics systems for FY 75. Total spending for FY 75 on electronics products as estimated by the Department of Defense is $9.6 billion [9,10]. Assuming a five-year lifetime of electronics equipment in the military, using marketing data for the past five years such as surveys performed annually by Electronics magazine, one can calculate a $6 billion inventory of equipment which must be maintained. This is done with a huge inventory of test equipment supported by a hierarchical laboratory system in each of the four services. To illustrate the magnitude of the problem, the 1972 edition of Air Force Technical Order 33K-1-100 lists by part number over 28,500 individual items in the inventory requiring calibration periodically. In excess of sixty percent of this inventory requires electrical measurements [17] for its support.

The Department of Defense is the largest single consumer in the country and, accordingly, wields a trememdous impact on the marketplace. Technical spin-offs from its programs, much as is the case with NASA - who, for example, are credited for the accelerated development of large-scale integrated circuit technology - have served to advance the technology base of our society.

The Department maintains a system of inspectors in various organizations (Defense Contract Administration Service; Air Force, Navy, Army Plant Representative Offices; etc.) to ensure compliance with the calibration and quality assurance providions of the procurement specifications listed in Sec. 2.2.1.1. In this way, it influences the nature of the measurement system in a large segment of industry.

As mentioned before, the main use of electrical measurements within the Department of Defense is to maintain its extremely large inventory of electronic systems and equipment and the test equipment used to support it. The major current problem areas are:

(a) the support of automatic test and checkout equipment [13,16];

(b) the support of equipment at remote locations; and

(c) in the face of decreased defense spending, to optimize the entire calibration and maintenance structure [13,15].

Problems in each of these areas have two aspects. The first is the need for dynamic standards and methods for their use to support or verify measurements made under time constraint with automatic test equipment, especially that under computer control. Such standards simply do not exist and their absence both prevents direct verification of the quality of individual measurements made by present equipment and limits the advance of automatic testing by confining its application to the measurement of those parameters for which static standards exist. For example, the so-called third generation ATE system makes measurements using sampling techniques and arrives at final results through harmonic or Fourier analysis software. System capabilities are given, however, only in terms of derated rms or average voltage measurement specifications as lack of knowledge of the information content of a single sample and a lack of arbitrary wave form standards precludes the precise calibration of such a system. (Specifications are derated relative to the potential accuracy of the sampling device.)

The second aspect has to do with the achievement of adequate measurement accuracy at acceptable cost. Accuracy requirements for the support of end items in the military inventory are gradually becoming more stringent as electronic components and systems increase in quality and sophistication and improved reliability is sought for strategic or economic reasons. At the same time budget decreases result in reduced resources for measurement support and quality activities. Support equipment for new systems and test equipment used in development and repair activities include new instruments with performance characteristics rivaling the best measurement capabilities of the typical DoD calibration laboratory.

These factors result in the need for the development of new calibration procedures, better training of technicians and, in some instances, exhancement of calibration and measurement accuracies through new standards or more sophisticated measurement experiments. Automated systems for the calibration of general purpose test equipment, the use of MAP techniques for the support of line calibration laboratories, and in situ tests of both ATE systems and electronics in aircraft, field installations and surface vessels are all being employed to deal with these problems.

Detailed technical problems within the system are dealt with by the professional staffs of the Air Force, Army, and Navy metrology engineering centers. Specific, long-term problems are dealt with by these people. In those instances where the advancement of measurement science or new standards are required, the DoD enlists the help of NBS through the sponsorship of engineering projects. Typical objectives of such projects are the development of an all-cryogenic voltage standard accurate at the part in 10^8 level; the design of a low-frequency, low-voltage measurement instrument to enhance vibration measurement capabilities; and the development of an automated capacitance bridge with which DoD primary laboratories can provide improved service at reduced cost. In addition to providing this measurement science support, the NBS serves as a basis of measurement uniformity for the DoD system by supporting the four primary standards laboratories through calibration services and MAP activities.

<u>The instrumentation industry.</u> This industry was covered in Sec. 2.2.2.2.

<u>Electric power industry (SIC 3825, 3511, 361, 362, and 491.</u> The electric power industry has two components, the generation and distribution of power (SIC 491) and the manufacture of equipment for the generation and monitoring of electric power.

The generation, distribution, and sale of electric energy is the largest single business in the U.S. Approximate sales in 1973 were $31.7 billion and in 1974 were $39.1 billion. In 1975 the industry sold over 1.7 trillion kilowatthours to nearly 82 million customers for an estimated revenue of $47.9 billion [18,19].

The production of turbines and turbine generator sets produced shipments valued at $2.4 billion in 1975. Shipments for 1976 are expected to increase by about eight percent to $2.5 billion. Seventy-three businesses employ 47,000 workers in the production of this equipment [18]. Production of transformers, switch gear, and industrial controls for power distribution (SIC Codes 3612, 3613, 3622) totaled $6.7 billion in 1975 and is expected to reach $7.1 billion in 1976. More than 200 firms are engaged in the production of transformers alone and employ over 50,000 people [9,10]. Electrical measurements are required by this segment of the industry for quality control purposes. The levels of accuracy to be found are generally lower than those at the state-of-the-art and readily achievable with off-the-shelf instrumentation, but they are required to enable quality of these goods. No major metrology problems are evident here.

In addition to being one of the key industries in the U.S., the electric power industry supplies most of the rest of industry with motive energy. This is done through a system of interlocking grids of independent power companies. Electrical measurements are necessary for the monitoring and control of the power flow in the grid as well as for energy metering by both power companies and their customers. Measurement problems include:

(a) the determination of transformer ratios at high voltages;
(b) the characterization of high voltage capacitors;
(c) the measurement of the dissipation factor of high voltage capacitors;
(d) the accurate calibration of watthour meters;
(e) the development of techniques for measurements in support of research to improve the transmission and distribution of electric power;
(f) the measurement of transient signals at high voltages; and
(g) the development of time-of-day metering techniques to enable the use of a rate scale in which the price of electricity increases during periods of peak demand.

NBS is involved in each of the above areas. The High Voltage Measurements Section is engaged in research and development programs generally supported by the Electric Power Research Institute and the Department of Energy designed to achieve the measurement capabilities at high voltages needed to support both basic research and power system operations. Examples of such projects are those to provide capability for measurement of pulses and transients of up to several million volts, to develop systems for the *in situ* calibration of coupling capacitor voltage transformers at voltages up to megavolt levels, and to improve the standards used for the measurement of current and power at power line frequencies.

In addition, NBS calibration services provide the basis for uniform measurement of electrical parameters necessary to day-to-day power company operations. NBS calibrations of standard cells, resistors, and watthour meters stand behind all measurements made for metering purposes, including those using the watthour meters found on every home in the U.S. Companies rely on NBS calibrations of high voltage capacitors, transformers and shunt reactors to maintain the efficiency of the power distribution system throughout the country. These services could not be provided without a strong, ongoing research effort in high voltage measurement technology such as exists in NBS today.

Research. In this category fall all independent research organizations, universities, and national laboratories. Since much of the research done in every field is experimental, the ability to make accurate electrical measurements is a necessity. An example of how precise measurements are needed is seen in a program at the University of Pennsylvania for the study of the electrical properties of solid-state, cryogenic Josephson junctions. The purpose of this work was to determine an experimental value for the quantity e/h with sufficient accuracy to enable its use in the verification of quantum electrodynamic theory. To do this, a measurement of its voltage output had to be made with the maximum available accuracy, that is 0.1 ppm relative to the legal volt. This necessitated the construction of a special instrumentation and the initiation of a special effort, both at NBS and the University of Pennsylvania, to verify the accuracy of the University's voltage standards.

A second example is to be found at Argonne National Laboratory, where extremely precise calorimetry work requires that voltage and resistance measurements be made with accuracies in the part per million realm. The experimenter is compelled to keep his own set of standards which are calibrated at NBS.

The energy crisis and the resulting perception that electricity will become the dominant means of energy utilization has fostered research, sponsored primarily by the Department of Energy (DOE) and the Electric Power and Research Institute (EPRI), for the increased generation and improved transmission of electric power. This research is being carried out in industry, at universities, and in various national laboratories, such as Brookhaven and Oak Ridge. Typical projects are the investigation of the use of superconducting transmission lines, ultrahigh voltage overhead lines, direct current transmission, solar energy, and cryogenic motors and generators. Approximately $14.3 million has been invested in FY 76 for transmission and distribution research by DOE and $20.6 million by EPRI for calendar year 1976 [19].

The success of such research hinges on the ability to make accurate measurements at high voltages and under difficult environmental conditions and in many cases adequate techniques and standards for such measurements do not exist. As mentioned in the previous section, NBS is undertaking a number of research projects to establish the required measurement methodology. Examples of projects specifically bearing on energy-related research are those of applying the Kerr effect to map electric fields, the design and construction of pulsed current and voltage generators and associated measurement apparatus to enable calorimetric determinations of thermal/physical properties of materials used in nuclear reactors, and the development of calibration techniques in support of instrumentation used to determine the effects of fields associated with voltage transmission lines on plant and animal life.

In other areas, NBS work in the fundamental constants field provides data contributing to the verification of physical theory, such as quantum electrodynamic theory. NBS has ongoing efforts in areas requiring precise electrical measurements. Determinations of the ampere, volt, Faraday, ohm, and the gyromagnetic ratio of the proton are presently underway. NBS has participated in the most recent (1973) least-squares adjustment of fundamental physical constants published by CODATA, the Committee on Data for Science and Technology. Another such adjustment is to be carried out in 1980.

As has been shown, the National Electrical Measurement System pervades most of the major industries and government agencies to a larger extent. As might be expected, measurement problems and requirements stem from two sources, the use of electronics as an implementor of manufacturing quality and process control, computations, and communications and the electric power industry and its needs for efficient power generation, distribution, and metering. Measurement technology in the former instance covers the range from dc to 1 megahertz at modest levels of voltage and power whereas in the second case measurements are generally of electrical parameters at dc and 60 Hz and high power and voltage levels.

Through its calibration and research activities, NBS provides the measurement system with its base, thereby ensuring needed stability and accuracy in terms of SI units. High-technology industries with the most stringent accuracy requirements provide the interface with NBS needed to enable virtually all electrical measurements made in the U.S. to be expressed in terms of the national units. Measurement accuracy in areas of more than modest requirement is ensured by systems in which the instruments used to make the measurements are calibrated periodically using standards or test equipment with accuracy capabilities from four to ten times better in each case. A chain composed of such calibration links reaches from most commercial instrumentation back to standards supported by NBS. The system remains viable due to measurement research performed at NBS and in the instrumentation industry.

3. IMPACT, STATUS, AND TRENDS OF THE MEASUREMENT SYSTEM

3.1.1 Functional, Technological, and Scientific Applications

The use of electrical measurements generally falls into one of four categroies - the production of reference data, setting and testing to specifications, maintenance and reliability activities, or the control of manufacturing processes. Reference data, including physical and engineering data covered in Section 2.2.3, is vital to designers of virtually all high-technology products. The Electrical Measurement System ensures that such data have universal meaning by providing common reference bases in the electrical units, both for those experimentalists who produce the data and for those designers who must use the characteristics of materials, circuits, etc. in an engineering application.

The next major use of electrical measurements is in vendor determination of performance characteristics of manufactured products and customer testing of those same devices to ensure that their specifications or the manufacturers claims are actually being met. Most commercial electronics and electrical merchandise is traded in this fashion. Electronic components, modules, instruments, devices and systems are generally tested, sometimes on a sampling basis, to specifications prior to their acceptance. The measurement system is the foundation for all aspects of this type of activity. The availability of universal units of measure permits interchangeability of electronic components and modules (a must for the mass production and subsequent maintenance of complex electronics) and multiple manufacturers of commonly used circuit elements. These factors, coupled with inexpensive production techniques, enable all electronics products to be produced inexpensively and to function with a high degree of reliability.

Electrical measurements are vital to maintenance and reliability functions throughout the electronics user community. Test equipment is used both to ensure the proper operation of functional electronic equipment, such as radar sets, inertial guidance units, etc. used in critical applications (i.e., space and weapons systems) on a periodic basis and as a means of trouble-shooting and repairing nonfunctional electrical and electronic equipment. This test equipment is generally checked or calibrated periodically using more accurate standards and equipment through the echelon system of standards and calibration laboratories which exists throughout industry and most government agencies involved with technology.

The final major use of electrical measurements is for the control of industrial manufacturing processes. Early automatic control of manufacturing processes was achieved through pneumatics and electro-mechanical servomechanisms. Besides being a prime source of power for the process itself, pneumatics gave the design engineer the ability to implement various control algorithms tending to optimize the process. The advent of electronic amplifiers enabled the implementation of these same functions electrically with many control adjustments difficult or impossible to achieve pneumatically. Also over the years the development of transducers, devices which produce electrical signals of a known relationship to the magnitude of a particular physical quantity, has gradually extended the versatility of electronic control. The advent of the inexpensive digital computer along with electronic instrumentation with digital data outputs has hastened the application of electronics in the control field. Control systems based on digital computers have the advantages of speed of response, economy, and software signal conditioning. Not only does the latter make possible the use of exceedingly complex control algorithims, but it also permits extreme flexibility of modification without extensive hardware changes.

The most stringent measurement requirements come from the instrumentation industry, the aerospace industry, and the Department of Defense. The DoD and the NASA generate stringent requirements for the accuracy and reliability of guidance, weapons, and navigation systems. Accuracy requirements of better then 0.001% for various electrical parameters exist in some of the new operational equipment itself. This level of requirement places a burden on the instrumentation industry which is called upon to provide the test equipment and support standards necessary to the development, production, testing, and maintenance of the operational equipment. Further the test equipment and standards themselves must be verified and maintained in all three of these areas of the economy. NBS plays a vital role in this function by providing calibrations of standards, Measurement Assurance Program services, reference data, and training services.

Less accurate — but in some cases no less stringent — requirements come from the electric power and the semiconductor industries. In addition to the routine measurements of electric power for revenue purposes, the power industry requires many difficult measurements under field conditions for both operational and research purposes. Examples of these are given in the previous section. Large scale integration techniques have permitted a great growth in complexity of circuit elements. Meanwhile, the ever-decreasing cost of these same products has lead to their use in many applications in which reliability is critical, such as electronic control of automobile brakes, medical life support systems and instrumentation, and aircraft navigation systems. Testing of these circuit elements must be done, therefore, accurately and rapidly to achieve utility and low cost. This simple factor has lead to a surge of interest in automated testing and requirements for support of electrical measurements made "on the fly". There is a plethora of dynamic data conversion devices on the market with which such measurements may be made. Lacking are the standards which form the means by which a translation may be made from traditional standards and measurements, which involve no time constraints, to the new requirements for dynamic measurements.

On the other end of the measurement spectrum lie those electrical measurements which are part of the day-to-day experience of the typical man on the street. Examples are those made in the course of tuning an automobile; for repairing television, radio, or high-fidelity audio equipment; to maintain home consumption of electric power; and to provide for the safe navigation of commercial airlines. Instruments used in the former two cases are generally only supported by the measurement system upon their failure. The accuracies required in support of most consumer services are readily obtainable since they lie in the 1 to 5 percent range.

Electrical measurements are used to control the quality of any item manufactured by an automatic process. The use of transducers, which convert other physical parameters into electrical parameters, coupled with electrical instruments with digital outputs enable any physical or chemical production process to be run under computer control. Thermocouples, strain gages, tachometers, and fluid level meters are examples of transducers. Table 11 lists some articles whose production is made possible by electrical measurements.

Table 11. Representative heavily measurement-dependent products

Electronic
Components (resistors, capacitors, etc)
Computers
Digital watches
Electronic calculators
Frequency standards
Guidance systems
Navigation equipment
Stereo receivers
Other
Engine blocks
Oil, gasoline
Plastics
Rayon, nylon fabric
Steel
Synthetic rubber

3.1.2 Economic Impacts - Costs and Benefits

The costs incurred by the economy annually for electrical measurements are very low by comparison with benefits received. A survey of the manpower available in the calibration laboratories listed in the NCSL Directory of Standards Laboratories shows a total of 878 engineers and 3208 technicians for all measurement areas [14]. A conservative estimate was made that there are roughly 1000 measurement engineers and 5000 technicians in that portion of the measurement system which provides standards and calibration support to the remainder of the system. Approximate labor and overhead costs for that number of people are estimated to total no more than \$130 million per year. The remainder of the system is many hundred times larger and difficult to quantify. The degree of capital intensiveness of the measurement system is illustrated by the annual expenditure of over \$5.6 billion for new measurement instrumentation, of which \$1.3 billion is test equipment [9].

The above manpower figures are totally exclusive of test engineers and technicians whose functions are not primarily concerned with calibration measurements. Virtually every electronics engineer (except digital logic designers) must rely on electrical measurements as a tool necessary to the performance of his function.

Over the past ten years, in excess of \$94 billion worth of electronic systems and communications equipment were sold in the U.S. [10,20]. All of this equipment requires maintenance support, and much requires periodic calibration to insure its proper operation. During the same period over \$11 billion worth of electronic test equipment was sold for that purpose [9,10]. All of this apparatus requires periodic calibration. The scientific apparatus inventory is estimated at \$12 billion for that same 10-year period [9].

The electronics market as a whole is supported by this measurement capability. Gross sales for the industry were forecast at \$64.9 billion in 1977 [21]. New automated systems developed explicitly for testing integrated circuits, which are becoming more and more complex, enabled achievement of this sales figure. This represents about a 9% growth, despite materials shortages and a general economic decline.

3.1.3 Social and Human Impacts

The largest social impacts of the electrical measurements system lie in the medical field and the public safety areas. Modern instrumentation has made possible great strides in diagnostic medicine. The bodies of patients in intensive care units are monitored on a twenty-four hour basis by computer-controlled instrumentation systems. These systems not only alert medical staff members to impending crises, but provide a powerful tool in the analysis of the patient's condition. There are under development automated systems which would give physical examinations to individuals without requiring a doctor in attendance. Electronic measurement equipment and computers form the basis for new systems to perform internal scans via ultrasonics or x-rays.

In the safety area, measurements are vital to ensure the reliability of electronic equipment such as braking and ignition systems for automobiles and navigation and landing systems for aircraft. The failure of any of these systems could be calamitous, whether due to component failure or electrical interference. Reliable measurements are necessary to avoid failures from either cause.

3.2 Status and Trends of the System

The electronics sector. At the present time the National Electrical Measurement System is capable of handling nearly all of the traditional measurement needs of our economy. The accuracies available within the system for so-called static electrical measurements, i.e., those in which the measurement is not constrained to take place within a particular time interval, far exceed any technical accuracy requirements. The common practice of insisting upon accuracy ratios in calibrations of between three- and ten-to-one, a practice fostered by the Department of Defense and NASA, generally ensures that specified accuracies are delivered within the calibration traceability chain. However, the system does have a serious fault which is not entirely technical in nature and which is being increasingly recognized and dealt with. This fault is the lack of redundancy or feedback in the rigidly stylized, hierarchical calibration/traceability structure to ensure that the applied measurements supported by the system are in fact appropriate and adequate and their quality has not been adversely affected by such factors as environment, electromagnetic interference, or poor power lines. Commercial and government organizations are slowly recognizing the need for periodic sampling of measurements being made on the production line, in the aircraft, or at the power substation.

There are several areas in which traditional measurements needs are, at present, unfulfilled. The most urgent of these are:

(a) characterization and specification of power line properties. There have been failures and erroneous data from instrumentation caused by spikes or hash in the power line. The medical profession and medical instrumentation industry are most severely affected by this problem due to the seriousness of potential consequences. A committee dealing with the problem has been formed under the auspices of the National Committee for Clinical Laboratory Standards. The establishment of specifications and measurement techniques for interfering signals on power lines will enable the design of better instruments and provide a basis for settling the issue of legal liability for consequences of error. This issue arises from the fact that instrument makers do not specify the limitations of their equipment in that regard and hospitals are not legally bound to ensure a specified purity of content of the power mains.

(b) measurement of ac voltages at low amplitudes (<50 mV) and frequencies (<50 Hz). This measurement capability would be used with transducers to make measurements of low frequency vibrations such as those characteristic of trucks and helicopters. The Department of Defense and the transportation industry require the ability to test the susceptibility of various items of critical nature to damage by truck or air transportation.

(c) impedance measurements in the upper ends of the low radio frequency range (20 kHz to 1 MHz). These impedances measurements are needed to support an increase in carrier frequencies in some communications systems. Increases in carrier frequency will result in proportional increases in message capability.

(d) studies relating to reliability and the predicition of long-term performance of components and assemblies based on short-term, high-precision data needed by the electronics industry for general improvements in their product line.

(e) measurements of phase angle in the frequency range from 1 Hz to 30 kHz. Phase angle measurements are important to the testing of components, solid state circuits, and test equipment used in and to support communications and weapons systems. In the latter, some of the more precise measurements are required for testing synchro's and resolvers used to position the antenna of search and target acquisition radar.

There are two other perceived problems which affect the system. Technical information is disseminated primarily by word-of-mouth (between colleagues), through sales efforts of instrument companies, and by technical publications in such journals as IEEE Transactions on Instrumentation and Measurement, Instrumentation Technology, Metrologia, and Measurements and Data. Articles in the above tend to be academic in nature. Despite the existence of the Government Industry Data Exchange Program, which has a library of calibration procedures, and the above-mentioned means of communication, useful technical information on a how-to-do-it level does not reach the bench-level metrologists and those outside the precise measurements field (i.e., quality control or automatic test equipment engineers). In many instances there is conflict instead of cooperation fostered by ignorance and no means of communication. NBS is planning a series of publications and seminars to help meet this need.

The second is in the area of manpower. Many of the highly-skilled technicians and engineers in the field are on the verge of retirement. New people in the field tend to remain there only temporarily. Metrology may in the future be caught in a three-way trap between the lack of communications and informal education opportunities, the decline of the armed forces as a source of experienced people, and the increasing sophistication of new instrumentation, which requires a higher level of education and appreciation for its proper support.

Two major factors presently affect the system and will apparently do so for the foreseeable future. These are the revolution taking place in the electronics industry, and the energy crisis. Advances in semiconductor fabrication technology and the application of new semiconductor structures to circuit design are resulting in the availability of very complex digital and analog circuits in small, component-sized packages. As a result an increasing number of standard circuits, such as amplifiers, computer processing units, power supplies, digital multipliers, analog-to-digital converters, etc., are as available to the designer as resistors, transistors, and tubes have been in the past. Because of this ready availability, electronic equipment has increased — and will continue to increase - in functional complexity and sophistication, while its cost has dropped.

The solid state revolution has fostered a parallel phenomenon in the computer field. Minicomputers, which have only readily been available for about the past 10 years, have so improved that new models offer sophistication which could be found only on large systems costing hundreds of thousands of dollars not long ago. Yet a system with a fair-sized memory, reasonable software, and a mass-storage peripheral can be purchased for well under $15,000 at the present time. And, now available are microprocessors, central processing units on a chip, with fairly comprehensive capabilities. These devices are inexpensive enough to permit their inclusion in electronic equipment to replace the hand-wired logic circuitry normally used there for controlling operations and transmitting data.

The above considerations have had and will continue to have a major impact on both measurement requirements and the tools or means by which measurements can be made. The increasing complexity of components, sub-assemblies, equipment items, and electronics systems have resulted in increasingly complex tests necessary to ensure quality in the manufacture of such equipment, proper performance while in use, and affordable maintenance for it in the event of malfunction. Typically, tests may be comprised of hundreds or thousands of measurements.

The only way that such tests can be performed in a reasonable time and with cost puter to control the measurements, acquire and process the data, and analyse the results. Cost effectiveness is increased by running the system at a higher rate of speed. Therefore, the thrusts of the instrumentation industry are in the direction of increased accuracy of measurement at increasing speeds, and of making the instruments as compatible as possible with computers. The impact of this industry on the measurement system is heightened by the fact that the designers of automatic test equipment (ATE) systems for both military and commercial applications design these systems using the specifications for off-the-shelf test instruments as building blocks in the design. This leads to performance problems if the instruments used do not perform as expected because of environmental noise, or ground problems. It may also lead to calibration support problems requiring high-grade portable standards.

The future will bring even more complexity. The Department of Defense now requires testability. Many new prime systems will have the functional capability to test themselves. Most circuits will be designed with testability in mind, that is, with special input and output lines with the sole function of expediting testing. Some digital devices will actually contain two similar circuits with auxiliary circuits to compare their behavior. Much is being done to lay the foundation for the development of system testers, portable devices which can exercise a test system under use conditions by simulating a typical units under test [13,15,16].

The industrial and commercial sector tends to have less stringent accuracy requirements for electrical measurements than the military/aerospace sector. This results from the lower technology level found in general industry. On the other hand, measurements are required to be made under severe ambient conditions. Because of this factor and the need for a means of coping with a general decline in productivity, the use of automatic test and control systems will increase rapidly in this sector over the foreseeable future. Much effort is being expended in development of computer-aided manufacturing (CAM) technology, the use of robots, and application of computer-aided design (CAD) techniques in various areas of industry, as well as in the use of automatic test equipment and transducers for quality assurance.

Automatic test equipment as used in the commercial sector differs in another way from that developed for the military/aerospace complex. Military and space operations have a critical nature due to the high potential for loss of life, property, and national existence. This fact and the often unique nature of the equipment employed in those programs leads to the procurement of specially-designed or "custom" measurement instruments and automatic test systems suited for testing of a specific prime system. In the commercial sector cost considerations tend to force the use of off-the-shelf commercial instrumentation for automatic testing purposes. This practice is expected to be positively affected by the recent adoption of standards (IEEE 488 and American National Standards Institute CAMAC standards) whose conventions for interfacing instruments and other devices to computers are beginning to be adopted in the instrumentation industry.

The improvements of semiconductor technology have had a significant impact on the instrumentation industry in a variety of ways as shown above. Perhaps the greatest impact is the growing use of microprocessors within instruments. Not only are these small computers used to perform calculations on raw data to enable the display of useful information (such as temperature instead of voltage for thermocouple applications), but in a more basic function, that of controlling the internal operation of the instrument. Contemporary voltmeters and other electronic measurement instruments function using dedicated logic circuits to control timing, range changing, and the conversion of analog signals to digital information. Changes in the mode of operation can only be made by circuit modification. Use of microprocessors will permit modification of the instrument's operation through software, resulting in more flexibility of design and lower production costs. Most instrumentation companies are actively engaged in the application of microprocessors to their product line. At this point in time, announcements have been made of new voltmeters, counters, oscilloscopes, and multi-channel scanning systems, all based on microprocessors.

At the present time, artifact standards, apparatus and standard measurement techniques to support dynamic measurements of electrical quantities simply are non-existent. Details of state-of-the-art dynamic measurement techniques are the proprietary secrets of the manufacturers of instruments and signal-conversion devices. As a result, manufacturers and users of automatic test equipment and systems attempt to ensure the quality of performance of such systems through the manual calibration of system components or the measurement of known static quantities by the system. Neither process gives valid assurance of adequacy of performance. Such assurance is virtually impossible without appropriate standards.

The lack of standards also affects the development of new systems. The designer may now use published equipment specifications (which in many cases are not uniform in meaning) to achieve an approximation of his design goal and then use measurement results to "fine tune" the system because standards are not available as design tools. He may alternatively over-specify in speed and accuracy to ensure good results. Unneeded accuracy and speed are costly and may lull the designer to believe he has no analog measurement problems when in fact one may be created by external considerations, such as the impedance characteristics of the interface between the system and the unit under test.

That the development and establishment of standards for dynamic measurements of electrical quantities are a necessity to ease future growth of technology was one of the conclusions reached during a workshop held at NBS in September 1974. The workshop, which had 24 participants, representative of bpth manufacturers and users, was convened to identify critical measurement needs and discuss standards for modern electronic instrumentation. A whole host of standards and measurement techniques whose need results from the semiconductor and computer revolutions were identified [13]. They are best summarized in the abstract of the workshop report, NBS Technical Note 865, given in Appendix C of this report.

The need for a static measurement capability will not diminish in the future. This is true as static standards must form the basis for uniformity and stability of performance with time for all dynamic instrumentation. The present electrical standards which provide the basis for accuracy for static measurements are of materials and combinations of materials inherently more stable than are semiconductor devices.

In addition, automated equipment is not yet capable of trouble-shooting and repairing electronics equipment. Although automatic fault diagnosis for both digital and analog circuitry is a rapidly expanding area, the techniques and philosophy are as yet primitive. The construction of present day equipment is such that machine repair would be prohibitively costly. General purpose maintenance instrumentation must be calibrated and repaired itself.

Consumer electronics is another rapidly growing field which will have an effect on the measurement system. At present, the main function of the measurement system in the consumer's market is to enable the maintenance and repair of equipment. However, the use of electronics for both safety and energy conservation purposes is growing rapidly in the automobile industry. The potential for disaster due to failure of electronic ignition or braking systems will lead to more measurements for reliability or quality control either voluntarily, as the result of government regulation, or as the economic consequence of successful litigation by crash victims or their survivors.

Another area of consumer electronics which will increasingly impact the system is that of medical instrumentation, both by increasing the amount of support required and by generating new measurement problems. Not only is this use of instrumentation in hospitals and medical research facilities on the increase, but the summer of 1976 will mark the beginning of regulation in this field by the Food and Drug Administration. Manufacturers of analytical instrumentation are aware of their liabilities resulting both from government action and from malpractice suits. A major problem at the present time is the electrical environment in which instrumentation must function. A means of quantifying the "purity" of the 60-Hz power line is needed, both to optimize the design of instrument power supplies and to enable hospitals to have proper electrical configurations.

The most important needs for the future generated by the electronics portion of the National Electrical Measurement System may thus be summarized as:

(a) the need for standards for the dynamic measurement of electrical quantities such as voltage, impedance, and power;

(b) the measurement methodology which must be used with the above standards;

(c) the education of systems designers in the necessity for and the use of the above, before maintenance and failure costs escalate to render system use impractical;

(d) the establishment of methods and apparatus to test computer-driven systems as systems, under conditions of actual use;

(e) the development of a theory to minimize the number of points requiring testing in a complex system;

(f) a standard and measurement method by which to assess the quality of ac power available from the mains;

(g) the characterization of long-term reliability and stability of electronic components on the basis of short-term measurements (perhaps of parameters such as noise);

(h) standards for phase measurements and for impedance measurements in the frequency range from 20 kHz to 1 MHz;

(i) the development of improved switches and relays;

(j) better mechanisms for the communication of technical and management information throughout the system;

(k) a mechanism to ensure that regulatory and other government agency requirements o n the system are technically, economically, and logistically relaistic; and

(l) standardization in the computer software used for systems implementation of measurements.

The electric power industry. This subset of the National Electrical Measurement System requires a considerable measurement capability, both to carry out its day-to-day operations, and in support of research, the urgency for which has been created by the energy crisis. Support of operations requires a capability to perform measurements of voltage, current, and impedance at voltages as high as 765,000 volts, a means of measuring energy accurately at 60 Hz, measurements of transient (lightning impulse, switching surges) voltages at levels in excess of 2 MV, and the characterization of dielectrics.

Line-to-line voltages for bulk power transmission in use or under consideration by the industry are generally grouped in one of three categories. The high voltage (HV) group extends from 69 kV (69,000 volts) to 230 kV. Overhead lines are used for both short and long distance movement of power while underground cables are restricted to short distances. A considerable amount of very long distance power transfer (e.g., between power companies) takes place on overhead lines at extra high voltages (EHV), some at 345 kV, but most at 500 kV. EHV lines at 765 kV are operational but under somewhat limited use. One option for power transfer in the future is by UHV (ultra-high voltage) lines. Voltages ranging from 1.1 to 1.5 million volts are being considered. For distribution of electric power, moderately high voltages between 200 and 45,000 volts are employed.

Measurements of voltage and current at these transmission and distribution voltage levels are performed by means of voltage and current transformers which reduce the magnitude of these parameters to a level where they may be handled using conventional low voltage meters. Both at HV and EHV levels, inductively coupled transformers are used, but at EHV there is a trend to use capacitive voltage transformers. Measurement capability for the calibration of transformers for the HV range is generally adequate throughout the industry. For the EHV range the capability of calibrating current and voltage transformers is generally limited to the manufacturers of high voltage equipment. The capability of calibrating capacitive transformers (coupling capacitor voltage transformers -- CCVT's) in the place of installation has recently been developed at NBS with the support of the Electric Power Research Institute. The use of high voltage reactors and capacitors to reduce circulating quadrature currents in transmission systems, and thus, reactive power, leads to a need for the accurate measurement of impedance and phase angle for this type of device. This capability is generally available only with the manufacturers.

Energy measurements are widely made by the electric power industry for billing purposes. This is a very well-established area; it relates ultimately to the accuracy of simple, residential-type watthour meters and to more complicated industrial, commercial, and inter-utility metering systems. There are over 80 million watthour meters in the U.S., practically all of them rotating, induction-type devices. State utility commissions legally require that such meters do not exhibit a certain maximum error, usually 2%. The systems by which these meters are calibrated are detailed in Sec. 4.2.1. That this portion of the Measurement System is under adequate control has been demonstrated by means of a round-robin experiment performed jointly by NBS and the Edison Electric Institute [22].

Testing of the integrity of insulation of equipment is an important part of the quality control process of the electric voltage equipment is subjected to very high steady state and transient overvoltages which must be measured with accuracies in the 3 to 5% range. Such accuracies are difficult to achieve as present instrumentation capable of handling the high voltages required has a poor pulse response characteristic. A commonly used transient is the standard lightning impulse (1.2 microsecond front, 50 microsecond tail) which, for existing transmission voltages, can be in excess of two million volts.

Another specialized test for the quality of insulation is that for the level of partial (corona) discharges. The problems here are the complexity of instrumentation needed and the necessity to isolate the measured phenomenon from interference. The basic accuracy is not a particular problem. Problems do arise, nonetheless, due to the sophistication of the measurement operation and the interpretation of data.

The following is a list of representative measurement problems presently being identified in day-to-day power industry operations:

1. Stability of EHV capacitive transformers is unknown. Hence, their usefulness in monitoring extra-high voltage is limited.
2. Means for calibrating impulse voltage measuring systems are insufficient. Traceability is usually only through the manufacturer of the equipment. Periodic rechecking is not widely practiced.
3. There is a lack of convenient and reliable instrumentation to measure the power of loads with very low power factors.
4. Measurement and test procedures to predict the life of insulation systems are inadequate.
5. Interpretation of data from corona and partial discharge measurements requires additional research.
6. There are problems associated with the very limited market of high voltage instruments. Often they are one of a kind; there is little opportunity to obtain enough experience to optimize the design.
7. There is need for more in-service testing since many equipment types cannot be removed from use for test purposes. In-service measurement methods and instruments are needed.
8. The industry could benefit from more training of personnel in measurement and test techniques.

The above problems must be resolved by the electric power sector in order to identify components of optimum systems for the future. The NBS role in solving these is to ensure that the required measurement capability exists and is available where these problems are addressed.

The energy crisis, the rapid depletion of petrochemical fuel reserves, and the future promise of thermonuclear energy have spurred a diversity of energy-related research efforts [19,23-26]. The effectiveness of many of these efforts depends on the availability of appropriate electrical measurement capabilities. In some areas, the key measurements are those generally associated with the electronics community. For example, the reliability of control and other auxilliary electronic systems is recognized as a problem area. The operation and security of future electric power networks are foreseen to be more heavily computer-based, and contain large amounts of sophisticated instrumentation for monitoring and control of various parameters [26].

Work is going on in energy storage and intermittent generation facilities to enable the main power system generators to handle only the base loads. Batteries are under development for storage of energy generated during off-peak hours for eventual peak-time consumption. Measurements must be made to characterize the discharge of prototype batteries, as well as to determine their behavior under rapidly varying conditions of use. Other areas dependent on electrical measurement are those involving magnetohydrodynamics and fuel cells [26,27].

By observing the current developments in electric energy measuring devices and in metering practices, one may expect early introduction of all-electronic metering systems. This meter may be a more sophisticated device combining the functions of watthour, demand, and power factor meters. It may be coupled to telemetry and computer systems for automatic reading and time-of-the-day metering. The accuracy requirements may be similar to those of conventional instruments, but the calibration procedures may be different.

Requirements for measurements at high voltages come largely from R&D efforts to improve the capacity and efficiency of the nation's system for the transmission of electric power from generating sites to areas of use and the distribution of that power within each area. In discussing these measurement requirements, the development of future electric power systems must be considered.

The principal driving forces appear to be: (1) a continuing increase in the consumption of electric power, requiring expanded transmission facilities; and (2) concern for usable systems. The right-of-way available for overhead transmission will be limited, requiring an increase in voltage to transmit more power. However, there are some doubts whether further increases will be permitted because of potentially adverse environmental effects. There will be pressures to put more transmission lines underground.

Some potential systems, for which research and development is underway or under consideration, are outlined below [23-29]:

- Transmission Systems
  - Overhead
    - UHV 60 Hz up to 1500 kV
    - EHV and UHV dc up to 1200 kV
  - Underground
    - Higher voltage tape cables (765 kV ac)
    - Higher voltage extruded cables (to 138 kV and 230 kV ac)
    - DC cables
    - SF_6-insulated systems
    - Cryogenic systems
  - Substations (SF_6-insulated)
  - Underground cables (improve reliability and efficiency, reduce cost)
  - Transformers (improve efficiency)
  - Metering (time-of-day metering, remote reading, all-electronic meters).

There will be requirements for many new types of measurement techniques at high voltages occasioned by the above. A few of these are the capability of making accurate dielectric loss measurements under cryogenic and other adverse conditions, the measurement of transient voltages at UHV, the performance of needed calibrations (transformers, reactors, capacitors) in an atmosphere of SF_6, and accurate measurements of electric fields in non-uniform regions for environmental safety purposes. In addition, new calibration techniques will probably be needed for such new types of measurement apparatus as electronic wattmeters, capacitive voltage transformers, and the electro-optical devices which may replace conventional current transformers at EHV and UHV levels.

In conclusion, the power industry subset of the NEMS generally functions well, although in several instances the industry could benefit from improved measurements and tests. The difficulty lies not so much in the accuracy which can be achieved under laboratory conditions and in the traceability to basic standards, but in the very hostile environment in which the measurements have to be performed. Many tests are difficult and expensive to stage because of high voltage considerations and the size of the equipment. Often, measurements are made to elucidate physical processes, e.g., those responsible for insulation aging and deterioration. In such a case, the problem is frequently associated with trying to relate the measurement results with the physical processes, a research problem on what to measure, not necessarily one of accuracy. Most of the above problems are dealt with by the industry itself or appropriate agencies in the Federal and state governments. NBS' responsibility is for the development of measurement techniques and standards needed to solve these problems. NBS has neither the mission or resources to tackle these problems directly itself.

Looking into the future, one sees great activity in the development of new and improved electric transmission and distribution systems. There is and will be a need for new measurements to facilitate the development and to enable the operations of new systems.

4. SURVEY OF NBS SERVICES

4.1 The Past

Calibration services for basic electrical standards have gradually improved in accuracy over the past twenty years. During that period, the concept of measurement assurance became the basis for new services as described later in this section. In the high voltage measurements area some reduction in capability within the NBS facility resulted from the loss of the Van Ness Street facility. In 1967, work was begun on a new method of dissemination, utilizing the measurement transfer approach. Spurred on by problems in the area of dc voltage measurements in standards and calibration laboratories, the effort culminated with the establishment in 1970 of the Volt Transfer Program as an alternative to standard cell calibrations at NBS. In this program, use is made of specially-tested transport standards to monitor the ability of the client laboratory to make measurements of high accuracy and precision, as well as to transfer the unit. The Program has proven to be a powerful tool for the diagnosis of measurement problems as well as a means for disseminating the volt at improved accuracies. Since then similar programs in capacitance, resistance, energy, and voltage ratio have been put into operation.

A new area of *in situ* high voltage measurements stemmed from the loss of NBS in-house measurement capability above 100 kV and the development of portable bridges based on the current comparator principle. NBS equipment and personnel calibrate transformers, shunts, and capacitors at the actual site and under the conditions of use. A similar approach is being taken for the calibration of high current transformers.

Over the years, the Electricity Division has contributed a wealth of new standards and equipment to the measurement industry. A partial list includes the Wenner bridge and magnetometer, the Rosa and Thomas-type standard resistors, the Hermach thermal transfer ac-dc voltage converter, the Cutkosky ac thermometer bridge and the Cutkosky fused silica dielectric capacitor. All of these have been adopted for commercial manufacture, or provided significant contribution to other products.

4.2 The Present - Scope of NBS Services

4.2.1 Description of NBS Services

Structure of the Electricity Division. The Electricity Division's goal is to provide within the U.S. the central basis of a complete and consistent system of electrical measurements, standards, and related data required by industry, commerce, government, and the scientific community in their efforts to advance science, technology, and equity in trade for the public good. To achieve this goal the Division has set the following objectives:

(a) to realize, with continuing improvement, the electrical units and to develop improved means for their maintenance and dissemination;

(b) to maintain and disseminate the electrical units and to test and calibrate electrical standards, instruments, and systems;

(c) to develop methods and instrumentation for the solution of problems requiring electrical measurement;

(d) to determine essential data and constants requiring or related to electrical measurements when not available with sufficient accuracy elsewhere;

(e) to serve actively in organizations which set standards for electrical measurements and devices and to otherwise disseminate the Division's specialized knowledge; and

(f) to evaluate the U.S. system of electrical measurements and to coordinate it with the systems of other countries to achieve international compatibility.

The basic responsibilities of the *Absolute Electrical Measurements Section* are to relate the U.S. legal electrical units, the ampere, farad, ohm, and volt, to the absolute or SI (Systeme International) units; to develop new and improved reference standards for the SI units; to develop means for maintaining surveillance of such referance standards; and to develop improved means for disseminating the electrical units.

Until recent years, the legal electrical units have been maintained by NBS using artifact (physical) standards, the stability of which depended upon materials whose properties are generally affected by environmental changes (temperature, physical shock, etc.) and impurities, either physical or chemical. For example, the value of a standard resistor, in addition to being sensitive to temperature changes, may undergo a long-term drift as the result of changes in the intermolecular structure of the wire of which it is made due to a physical shock and consequent deformation. This structure would in time tend to slowly return to that of an annealed state and the wire resistivity would reflect this slow change by its drift. Although so-called absolute experiments, which relate the electrical units to the mechanical units, are performed from time to time, they cannot because of their very nature be performed often enough nor, for most parameters, accurately enough to be of use in ascertaining the drift rates of the artifact standards in which are embodied the legal units.

It is natural, therefore, that a significant portion of the Section's activity is taken to exploit processes whose propeties depend upon fundamental physical constants for use as primary electrical standards. For example, the U.S. legal volt has been defined since 1972 in terms of e/h, the ratio of the electronic charge to Planck's constant. This is done by the use of Josephson junctions, weakly coupled junctions of superconductors which act as precise, linear, frequency-to-voltage converters for which e/h is a conversion factor. Section work currently includes the development of all cryogenic instruments based on the Josephson effect and dc current transformer techniques to improve the quality of the volt (reduce random error) by an order of magnitude to one part in 10^8 and the exploitation of the Josephson effect for commercially-available laboratory voltage standards at the one part per million level. Because of the nature of the process, such a device would never need calibration.

Work in this area and on related voltage measurements has led to a number of "spin-off" advancements in measurement technology. Examples include the development of high accuracy, sub-millivolt potentiometric methods, new techniques for the dissemination of the volt (MAP's), application of sophisticated statistical techniques to standard cell intercomparisons and other measurements, development of automation techniques, and the design of the world's "cleanest" automated switching systems.

Present activity in the area of absolute measurements includes the determination of the farad and ohm from the unit of length via the calculable capacitor. This device is capable of producing a change in capacitance very precisely related to the displacement of its guard electrodes. After a development period of a decade, a preliminary measurement of the ohm has been made with an accuracy of 0.05 parts in a million [3]. Perhaps equally significant are the developments which were required to achieve the capabilities of maintaining the farad at the commensurate level of stability and of making the translation between the unit of capacitance at 5 picofarads, as measured using ac techniques, and the unit of dc resistance at one ohm. New capacitance standards based on the use of a deposited, fused silica dielectric were developed. Although they are inherently quite stable (less than 0.1 ppm per year drift), their large temperature coefficient required development of temperature control and measurement techniques at the microkelvin level of precision. These were later successfully applied in the construction of a new type of standard cell enclosure. More sensitive amplification and bridge techniques developed for the necessary scaling from 0.5 to 1000 pF (10^5 ohms at 1592 Hz) are now being employed in the development of automated equipment for impedance intercomparisons.

Other measurement activities currently underway in the Absolute Electrical Measurements Section include measurements of the proton gyromagnetic ratio, using the low-field method; the measurement of the Faraday, using the silver coulometer; the planning of new experiments of the ampere and γ_p using the high-field method; and the exploitation of cryogenic techniques for the measurement of resistance standards.

The equipment and facilities available cover the range from cryogenic and microwave apparatus to precision dc potentiometers and ac bridges. The NBS nonmagnetic facility, under the jurisdiction of the Section, is available for research requiring a well-characterized and controllable magnetic environment. A sputtering laboratory is presently being set up as a tool for cryogenic and solid state thin film research.

The Absolute Electrical Measurements Section provides the technical base for all of the measurement activities of the Division. It disseminates the units of capacitance and voltage to the Electrical Reference Standards Section which, in turn, passes needed units to the other two sections. The latter three provide the majority of direct technical services to the National Measurement System.

The Electrical Instruments Section is responsible for the development of standards and measurement methodology to support modern, high-speed, electronic instrumentation. Efforts are underway to provide for the determination of the accuracy of modular analog-to-digital and digital-to-analog converters under both static and dynamic conditions. The characterization of high-speed sampling devices will also be investigated. Time and speed-related properties which require standards for measurement are risetime, dynamic or instantaneous input impedance, settling curve characterization, aperature time (length and start point), etc. It is expected that the techniques discovered will "spill over" into the lower speed, high accuracy instrumentation area. Previous work done in the Section on measurements of rms ac voltage using thermal converter techniques is being applied to the development of improved ac voltage standards, needed for the support of modern instrumentation.

Experience gained from earlier work on the development of a sampling wattmeter will be used to solve two critical problems. The sampling techniques and mathematical theory with which to compute the phase angle difference between two alternating signals are known. Their application to the actual measurement situation is being made. The feasibility of using sampling techniques for the measurement of the power of irregular waveforms is being studied as well.

The *High Voltage Measurements Section* provides measurement support for the electric power industry and its suppliers and users, in addition to conducting research and development in measurement techniques and instrumentation for use at voltage and power levels which exceed those normally encountered in a standards laboratory. Calibration services are provided for current, voltage, and energy measurements at power line frequencies and voltages, as well as for high voltage devices, such as transformers, dc and ac voltage dividers, and impulse dividers. Typically, the Section is concerned with measurements at voltages in the range from several hundred volts to several hundred kilovolts; reactive power levels are frequently of the order of several hundred megavolt-amperes.

The scope of the Section activities is illustrated by the following current research and calibration projects:

(a) alternating voltage measurements - voltage (potential) transformers and other types of high voltage dividers; bridges and comparators for calibrating voltage transformers and dividers;

(b) direct voltage measurements - resistive dividers; generating voltmeters; electrostatic voltmeters;

(c) measurement of transient voltages - electro-optic techniques (utilization of Kerr cell); resistive pulse dividers;

(d) impedance measurements at high voltage - high voltage standard capacitors; standards for power factor correction capacitors; high voltage capacitance bridges; self-balancing bridges for measuring losses in shunt reactors; and

(e) measurement of current in high voltage lines - optical telemetry techniques.

The *Electrical Reference Standards Section* is primarily responsible for the dissemination of the basic U. S. legal electrical units (capacitance, inductance, resistance, and voltage). These units are disseminated through the calibration in NBS laboratories of standard resistors, capacitors, inductors, and voltage cells owned by organizations from all segments of industry and government. The units are extended through the calibration of potentiometers, bridges, volt ratio standards, inductive voltage dividers, and other ratio devices.

The units of capacitance, resistance, and voltage are disseminated additionally by means of cooperative Measurement Assurance Program (MAP) services for those laboratories requiring the ultimate in accuracy or desiring to characterize their measurement processes. These programs employ the use of extremely accurate transportable standards and carefully designed experiments to determine the uncertainty with which the client continues the dissemination process.

The Section also engages in applied research work to advance the state-of-the-art of both the maintenance and dissemination processes. One example of such work is the development of the Measurement Assurance Program for capacitance. The measurement assurance concept leads to determination of an all-embracing uncertainty statement, the product of characterizing the capability of a client's laboratory to make a specific measurement. This is done by regarding the total calibration, maintenance, and dissemination process to any point as a system and statistically sampling the output of that system on a basis dictated by the measurement needs of the system. Through the use of NBS transport standards, all random and systematic errors are determined, including effects of time, transportation, operators, equipment, grounding, and ambient conditions. After satisfactory performance has been documented, information from the system is used as feedback to reassign the values of the client's standards to agree with the legal units. The pursuit of a MAP service for capacitance entailed a study of the transport and temperature characteristics of commercial capacitors at the 1000-pF level and, as a result, the design, construction, and testing of a new transport standard.

The Division also serves the National Measurement System through its committee activities, consulting efforts, outside-sponsored research and development work, and by publishing the results of its research and development work, including that done to support NBS measurement services. Table 12 shows the various technical outputs of the Division and the approximate level of effort expended in each. It must be noted that, because of overlap, the percentages add to more than one hundred.

External sources of program guidance direction are the Office of the Director, IBS; Office of Measurement Services, IBS; the U.S. Army; the U.S. Navy; the Department of Defense Calibration Coordination Group (CCG); Department of Energy (DOE); the Electric Power Research Institute; the National Conference of Standards Laboratories; the NAS/NAE/NRC Evaluation Panel; and colleagues in industry. Since we work in close cooperation on a day-to-day basis with counterparts in the primary laboratories of the three DOD services, we are kept keenly aware of measurement needs in those laboratories. The CCG funds projects of joint interest to the Division and the military calibration structure. Recently, relations have been formalized with the National Conference of Standards Laboratories which represents the largest part of the Division's constituency.

Thus, the Electricity Division realizes, maintains, and disseminates the electrical units and related quantities to the Electrical Measurement System. These parameters are disseminated through the Measurement Assurance Programs and through the calibration of electrical standards and instruments. The quantities disseminated by the Division are all derived from three basic maintained units, those of resistance, capacitance, and voltage, and the unitless electrical quantities of resistance ratio, impedance ratio, and ac-dc current difference. The units and related quantities disseminated and the means of their dissemination are shown in table 13, page 48.

The technical infrastructure has two components. One is created as a result of the measurement support requirements of the electronics field and the other is the result of requirements of the electric power industry. The requirements of the electronics industry are of higher accuracy and over a more limited range of voltage and current than those of the power industry. They cover a wider frequency range, however, going up to 1 MHz in some cases. Power companies are generally concerned only with dc, 60 Hz, and pulse measurements, but at voltage and currents as high as 2 million volts and 50,000 amperes, respectively.

Measurements for Electronics.

(a) DC Measurements.

Voltage measurements of signals ranging from a few millivolts (thermocouple outputs) to 100 volts (power supplies for cathode ray and other tubes) are required by the electronics field. The basic unit of dc voltage is disseminated by the Electricity Division in two ways. The more accurate is the Volt Transfer Program in which an NBS transport standard is used to determine the difference between the client's unit of voltage and the legal unit. The uncertainty of this process

Table 12. Electricity Division technical outputs

Results and Reports from Sponsored Research and Development	20%
1. DoD CCG (71.5k$) 2. DOE (262.7k$) 3. Health, Education, and Welfare (FDA/BRH) (5k$) 4. Navy (36k$) 5. Electric Power Research Institute (148k$ - over several years) 6. DoD (20k$) 7. DoD (Army (7.5k$)	
Committee Activities	5%
1. IEC (International Electrotechnical Commission) 2. ANSI (American National Standards Institute) 3. IEEE (Institute of Electrical and Electronics Engineers) 4. OIML (International Organization for Legal Metrology) 5. Internal NBS activities	
Consulting	78%
1. Army 2. Navy 3. Air Force 4. NBS 5. Aerospace Industry 6. General Industry 7. Electronics Industry 8. Standards Producers	
Calibrations and Testing (Estimated 377k$ FY76 Income)	78%
Industry (80%) - Aerospace, Electronics, Instrumentation, General, Power Other NBS - Heat Division, Physical Chemistry Division, Office of Weights and Measures, Applied Radiation Division, Optical Physics Division, Electronic Technology Division Government (15%) - Navy, Army, Air Force, NASA, Interior (Bureau of Reclamation), NOAA, FAA, FDA (HEW), Bonneville Power Administration, Public Health Service (HEW), EPA, TVA	
Measurement Assurance Programs (Estimated 45k$ FY76 Income)	12%
1. NASA 2. DOE 3. Aerospace Industries 4. Power Industry 5. DoD 6. Instrumentation Industry	
Publication of NBS-Supported Research and Development	40%
1. Metrologia 2. IEEE Transactions 3. IEEE Proceedings	

Table 13. Dissemination services of the Electricity Division

Quantity Disseminated	Means
DC Volt	Volt Transfer Program Standard Cell Calibrations Solid State Voltage Reference Device Calibrations
Resistance	Resistance Transfer Service Standard Resistor Calibrations Shunt Calibrations
Capacitance	Capacitance Transfer Service Standard Capacitor Calibrations Calibration of Power Factor Capacitors
Inductance	Standard Inductor Calibrations
Ratio	Inductive Voltage Divider Calibrations Current & Voltage Transformer Calibrations HV Transformer Calibrations Pulse Divider Calibrations Volt Ratio MAP Volt Box Calibrations Resistive Apparatus Calibrations Resistive Voltage Divider (HV) Calibrations
AC-DC Difference	Thermal Voltage & Current Converter Calibrations
Power	Wattmeter Calibrations
Energy	Watthour Meter Calibrations

is about 0.42 ppm. The other way is through the calibration of saturated standard cells submitted by the client to the Division for test. The uncertainty of the test is 0.4 ppm, but transportation effects can raise that to 1.0 ppm in any context of use.

Resistance measurements are used for a large variety of purposes in the electronics industry. The most stringent requirements come from the instrumentation industry where precision resistance components are used in ratio applications such as ladders (resistive scaling networks) for analog-to-digital converters and in operational amplifier circuits to provide accurate gain factors. The unit of resistance is disseminated in two ways from the Division. The Resistance Program service in which, like the Volt Transfer Program, a set of transport standards is used to determine the difference between the unit as disseminated by the client and the legal unit. The Division also provides for the calibration of standard resistors of decade values between 10^{-4} and 10^{14} ohms. The uncertainty associated with the Resistance Transfer Service depends upon the nominal value of resistors used and the capability of the client. Transfers at the one- ohm level have been made with a total uncertainty of 0.2 ppm. The uncertainty of a regular calibration is 0.08 ppm at that level, but transportation effects and errors incurred in the client's laboratory are not included.

Resistance ratio measurements are used primarily as tools to scale or subdivide the units of voltage and resistance. They are used in the calibration of test equipment such as digital voltmeter calibrators and digital multimeters and in the calibration of other resistive apparatus such as resistance bridges, potentiometers, volt boxes, and ratio sets.

The types of devices used for such measurements are potentiometers, volt boxes, voltage dividers, universal ratio sets, and Kelvin-Varley dividers. Of these, the last two are the least specialized. They may be used to calibrate any of the others. They can also serve as instruments for two and four-terminal resistance measurements and voltage measurements.

Resistance ratios have the useful quality that they can be established to very high accuracies without the use of standards. Consequently, measurements of ratio quantities are not legally required to be traceable to national standards. However, the Division calibrates ratio measuring devices since the facilities for doing so, with very high accuracies and with a minimum of difficulty, are available. Calibration uncertainties for these devices are generally related to the resolution of the device (except for volt boxes) and range from 0.02 ppm to several hundred ppm.

The Division also offers the Volt Ratio Measurement Assurance Program. It is similar in concept to both the Volt Transfer Program and the Resistance Transfer Service except that, if measurement difficulties are encountered, a transportable measuring instrument can be sent to the client to be used as a trouble-shooting device. The uncertainty, due to transportation and measurement, of such a transfer is 1.5 ppm and it embraces uncertainties due to transportation and measurement errors at the client's laboratory, as well as at NBS.

(b) AC Measurements.

The unit of capacitance is disseminated mainly through the calibration of standard capacitors with values of 10, 100 and 1000 pF at 50, 60, 400 and 1000 Hz. The uncertainties of these measurements are 0.5, 0.6 and 5.0 ppm, respectively. The large increase in uncertainty for the 1000-pF capacitor is due to the different construction of the standards used at that level. A typical standards laboratory should be able to use these standards to make measurements of capacitance in that range of magnitude with no large increase in uncertainty. Such a laboratory would usually have a group of 1000-pF capacitors as a standard and with normal equipment should be able to make measurements with a total uncertainty of less than ten parts per million. This has been borne out experimentally in tests with military laboratories.

Inductance measurements are primarily used industrially for testing of component chokes and for quality checking of magnetic recording heads during production. Accuracies required and available in this area are low. Bridges used to make inductance measurements on the production line are accurate to 1% at best, and the capability of the Electricity Division to report the values of standard inductors with an accuracy of 200 ppm is apparently adequate for current and known future needs.

AC voltage measurements are made primarily with digital voltmeters at the applications level. Accuracies of such meters can be as high as 0.05% over a range of voltages from 0 to 1000 volts. They are calibrated using commercially available calibrators which are accurate to about 0.02%. These devices are calibrated by using an ac-dc thermal voltage converter to permit comparison between their outputs and those of very well-calibrated dc sources, known as calibrators. The dc calibrators are then verified using standard cells and resistive ratio devices. The ac-dc thermal voltage converter is the critical element in this chain since it permits the determination of rms values of ac voltage using dc voltage standards. These devices are calibrated by the Electricity Division with ranging between 5 and 200 ppm accuracies.

AC impedance ratio measurements are primarily used as calibration tools. The most commonly used device in the electronics field is the inductive voltage divider. This device is used to subdivide input voltages with amplitudes as great as 100 volts with a minimum adjustment of 10^{-7} of the input voltage. Such devices are calibrated by the Division with accuracies of 0.5 ppm of input voltage (in phase) and 5 ppm of input voltage (quadrature).

Measurements for the Power Industry. The power industry used electrical measurements in the control and monitoring of power. The main quantities measured are energy, voltage, voltage and current ratio, and capacitance.

Energy measurements are used to meter energy distributed within the power system for billing purposes. As stated previously, the power companies are required by the various state regulatory power commissions to supply users with watthour meters accurate to 2% with a 98% probability. Meter accuracies are checked by sampling. Higher accuracy in such measurements can result in smaller sample sizes, leading to considerable savings. Typically, power companies prefer to make such measurements to 0.5% to minimize the probability of fiscal loss by carrying out tests at higher levels of confidence. A sampling of several utility companies revealed that new meters were well within ±0.5%; old meters, retested in sampling operations, were within 1%. Meter manufacturers must accordingly use strict measurement tolerances.

There are two routes whereby a utility can obtain electric energy standards from NBS. The most direct one is via a client's rotating watthour meter standard which is sent to NBS for calibration. A variation of this route is the Measurement Assurance Program (MAP) whereby an NBS-owned meter is shipped to the client, who calibrates it as an unknown item in his test circuit. This procedure is preferable since it permits testing of the client's entire system.

The second, or the dc calibration route, consists of the client obtaining from NBS the standards of resistance, voltage, (both dc) and frequency. In addition, the ac-dc difference of the client's special wattmeter is also determined by NBS. The standards of resistance and voltage provide the client with the standard for the dc power. Utilizing the ac-dc difference of his wattmeter, he can produce a known ac power. This is integrated using standard time (obtained from standard frequency signals) to produce the ac energy. See figure 3.

In the past, the dc standards were considered more stable and more easily transferable than the rotating watthour meter. Establishing an ac energy standard in this manner requires more work on the client's part. Until recently, the rotating standard was considered as too fragile a device for transport, unless hand-carried. During the past four years, NBS has successfully shipped rotating standards within the Measurement Assurance Program without adverse effects. It should be added that while most of the largest utilities get their standards directly from NBS, there are utility companies, particularly the small ones which rely on the standards of other utility companies.

High voltage measurements are used for the monitoring of energy flow in high voltage lines. This is done by using transformers to reduce voltages and currents in transmission lines to a level at which they may be measured by low voltage instrumentation such as watthour meters.

The accuracy requirements for transformers in metering service are specified in American National Standards Institute publications. The Standard C12-1975, Code for Electricity Metering, states that corrections for transformer errors do not have to be applied if the transformers are of the 0.3% accuracy class (correction less than 0.3%). Another standard, C57.13-1968, Requirements for Instrument Transformers, requires that the equipment for calibration of metering transformers be accurate to 0.1%. No standards exist for the higher echelon devices - the reference transformers. The NBS-reported accuracy of 0.03% for transformers above 100 kV has not resulted in any complaints; nevertheless, a desirability for 0.01% or even 0.002% accuracy has been mentioned by various individuals in the industry.

High voltage impedance measurements are used to measure the capacitance and loss angle of power factor correction capacitors, and the impedance and phase angle of shunt reactors. These devices are used to reduce the reactive power in a transmission system. Failure to do so would result in power circulating uselessly through the system. Such devices are calibrated by the manufacturer using as a standard a gas dielectric capacitor. The manufacturer's measurement system may be checked out by an on-site calibration of his standard and bridge using an NBS bridge and standard. Calibrations of capacitors rated up to 1000 μF and 100 kVA ratings can be done at NBS.

Appendix B contains a list of primary and working standards used at NBS in support of the measurement system.

4.2.2 Users of NBS Services

The users of the services made available by the Electricity Division fall into the same general categories as do the major components serviced by the Measurement System. The major categories are given below.

Table 14. Users of NBS services

Instrumentation Industry
Department of Defense
Aerospace Industries
Communications Systems Manufacturers
Electric Power Industry
Electrical Component Manufacturers
General Manufacturing Industries
Independent Calibration and Testing Laboratories
Civilian Government Agencies
Universities

User categories are listed roughly in order of their dependence upon the services offered. As has been stated previously, the services provide the basis for accuracy of all measurements which are in turn used to assure the quality, volume, and advancing technology of produced goods.

4.2.3 Alternate Sources

There are no alternate sources for the most important service that the Electricity Division renders the Electrical Measurement System. The Division provides the research and development effort necessary to enable the system to fulfill its needs in a timely fashion. Other organizations are well-equipped, have competent staffs, and are able to supply calibrations of standards at accuracies approaching those available at NBS for certain parameters. But none are motivated to make the magnitude of investment required for, nor have the responsibility for providing for, the research and development in basic metrology needed to support the entire system. No one organization matches the breadth of the NBS capability and none match its capacity for future improvements or for responding to changing needs. For the measurement system to function in an optimum way, services and research must go hand in hand.

Commerce and industry today, even more than at the turn of the century, require traceability of measurements to a single source as a necessity for accuracy, without which interchangeability of parts, ready repair, compatibility of electronic devices, and ease of design would all be impossible. In addition, because of its role as the premier source of standards for electro-technology and the fact that it is funded publicly and represents no special interest, the Electricity Division is able to act as a neutral third party - an arbiter in areas of technical dispute involving measurements.

Scenarios have been proposed to consider what would be the results of turning the bulk of the metrology dissemination and calibration work over to state or private calibration laboratories. To do so would result in isolation of the Electricity Division from the bulk of its user community and hence render it less, rather than more, responsive to the needs of the system. The difficulty of moving technology out to the system would increase due to this isolation.

4.2.4 Funding Sources for NBS Services

The development of new services and the improvement of existing calibration services are supported by congressionally-appropriated funds (NBS budget), augmented by funding from private and government agencies outside NBS on a contractural basis. Typically, the Division has about 20% of its budget provided in this manner. Most of this comes from the Department of Defense, to augment work in support of its measurement systems; and from EPRI, the Electric Power Research Institute, and the Department of Energy, for energy-related work. In addition, federal law requires the complete recovery of the costs of providing calibration, measurement transfer, and other routine services from the users of such services. Revenue from this source constitutes approximately 14% of the Division's budget.

4.2.5 Mechanisms for Supplying Services

Dissemination services take place through three mechanisms: the calibration of client standards at NBS; Measurement Assurance Program services, which involve the use of NBS transport standards to sample the measurement process output at a given place; and *in situ* calibrations of such devices as high voltage transformers and capacitors by NBS personnel using NBS apparatus and standards.

Dissemination of metrology information is provided for by sponsorship of Division seminars and workshops, publications in the scientific literature, participation in standards committee activities by staff members, publication of tutorial articles such as Technical Notes, and by individual personal interaction with members of the metrology fraternity at large.

4.3 Impact of NBS Services

4.3.1 Economic Impact of Major User Classes

Although no accurate quantitative assessment of leverage is possible, an appreciation of the potential impact of NBS services may be gained by a consideration of the gross annual sales figures of those segments of industry it supports as shown in table 15.

The Defense Department, of course, is vital to the well-being of our nation. It depends on measurements to ensure weapons system reliability, and indirectly through the aerospace and electronics industries,

Table 15. Electricity Division user classes

	SIC Code	Number of People	Value of Shipments (billions of $) CY 75	Number of Companies
Electronic Systems	3662	330,000	9.6	86
Components	367	412,000	10.6	1420
Computers	3573	175,000	9.7	610
Engineering & Scientific Instrumentation	3811	43,000	1.4	721
Measuring & Control Instrumentation	3821	72,000	2.1	817
Test Equipment	3825	70,000	2.2	622
Power Equipment	351	44,000	2.4	74
Transformers	34433	18,000	.9	40
Electric Power	491	317,000	47.9	225
Aerospace	372,376	615,000	26.2	1225

superiority through technical sophistication. All of these industries, with the exception of the electric power industry, produce high technology products and contribute heavily to our high standard of living. The power industry applies research and uses high technology to provide us with the means to utilize energy conveniently and is responsible in large measure for the industrial base of the country.

4.3.2 Technological Impact of Services

Calibration and MAP services of the Electricity Division provide both the electronic and electrical power industry segments of the measurement system with the stable, basic electrical units upon which the accuracy of measurements throughout the system depends. This support is vital to the development of new, sophisticated instrumentation and to the maintenance and continuing effective use of the very large existing national inventory of test equipment and measurement instrumentation. This inventory of electrical measurement apparatus is the only viable means of providing quality control for manufacturing processes throughout industry, ensuring operational readiness of our sophisticated weapons systems, enabling the high degree of reliability of electronics and equipment vital to our manned space operations, making possible the reliable and smooth functioning of the nation's communications and transportation networks, and providing for the efficient and effective distribution of electric power to industrial and domestic consumers throughout the country. The importance of instrumentation and the measurements it makes is borne out by two factors. The expected increase in test and measuring equipment for electrical quantities alone is 11% between 1975 and 1976 and that growth rate is expected to continue through 1985, by which time $6.5 billion in instruments will be produced annually [11]. This growth rate, especially in times of economic hardship, is an indication of the need for measurements. Secondly, to this must be coupled the fact that the measurement capability per unit cost of instrumentation is rising dramatically due to the semiconductor revolution and the inclusion of microprocessors in individual instruments [30]. Standards maintained by the Electricity Division and used to disseminate the electrical units allow measurements made by this instrumentation to be consistent throughout the country and stable over time.

NBS services, such as consultative and committee activities and publication of metrology research and development work, are aimed at promulgating measurement technology so that measurements may be made more efficiently, effectively, and accurately throughout the system. NBS representation is most widespread on those technical committees of the Institute of Electrical and Electronics Engineers, the American National Standards Institute, and the International Electrotechnical Commission which deal with electrical measurements. Literally hundreds of inquiries per year about various electrical measurements problems are handled by staff members.

Publications concerning measurement techniques have a heavy impact on the measurement community. Over 3000 copies of NBS Technical Note 430, Designs for Surveillance of the Volt Maintained by a Small Group of Saturated Standard Cells by Eicke and Cameron have been distributed. The measurement techniques set forth in this document were at the time of publication virtually unknown in the electrical measurements field outside of NBS and have since been adopted by a significant number of metrology laboratories. This has resulted in general improvement in the quality of voltage measurements in standards laboratories as well as permitted the identification of potentially serious measurement problems.

Some of the areas of technology and industry heavily supported in both development and operational phases by the measurement system are semiconductors, discrete electronic components, instrumentation (a user as well as an implementor); communication; navigation; chemistry; metals; and computers. Electrical measuring instruments provide the basic tools for physical, biomedical and chemical research as well.

4.3.3 Pay-off from Changes in NBS Services

Two notable changes have occurred in recent years in services offered by the Electricity Division. The first is the increasing use of Measurement Assurance Program services, starting with the Volt Transfer Program, for the dissemination of the electrical units. In the case of all of these services there have been two immediate technical effects: the units have been transferred with higher accuracy; and invalid measurement techniques at users' locations have been identified and their use curtailed due to NBS analysis of data.

In a number of cases, there has been a third payoff. The techniques used in the process have been successfully applied to the users' individual measurement system.

The most definitive economic benefit has been the extension of the interval between calibrations for the clientele using these services. This is made possible by the improved accuracy of the transfer and the methodology by which the data are reduced, in comparison with usual methods used to ensure measurement traceability. The greatest measurable economic impact of this type of service will most likely result from the application of these specific techniques to effect a reduction in cost of supplying measurement support to production lines and throughout quality control systems.

For a group of five California companies, the availability of MAP services has meant a completely new method of establishing traceability. In the past, each company sent standards of voltage and resistance annually to NBS for intercomparison. Now, each year only one of the companies becomes involved in an NBS voltage or resistance transfer. During the same period of time, the group undertakes a five-way intercomparison of the appropriate units for each company, using measurement transfer techniques. They have reduced the cost of traceability significantly in this fashion and each now has confidence in the standards of the others should a failure occur in his own [31].

The second major change in the Division's services occurred as a result of closing the old NBS high voltage (HV) laboratory in Washington, DC. In 1970, a decision was made and implemented to move the low and intermediate voltage support facilities and offices of the High Voltage Measurements Section to the Gaithersburg site. The HV laboratory was intended to be retained as a field station and used whenever the need arose for voltage levels above 50 kV.

However, in 1971, the General Services Administration, the owner of the laboratory and site, asked NBS on short notice to vacate the facilities in order to make the land available for the Washington Technical Institute. NBS abandoned the laboratory and transferred the equipment for a nominal sum to another government agency. Thus, NBS gave up, and the Division lost, a facility whose replacement cost today would range from $5 to $10 million.

The basic reasons for this closing were complex: low calibration workload, a lack of funding of high voltage research by other agencies; its vulnerable position as an isolated facility away from the main NBS campus; and NBS program priority decisions.

To retain some capability for calibrations and research in the high voltage measurements area, especially for measurements required in revenue metering, a new mode of operation was begun. Instead of doing all HV work in-house at NBS, measurement services above 100 kV are offered as on-site calibrations. Division staff members go either to customers' high voltage laboratories or to one which belongs to an acceptable third party. The NBS instruments and standards used are designed with portability in mind. For calibrations and research below 100 kV, and intermediate voltage in-house facility has been established at the NBS Gaithersburg (MD) location.

This change in NBS facilities extensively affected the electric power industry. While retaining an acceptable calibration capability, it reduced the Division's capability and flexibility to contribute to the research requirements of electric power transmission systems. The level of power industry support in the sixties, when the future of the NBS high voltage laboratory was debated, may not have indicated the need for it. However, the situation changed significantly in the past few years.

The principal reason is the energy crunch and the associated emphasis on energy-related R&D. Electric power R&D in industry has been focused by the formation of the Electric Power Research Institute (EPRI), which is the R&D arm of the power industry; and the Department of Energy, which controls the public funds related to energy research.

The combined transmission and distribution (T&D) budget for these organizations is about $40 million annually. The size of the measurements component is difficult to assess exactly since it is diffused throughout the entire program, but a safe estimate, based on the problems of which NBS is aware, would be at least 1% of this or $400k annually.

In the past two years, power systems related OA work in the Electricity Division has increased from a negligible amount to about $250k annually. Further increases still could be made if facilities and manpower were available.

In summary, the potential need for measurements R&D related to electric power systems is at least $400k annually. Even if other constraints were removed, we could not undertake such a program fully without having access to our own or a closely located HV laboratory. It also must be added that T&D research (including measurements R&D) relates to a projected capital investment of $150 to $200 billion over the next 15 years.

4.4 Evaluation of NBS Program

The Electricity Division program is generally consistent with the needs of the electrical measurement system but inadequate in several areas, such as the dynamic electrical standards area, due for the most part to limited resources, both of personnel and funding. The most powerful tool for determining the needs of the measurement system for the Division's services and output is the expertise of the technical staff of the Division. By keeping current with trends and advances in instrumentation and electronics, staff members identify potential areas where NBS measurement support will be needed as well as up-to-date tools to help supply that support.

Other agency sponsors constitute a powerful means of identifying needs. In the electrical power area, responsibility for the development of nearly all future technology is in the hands of the Division's two major sponsors, the Department of Energy (government) and the Electric Power Research Institute (private sector). Widespread Division contacts within these two organizations ensure early recognition of needs within the power industry.

State-of-the-art advancements in electronics, systems, and instrumentation generally result from fulfillment of the new weapons requirements of the Department of Defense. The Division has a very close coupling with the Defense Department through its Calibration Coordination Group. This DoD group, which over the years has sponsored a large amount of metrology development work in the Division, apprises NBS staff members of future measurement requirements in the military system.

The National Conference of Standards Laboratories is a management-oriented organization comprised of companies and government agencies with metrology interests. This group is highly representative of the Electricity Division's clientele as there is greater than a 80% overlap of NCSL member companies and the Division's calibration services users. Recently, the Executive Board of that organization approved a plan to constitute an NCSL liaison board to the Electricity Division. This board will serve both to provide inputs for future planning in the Division and as a vehicle for the dissemination of technical and management information from NBS to NCSL member companies.

The National Academy of Sciences/National Academy of Engineering/National Research Council Evaluation Panel for the Electricity Division reviews the programs in the Division, generally on an annual basis, and provides valuable input for the determination of future program directions. The most recent such panel had eight members representing the viewpoints of the power industry, the Federal energy research program, the Department of Defense, the academic community, the electronics industry, the research community, and the instrumentation industry. The Panel's reports contain comments and recommendations on technical, managerial, and administrative matters as well as suggestions for new directions. The annual meetings between the Panel and staff members, although perhaps too brief, are very beneficial for the exchange of technical information and views too detailed to be of use in management reports.

The most recent Panel was in full support of the Division's ongoing programs, and especially highlighted the need for work to be done in the areas of measurements in support of high voltage research and development and high-speed dynamic standards for modern electronic instrumentation. The Panel identified communications between the Division and its constituency as being a major problem and commented on the process of setting long-term development goals in the rapidly developing area of modern instrumentation.

As needs are identified, program priorities must be established. These priorities are the result of careful consideration of the degree to which response to the need falls within the NBS mission, the magnitude of the need, the resources (including expertise) available to deal with the problem, and the likelihood of success in an appropriate time frame.

Major needs of the system for NBS services include those for:

(a) basic standards to maintain stable national electrical units;
(b) means of disseminating the units;
(c) "how-to-to-it" metrology information;
(d) dynamic measurement standards for modern instrumentation;
(e) techniques for the measurement of impedance, voltage, current, and dielectric properties at high voltages; and
(f) the determination of fundamental physical constants, such as the Faraday and 2e/h.

The Electricity Division has on-going programs to respond to each of these areas of need. Because of the widespread need of these services and the need for an impartial, technically competent organization to deliver them, it is clear that they can be performed only by a federal government agency. NBS is the only agency with the expertise and statutory responsibility for providing them.

4.5 The Future

Activities in the Electricity Division are at present undergoing a period of change. Advantage has been taken of the completion of a large number of projects in traditional areas to effect reprogramming to bring effort to bear on the solution of problems in new measurement areas. The Electricity Division's capability to provide support for static measurements in the general instrumentation are generally more than adequate to meet present needs. However, similar support is lacking for the dynamic measurements (i.e., those made under a time constraint) of electrical quantities such as are made under computer control. Hence a considerable effort is being devoted to a program to establish measurement methodology and standards in support of modern, high-speed instrumentation. Investigations are proceeding to establish standards and instrumentation to investigate high-speed analog-to-digital and digital-to-analog conversion modules. A program to establish methodology for the proper support and implementation of electronic test equipment of high accuracy is underway on a modest scale. The Division is midway in the development of a system to provide an accurate measurement base for the semiconductor industry at the 10-volt level.

All of this activity is in response to the needs perceived by Division personnel which led to a workshop in September of 1974 to identify and quantify Critical Electrical Measurement Needs and Standards for Modern Electronic Instrumentation. The Workshop was attended by 24 engineers and scientists representing a variety of industrial viewpoints. Automatic test equipment users, instrument manufacturers, systems users and manufacturers, and the semiconductor module industry were represented, mostly at the engineering manager, or vice-president level. The general conclusion of the Workshop supported the Electricity Division's perception of needs in this area. Other hitherto unidentified needs were made known, most notably in the areas of pulse responses of components, dielectric hysteresis, and the characterization of ac line voltage with respect to transients, dynamic impedance, etc. [see Appendix C].

In the area of dissemination of information, a program has been started to generate a series of tutorial publications covering various aspects of electrical metrology useful to the personnel of a typical standards or calibration laboratory. An effort is being made to establish an Electricity Division newsletter in one technical journal and to publish overview articles in other, more generally based, periodicals, in order to expose Division programs to the scientific and engineering community and thus engender feedback.

In discussing the measurements for electric power systems this report implicitly and explicitly recognizes two areas: (1) the areas related to the "traditional" quantities such as voltage, current, impedance and, especially, power and energy; and (2) that area related to research and development of new apparatus and systems, primarily for transmission and distribution. In the latter area are also included those specialized and difficult measurements employed in the design and quality control of present systems.

The delineation between the two areas is not very rigid and the term "traditional" must be tempered since it does not imply lack of need for research and development activity. As the instrumentation and transmission technologies change, NBS must meet the changing measurement requirements for these basic electrical quantities. As discussed elsewhere in this report, a very important item in this first category is the measurement of electric energy. Although currently this area is well in control, new instrumentation and metering practices will be introduced within the next five years which will place additional requirements on the NBS services. Electronic watthour meters are appearing in interutility and large commercial and industrial metering installations. Load management based on variable rates for electric energy is being considered. A more sophisticated instrument combining the functions of a watthour meter and a demand meter has been suggested. As with the conventional induction-type watthour meters, not only will the accuracy and reliability be of concern, but also the ease of remote reading and control and interfacing with a central computing facility. Although its role is not entirely clear at the moment, NBS will be required to provide rather different kinds of supportive measurement services in the future in addition to the present routine calibrations and MAP services. New developments in this area will be closely watched.

In measuring the traditional steady state quantities, problems exist in calibrations at higher voltages, where relatively few organizations have a capability of calibrating voltage transformers. Traceability to the fundamental NBS-maintained standards is weak. The Electricity Division will try to alleviate this situation by promoting field calibration services and through specific projects such as the development of the system for calibration of coupling capacitor voltage transformers in substations.

With respect to the other area concerned with R&D and specialized measurements, there are numerous unresolved problems now and certainly more will become evident as the R&D in new transmission systems progresses. The weakest area now is concerned with the measurement of high voltage transients, especially at extra high voltage (EHV) and ultra-high voltage (UHV) levels. NBS will continue to work in impulse measurements with particular emphasis on transferring our capabilities to the power industry. Contingent upon the availability of resources, work should be done on devices for measuring voltage, current and power in high voltage dc transmission systems.

The Division will follow the developments of new transmission systems and provide its expertise for solving measurements-related problems. This area is proper for extra-NBS support. An example is the development of a superconducting ac transmission system. High voltage measurements research related to the insulation of superconducting cables is already being performed. Superconducting systems will have very high current capabilities. New methods will be needed to measure these currents.

Another new transmission system under development uses SF_6-insulated conductors. Nonconventional measuring methods appear to offer cost and accuracy advantages in these systems. This entire area is ripe for exploration.

If overhead transmission enters the UHV region, electro-optical current transformers will become very attractive. The NBS will be in the best position to evaluate their accuracy capabilities by virtue of measurement techniques in the UHV region developed here.

Potentially adverse effects on environment due to high electric fields, audible noise and electromagnetic interference are of great concern in connection with new EHV and UHV overhead systems. The Division will offer measurement assistance to the agencies primarily concerned with this problem.

Reprogramming efforts to respond to all of these needs made evident a serious weakness in the Division. The Division simply lacks the proper resources, people, and funding to mount a comprehensive program in each area without seriously eroding the supporting basic measurement program - there is concern that a proper job cannot be done without ignoring clear responsibilities in the traditional areas.

On the other hand, there would be a large negative impact if the Division were to fail to meet the needs being addressed by these various activities. The state of the electronic marketplace is one of chaos with respect to high-speed electronics. Lack of common terminology and universally accepted test procedures makes procurement by specification a difficult and hazardous procedure. Since the definitions of temporal parameters are nebulous, different interpretations are used by different manufacturers and the buyer has no means of evaluation except in terms of a specific application. The net result is that much money is wasted on useless purchases and the over-specification of components to ensure adequate performance. The presence of an authoritative, technically competent, neutral "third party" such as NBS, is urgently needed in the area to establish commonality.

Why should NBS be involved in any of this? The Federal government is the only organization that can afford to look past tomorrow to the future in the area of measurement science and standards. Industrial concerns must have staying-in-business as a first consideration. That generally means a minimum of long-range (10-20 year) research programs, and a great deal of motivation for keeping potential profit-making results of such research secret.

The National Bureau of Standards is the only government organization with the base, the expertise, and the legislative charter to perform these functions. No other government laboratory has appropriate facilities or staff. Research in measurement methodology would not be the primary concern where other national needs such as national defense are the responsibility of the organization. The country needs one organization in which measurement activities and standards are the primary concern as at NBS.

5. SUMMARY AND CONCLUSIONS

The National Measurement System for Electricity has two major components; those of electronics and the electric power industry. These are separately identified because of the distinctly different nature of the measurements required in each. The former is comprised of the electronics and instrumentation industries and their users, while the power subset of the system is comprised of the electric utilities, manufacturers of generating, transmitting and distributing apparatus and, to some extent, the users of electric energy.

The present measurement capability of the electronics subset is more than adequate to support traditional measurements (those made manually or without time constraint) except in a very few limited cases such as, low frequency, low amplitude ac voltage measurements and upper audio and lower radio frequency impedance measurements. However, due to the impact of advances in semiconductor technology on the instrumentation, computer, and electronics industries, and the resultant increases in complexity of components, devices, and systems, a larger and larger percentage of measurements is being made by electronic instrumentation under computer control and under conditions in which time is a constraining factor. This leap forward in measurement technology has not been matched by the development of appropriate standards of measurements. Designers of automatic test systems and equipment do not have the benefits of either physical or written standards for dynamic electrical measurements as tools. Common terms, such as aperature and settling time, used to describe dynamic properties of measurement equipment, do not have universally accepted definitions. Also physical standards, analogous to standard resistors, capacitors, and cells, for the quantification of dynamic properties do not exist. Designers and users of modern test equipment and instrumentation must use costly trial and error or "overkill" methods for both the development and maintenance of such equipment. Development of future, more accurate and faster systems will be hampered by lack of such standards.

In the electric power industry subset, which deals basically with energy, voltage, current, and impedance measurements at 60 Hz, some at very high voltage and impulse measurements at high voltages, the present capabilities are generally adequate to support today's operational requirements. However, the electric power industry is beginning an era of great change. The main forces for change are the energy crisis and the appreciation of the small size of the remaining supply of petroleum. Research efforts to improve the capacity and efficiency of elecpower generation, transmission, and distribution have been expanded greatly over the past few years. New measurement methods and standards are drastically needed to enable this research to reach fruition and to support and maintain the new power systems expected to result. Measurement methods are needed for such things as calibration of capacitive coupled voltage transformers (CCVT's) for use at 500 kV and above; evaluating various types of prototype distributions systems, such as underground dc and gas insulated, cryogenic, or extruded insulation systems, and overhead systems ranging as high as 1.5 million volts; evaluation of environmental and interference effects of ultra-high voltage overhead lines; and development of tests to ensure that equipment on such lines can withstand transient overvoltage and surge currents caused by lightning and switching. Energy metering, done largely at the present time using rotating electrodynamic meters, will require new measurement support with the advent of electronic meters which will be used for demand and time of day metering purposes and may eventually employ telemetry techniques for instant transmission of consumption information to the utilities.

There are a few common problems with widespread effects on the entire system. Among them are:

(a) a lack of availability of "how-to-do-it" measurement information throughout the system;

(b) a shortage of manpower with specific metrology training and a resulting widespread lack of sophistication in measurement technology as practiced;

(c) heavy emphasis on "traceability", largely fostered by Department of Defense quality requirements, which causes much attention to be focused on equipment specifications and calibrations rather than measurement technology. This tends to slow the development of new and improved methods of providing measurement support where it counts, on the production line or at the weapons system; and

(d) a lack of recognition of the formal metrology structure as an asset rather than a required artifact in a large percentage of industry.

Specific recommendations resulting from this study are:

General

Develop a mechanism to foster and support the use of Measurement Assurance philosophy and techniques within industry to provide subsistence to measurements made for quality control, manufacturing, or maintenance purposes.

Develop more formal contact between the Electricity Division and the instrumentation industry, perhaps through the aegis of the Scientific Apparatus Manufacturers Association.

Establish national standards and improved measurement methodologies for the ac measurement of conductivity in metals in support of non-destructive testing in industry.

In support of electronics

Investigate new technology for providing measurement support for automatic test systems, perhaps in conjunction with Defense Department efforts in this area.

Examine microprocessor technology and the applications of microprocessors to instrumentation to lay the foundation for support for future generations of sophisticated "smart" instruments.

Provide improved methods for the measurement of ac voltages at low amplitudes in the sub-audio frequency range and the measurement of impedance in the upper audio range for the support of vibration and communications instrumentation respectively.

In support of the power industry

Provide for development of measurement methodologies for the characterization of the insulating properties of various materials and systems at high voltages and under various conditions and configurations (such as for superconducting cables).

Contribute to the development of electronic watthour meters to develop the new standards and measurement techniques necessary to their support.

Promote the use of field calibrations and measurement assurance programs in the area of high voltage.

Continue research in high voltage impulse measurements and develop mechanisms to disseminate the resulting technology to industry.

Develop new approaches and devices for the measurement of voltage, current, and power in high voltage dc transmission systems.

Investigate methods for measurement of the extremely high currents which will be carried by superconducting cables.

Develop methods for the precise measurement of electric fields in regions of extreme nonlinearity for environmental protection and safety testing purposes.

APPENDIX A

THE MEASUREMENT SYSTEM STUDY

The starting point in efforts to date has been the group of organizations constituting our calibration clientele. The general plan for this study is outlined below:

a. Identify calibration clients and associated economic data.
b. Classify clients by industry or major product(s).
c. Select sample of clients to visit to determine measurement needs, technical problem areas, and organizational structure.
d. Identify corporations and industries who are not clientele but who are engaged in the same kinds of endeavors.
e. Sample non-client organizations of maximum economic, social, and political importance to determine the methods employed to achieve product quality assurance in those organizations.
f. Garner detailed information about specific needs via interviews, workshops, etc.

Using information supplied by the Office of Measurement Services (NBS), a listing of all users of our calibration services in FY 72 has been compiled. The clients on this list were then classified in one of the categories shown subsequently. Each organization was assigned up to three numbers representing one primary and two secondary activities. These were based on personal knowledge and on descriptions found in *Standard and Poor's Index*. In addition, annual income figures from either the *Standard and Poor's Index* or the *Dun and Bradstreet Million Dollar* and *Middle Market Indicies* were gathered for each customer. This information was added to that supplied on punch cards by the Office of Measurement Services and sorted. There were three sorts made, one by each of the primary and secondary activities of each company. As a result of the first sort, 52 companies are unclassified; 17 are in the aerospace industry; 49 manufacture instrumentation; 21 manufacture components; 43 are power industry-related; 7 are universities; 9 are other Federal government agencies; and 32 are in general manufacturing, for a total of 230 companies. A meeting of the study authors was held on the receipt of these printouts and a number of pertinent decisions were made.

It was decided that a separate substudy should be made of the power industry in view of the percentage of the Division's clientele it represents, the annual income it has, the role it plays in our society, and the energy crisis. The chief of the High Voltage Section undertook this substudy because of the mission of the Section and his personal contacts within the electric power industry.

A minimum sample size for each of several categories was decided upon, based upon the perception of the degree of impact NBS has on each category and knowledge of the uniformity of measurement technology within the category. The table below gives each of these categories and the sampling size chosen.

SAMPLE SIZE FOR CLIENTS

Category	Sample Size
201 Precision Apparatus	100%
212 DC-LF Test Equipment	100%
100 Aerospace Industries	25%
209 Systems	10%
600 Other Agencies	100%
300 Component Manufacturers	2 of each subcategory
800 Calibration Laboratories	As many as possible

The type of information which would be sought of each sample was also discussed. Answers to the following questions would be sought:

a. What are the corporate quality control organizational and technical structures?
b. Do you perform calibrations for other organizations? How Much? For whom?
c. What is the name of the key researcher in your company (Chief Scientist, perhaps)?
d. What is the annual expenditure on electrical measurements in your company? How is it spent?
e. What measurement areas are most critical to your final product?
f. What measurement or measurement-related problems do you have? Can NBS help?
g. What products are most critically affected by measurements?
h. Would you be aided by improved or new NBS services? What areas? Why?
i. What are the desired accuracies of measurements at the end item? Who determines these? Why are they what they are? What are the consequences of not supplying the desired accuracies?
j. Are you a military contractor? Are you subject to any regulatory agency policies?

It also seemed desirable to inform our contact, in advance of a visit by Division personnel, of the capabilities of the NBS and especially of the Division. Accordingly, an effort has been made to inform him by letter or telephone of the specific purpose of the visit so he could be prepared. It would be difficult, otherwise, to get past the corporate standards laboratory into the applied areas of the system.

In gathering information from *Standard and Poor's Index* and from the two publications of Dun and Bradstreet, it became apparent that NBS has direct contact with only a small percentage of the electrical measurement system. It had been originally decided that the Division must sample that part of NEMS it does not normally interact directly with. To do that the services of Dun and Bradstreet were enlisted. The list of clients previously mentioned was expanded to include FY 73 clients and each plant location served. The local office of Dun and Bradstreet determined the primary Standard Industrial Classification (SIC) Code for each company of a large sample. After discarding 17 of the 35 SIC codes thus obtained due to obvious lack of relevance, a contract was issued to Dun and Bradstreet to supply the Division with Dun's Market Identifiers for each of the companies in their file having one of the 16 primary SIC codes and more than 20 employees. Information has been supplied for 12,865 companies in the United States.

We hope to obtain additional samples by interrogating people who visit the Division.

In the past four years over 90 plant locations have been visited by Electricity Division personnel. Before this study was formally initiated, the purpose of most visits was the discussion of measurement problems. The next pages contain a representative list of locations visited.

Technical forecasting is always involved in program planning, whether explicitly or implicitly. In the past, technology forecasting for this Division has been done by two groups of experts, one (unorganized) within the Division and the other outside of the Division, the NAS/NRC/NAE Advisory Panel.

The technology forecasting portion of this study has been accomplished by doing a formal review of trends and forecasts already published for the electrical field by trade and industrial associations, professional societies, and other government agencies.

SAMPLE LIST OF PLACES VISITED

Associated Engineering Company
Matthew, NC 29105

Autonetics
Rockwell International
3370 Miraloma Avenue
Anaheim, CA 92803

Ball Brothers Research Corporation
P. O. Box 1062
Boulder Industrial Park
Boulder, CO 80302

Baltimore Gas and Electric Company
531E Madison Street
Baltimore, MD 21203

Beckman Instruments, Inc.
2500 Harbor Boulevard
Fullerton, CA 92634

Bendix Environmental Science Division
1400 Taylor Avenue
Baltimore, MD 21204

Boeing Company
Aerospace Division
P. O. Box 399
Seattle, WA 98124

Brookhaven National Laboratory
Brookhaven, NY

Dickson Electronics Corporation
P. O. Box 1390
Scottsdale, AZ 85252

Duke Power Company
P.O. Box 2178
Charlotte, NC 28201

Fairchild Semiconductor
4300 Redwood Highway
San Rafael, CA 94902

Ford Motor Company
21500 Oakwood Boulevard
P. O. Box 1704
Dearborn, MI 48121

General Electric Company
Ordnance Systems
100 Plastics Avenue
Pittsfield, MA 02101

Global Associates
Mississippi Test Facility
Bay St. Louis, MS 39520

Hewlett Packard Company
815 SW 14th Street
Loveland, CO 80537

Hewlett Packard Company
Automatic Testing Division
Mountain View, CA

Hewlett Packard Company
Microwave Division
Palo Alto, CA

Honeywell Industries
5558 Port Royal Road
Springfield, VA 22151

Honeywell, Inc.
Government & Aeronautical Products Div.
2600 Ridgway Parkway
Minneapolis, MN 55413

Honeywell, Inc.
Test Instruments Division
4800 East Dry Creek Road
Denver, CO 80217

Honeywell, Inc.
5303 Shilshole Ave., NW
Seattle, WA 98107

Hughes Aircraft Company
Centinela & Teale Streets
Culver City, CA 09230

IBM
Systems Manufacturing Division
Monterey & Cottle Roads
San Jose, CA 95193

Jet Propulsion Lab
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91103

John Fluke Manufacturing Co.
P. O. Box 7428
Seattle, WA 98133

Julie Research Laboratories
211 West 61st Street
New York, NY 10023

Leeds & Northrup Company
Sumneytown Pike
North Wales, PA 19454

Linde Corporation
Tarrytown, NY

Lockheed Missiles & Space Company
P.O. Box 504
Sunnyvale, CA 94088

Martin Marietta Corporation
Denver Division
P. O. Box 179
Denver, CO 80210

Melpar
Division of LTV Electrosystems
7700 Arlington Boulevard
Falls Church, VA 22046

3M Company
3M Center
Bldg. 216-1S
St. Paul, MN 55101

Newark Aerospace Guidance &
Metrology Center
Newark Air Force Station, OH 43055

Optimation Industries
Northridge, CA

Patuxent Naval Air Station
Patuxent River, MD 20670

Oak Ridge National Laboratory
Oak Ridge, TN

Philadelphia Electric Company
2301 Market Street, N4-1
Philadelphia, PA 19103

Rosemount Engineering Company
12001 West 78th Street
Eden Prairie, MN 55343

Shallcross Manufacturing
Preston Street
Selma, NC 27576

Sperry Rand Corporation
UNIVAC Division
Univac Park
P.O. Box 3525
St. Paul, MN 55101

TRW Systems Group
One Space Park
Redondo Beach, CA 90278

United Air Lines
San Francisco International Airport
San Francisco, CA 94128

Westinghouse Electric Corporation
P. O. Box 1637
Baltimore-Washington International
Airport
Baltimore, MD 21303

Westinghouse Electric Corporation
Astronuclear Laboratory
P. O. Box 10864
Pittsburgh, PA 15236

Westinghouse Electric Company
Raleigh, NC

CATEGORIES OF CALIBRATION CLIENTELE

100 Aerospace Industry
- 101 Prime Contractors (Airframe)
- 102 Subcontractors (Miscellaneous)
- 103 Subcontractors (Propulsion)
- 104 Subcontractors (Guidance)
- 105 Consultants

200 Instrumentation
- 201 Precision Apparatus Manufacturers
- 202 DC-LF Test Equipment Manufacturers
- 203 Analog-to-Digital, Digital-to-Analog Conversion Equipment
- 204 Medical Instrumentation
- 205 Process Control Computer and Data Acquisition Products
- 206 Nuclear Instrumentation
- 207 Communications Equipment
- 208 Recording Equipment
- 209 Systems
- 210 Chemical Instruments
- 211 Pollution Monitoring Equipment
- 212 Microwave Test Equipment
- 213 Temperature Measuring Equipment

300 Component Manufacturers
- 301 Resistors
- 302 Capacitors
- 303 Inductors
- 304 Solid State Reference Devices
- 305 Integrated Circuits
- 306 Switchgear
- 307 Electron Tubes
- 308 General
- 309 Batteries

400 Power Industry Related
- 401 Transmission Monitoring Equipment
- 402 Generating Equipment Manufacturing
- 403 Power Measuring Equipment
- 404 Power Generation
- 405 Consultants

500 Universities

600 Other Government Agenices
- 601 Army
- 602 Navy
- 603 Air Force
- 604 NASA
- 605 Bonneville Power Administration
- 606 Public Health Service
- 607 FDA
- 608 NOAA
- 609 FAA
- 610 EPA
- 611 TVA
- 612 Bureau of Mines
- 613 ERDA

700 General Industry
- 701 Automobile Industry
- 702 Waste Management
- 703 Electric Motors
- 704 Electric Generators
- 705 Metals Products
- 706 Nuclear Research
- 707 General Research
- 708 Computer Manufacturing
- 709 General Manufacturing
- 710 Chemicals
- 711 Consumer Products
- 712 Services
- 713 Sales

800 Calibration Laboratories

APPENDIX B

NBS PRIMARY AND WORKING ELECTRICAL STANDARDS

The following identifies the number and type of standards used to maintain the various electrical units and working standards for the dissemination processes. The term "primary" as used below refers not only to those standards used to maintain the basic electrical units, but to those which enable measurements to be made under conditions differing from those under which the basic units are maintained. Examples of the latter are standard resistors especially designed for stable characteristics at very high currents. The list does not contain measurement apparatus (except when such apparatus embodies a unit), or intermediate standards used for scaling, or the check standards used to maintain statistical control over the various measurement processes.

Sec. 1. RESISTANCE

Primary Standards

5 Thomas (NBS) One-ohm Standard Resistors

Working Standards used at Low Currents (0.01 W or less)

10^{-4} ohm	4 Reichsanstalt (commercial) Standard Resistors
10^{-3}	4 Reichsanstalt (commercial) Standard Resistors
10^{-2}	4 Reichsanstalt (commercial) Standard Resistors
10^{-1}	4 Reichsanstalt (commercial) Standard Resistors
10^{0}	5 Thomas (NBS) One-ohm Standard Resistors (The Primary Group)
10^{0}	15 Thomas (commercial and NBS) One-ohm Standard Resistors (MAP)
10^{1}	4 Rosa (commercial) Standard Resistors
10^{2}	2 Special, high-stability (commercial) Standard Resistors
10^{2}	2 Special, high-stability (commercial) Standard Resistors (MAP)
10^{2}	2 Special, high-stability (commercial) Standard Resistors
10^{3}	2 Special, high-stability (commercial) Standard Resistors (MAP)
10^{4}	4 Special, high-stability (commercial) Standard Resistors
10^{4}	4 Special, high-stability (commercial) Standard Resistors
10^{5}	4 Rosa (commercial) Standard Resistors
10^{6}	4 Rosa (commercial) Standard Resistors
	2 Wirewound (commercial) Standard Resistors
10^{7}	2 Film (commercial) Standard Resistors
	2 Series/parallel (NBS) Resistance Boxes
10^{8}	2 Wirewound (commercial) Standard Resistors
	2 Film (commercial) Standard Resistors
	2 Series/parallel (NBS) Resistance Boxes
10^{9}	2 Film (commercial) Standard Resistors
	1 Series/parallel (NBS) Resistance Boxes
10^{10}	1 Series/parallel (NBS) Resistance Box
10^{11}	1 Series/parallel (NBS) Resistance Box
	Scott (NBS) Capacitive Discharge Apparatus
10^{12}	Scott (NBS) Capacitive Discharge Apparatus
10^{13}	Scott (NBS) Capacitive Discharge Apparatus
10^{14}	Scott (NBS) Capacitive Discharge Apparatus
10^{15}	Scott (NBS) Capacitive Discharge Apparatus

Primary Standards for Resistance at High Currents

10^{-5} ohm	1 Wolfe (commercial) High Current Standard
	1 Reichsanstalt (commercial) High Current Standard
10^{-4}	1 Wolfe (commercial) High Current Standard
	1 Reichsanstalt (commercial) High Current Standard
10^{-3}	1 Wolfe (commercial) High Current Standard
	1 Reichsanstalt (commercial) High Current Standard
10^{-2}	3 Reichsanstalt (commercial) High Current Standards
10^{-1}	3 Reichsanstalt (commercial) High Current Standards
10^{0}	2 Reichsanstalt (commercial) High Current Standards
	1 Thomas (NBS) Standard Resistor

All except Primary Low Current Standards are also Working Standards

Sec. 2. PRECISION APPARATUS

Primary Standards

Primary Low Current Resistance Standards (Sec. 1)
2 NBS-specified (commercial) Universal Ratio Sets
1 Dunfee-Dziuba (NBS) Primary Volt Ratio Standard
Two-stage (NBS) Inductive Voltage Divider
One-stage (commercial) Inductive Voltage Divider

Working Standards

2 NBS-specified (commercial) Universal Ratio Sets (same as above)
1 Dunfee-Dziuba (NBS) Primary Volt Ratio Standard (same as above)
2 Dziuba (NBS) Portable Volt Ratio Standards
1 Wheatstone (commercial) Bridge
1 Direct Reading Ratio Set (commercial)
1 Direct Reading Ratio Set (NBS)
12 Rosa (commercial) 100-k ohm Resistors
1 Two-stage (NBS) Inductive Voltage Divider (same as above)
1 One-stage (commercial) Inductive Voltage Divider (same as above)

Sec. 3. IMPEDANCE MEASUREMENTS

Primary Standards

1 Cutkosky (NBS) Valculable Capacitor
10 Cutkosky Fused-Silica Dielectric Capacitors (10 pF)
Primary Low Current Resistance Standards (See Sec. 1)

Working Standards for Measurements of Capacitance

1 Cutkosky (NBS) Fused-Silica 10-pF Capacitor
1 Type-12 (commercial) Capacitance Bridge
5 Nitrogen Dielectric (commercial) Standard Capacitors

Working Standard for Measurement of Inductance

1 Maxwell-Wein (NBS) Bridge

Sec. 4. VOLTAGE

Primary Standard

Denenstein-Finnegan (NBS) AC Josephson Effect Apparatus

Working Standards

2 Cutkosky (NBS) Standard Cell Enclosures
1 NBS Oil Bath (NBS 11)
8 (commercial) Standard Cell Enclosures (MAP)

Sec. 5. AC-DC TRANSFER STANDARDS

Primary Standards

12 NBS-specified (commercial) Single-junction Evanohm Thermoelements
2 NBS-specified (commercial) Multi-junction Evanohm Thermoelements

Working Standards

2 sets (NBS) Coaxial Voltage Converters
2 sets NBS-specified (commercial) Thermal Current Converters
1 (NBS) Wattmeter
1 Yokagawa (commercial) Wattmeter

Sec. 6. TRANSFORMERS

Voltage

Primary & Working Standards

Petersons (NBS) High Voltage Current Comparator Bridge

Current

Primary Standards

2 Souders (NBS) Two-stage Transformers

Working Standards

3 Compensated (NBS) Current Comparators

Sec. 7. HIGH VOLTAGE & ENERGY

DC Voltage Dividers

Primary Standards

Primary Resistance Standards (Sec. 1)
3 Park (NBS) High Voltage Dividers

Working Standards

3 Park NBS High Voltage Dividers (same as above)
10 Rosa (commercial) Standard Resistors

DC Kilovoltmeters

Primary Standards

Primary Resistance Standards (Sec. 1)
Primary Voltage Standards (Sec. 4)
3 Park (NBS) High Voltage Dividers

Working Standards

3 Park (NBS) High Voltage Dividers (same as above)
1 (commercial) Digital Voltmeter

AC Voltage Dividers

Primary & Working Standards

Petersons (NBS) High Voltage Current Comparator Bridge

AC Kilovoltmeters

Primary Standards

Primary Voltage Standards (Sec. 4)
Petersons (NBS) High Voltage Current Comparator Bridge

Working Standards

Petersons (NBS) High Voltage Current Comparator Bridge (same as above)
1 (commercial) Electrostatic Voltmeter

Capacitors (High Voltage)

Primary Standards

Primary Capacitance Standard (Sec. 3)
Hillhouse (NBS) High Voltage Capacitor

Working Standards

2 Nitrogen Dielectric (commercial) Standard Capacitors

Watthour Meters

Primary Standards

Primary Voltage Standards (Sec. 4)
Primary Resistance Standards (Sec. 1)
Primary Time Interval Standards

Working Standards

Lentner (NBS) Current Comparator Energy System
4 Rotating (commercial) Watthour Meters

Impulse Dividers

Primary Standards

Primary Resistance Standards (Sec. 1)
Primary Voltage Standard Resistive Divider (Sec. 4)

Working Standard

Kerr Cell Apparatus

APPENDIX C

"CRITICAL ELECTRICAL MEASUREMENT NEEDS AND STANDARDS FOR MODERN ELECTRONIC INSTRUMENTATION"

WORKSHOP REPORT ABSTRACT, PREFACE, AND LIST OF ATTENDEES

Abstract

Recognizing the proliferation of sophisticated modern electronic instrumentation in the field of electrical measurements, the Electricity Division of the National Bureau of Standards recently initiated a new program in the general area of dynamic measurements and standards in support of such instrumentation. Recognizing further that the vastness and complexity of the field would require, at the earliest stages of the program, identification of the most critical problem areas, the Electricity Division held a workshop on 23 and 24 September 1974, at the Bureau's Gaithersburg site, to assist it in ascertaining just what these areas in fact were. The basic idea of the Workshop was to bring together a broadly representative group of some 25 leading manufacturers and prime users, working in a free and open atmosphere, in order to have them delineate the present and future critical support needs in the field of dynamic electrical measurements for modern electronic instrumentation, with emphasis on physical standards, standardized measurement methods, new calibration and measurement assurance services, relevant data, and, most important, new measurement methodologies. The overall objectives of the Workshop were generally met, and a number of significant specific programs and projects consistent with the mission of the Electricity Division were identified. Three categories broadly cover the needs as defined at the Workshop:

1. The need to introduce time as a measurement parameter has resulted from the requirements of automatic test and control systems. Specific areas considered critical are:

a. Pulsed component measurements.
b. Dynamic performance characterization for modern signal conditioning and data conversion devices: Digital-to-analog and analog-to-digital converters, sample-and-hold amplifiers, comparators, etc. Required measurements include settling, aperture and acquisition times. Basic new capabilities will be needed, including precision, non-sinusoidal waveform generation and "standard" digital-to-analog converters.
c. Methodologies and techniques for characterizing precision ac and dc sources and measurement devices with respect to settling time.

2. The emergence of measurements into the "real world" or the production line via the automatic system has introduced a host of new parameters. Areas requiring significant effort include:

a. Investigation of transportable standards for validation of static and dynamic system performance: ac and dc voltage, impedance, pulses, settling times.
b. Techniques for characterizing sources and measurement devices with respect to switched or dynamic loading.
c. Prediction of long-term performance, reliability and lifetime from short-term evaluation for a host of passive components, semiconductors, and signal sources.
d. Noise standards and methodologies.
e. Continuing effort to improve transportable dc standards and dissemination at higher voltage levels.
f. Characterization of the ac line voltage-waveforms, under- and over-voltages, transients, dynamic impedance, etc.
g. Inclusion of a capability for environmental control and variation for devices and instruments under calibration, in all work undertaken by the Bureau.
h. Extension of Measurement Assurance Programs (MAP's), especially into the above new areas.

3. Recent work at the leading edge of measurement technology in electronics has resulted in the need for new, or higher accuracy, measurements. For example:

a. Increased dependence on capacitors as storage devices has made dielectric hysteresis a parameter of importance. Significant measurement work should be started in this area.
b. Phase difference measurements to extremely high accuracies are needed to calibrate industrial instrumentation.
c. Higher accuracy power measurements, particularly for non-sinusoidal waveforms, are needed to calibrate instrumentation in the field.

d. Non-sinusoidal, high crest-factor precision signals are needed to calibrate true RMS converters and meters.

e. High accuracy electronic instrumentation requires reduction in ac calibration uncertainties to 10 ppm, at least over the audio range.

Longer-term, "frontier" areas in each of the above groups were also identified. They are not specified in the above listings since they involve work at still more basic levels, on ground that is presently terra incognita. Nevertheless, they furnish insight into the overall technical/philosophic climate, and are useful for that reason. Items in this category include:

1. Measurement problems in systems, including effects of history, measurement interactions, self-calibration, etc.
2. Evaluation and standardization of system software.
3. Calibration of medical equipment.
4. Replacement of standard cells.
5. Replacement of thermal ac/dc converters.
6. Non-swept but broad-response measurements - impulse, noise, other.
7. Basic work on the physics of dielectric absorption; component drift; device noise; failure mechanisms; switches; and relays.
8. Provision of improved measurement accuracy for virtually all dynamic measurements, at the wafer probe level.

In addition to the identification of these specific and general needs, the Workshop provided strong evidence that both the manufacturing and user communities in the electronic instrumentation field look to the Electricity Division to provide the technological leadership in these newer areas that it has previously furnished in the more traditional electrical measurement areas. Indeed, there was a good deal of support for the idea of keeping the electronics community informed of Division work-in-progress, with emphasis on projects targeted by the Workshop.

Keywords: Data conversion; dynamic measurements; electrical measurements; electronic instrumentation; signal conditioning; system; time domain.

Preface

It is apparent that the continued, orderly growth of the electronics industry is increasingly hampered by a lack of standards and methodologies in a number of crucially important electrical measurement areas.

The explosive growth of electronics during the last decade has brought with it a host of unsolved measurement problems. Yet at this critical historical juncture, electronics is a key technology in the prospective solutions to some of society's major outstanding concerns including energy, pollution, and productivity, to name but three. It is, therefore, mandatory that a responsible, capable organization without specific industrial affiliation, assume a leadership role in providing the necessary measurement standards and methodologies, as well as in establishing new electrical measurement programs for which need is both broad and identified, but whose implementation by specific industrial organizations would be impractical.

The Electricity Division of the National Bureau of Standards has traditionally dealt with the measurement and generation of electrical signals in the dc to 30 kHz range, as well as with the properties of electrical components in that range. In effect, with the one possible minor (philosophical) exception of phase, the Division has devoted itself to <u>amplitude</u> or <u>magnitude</u> measurements for the various electrical parameters. Some of these have been generated and/or transmuted by mechanical and electro-mechanical means, others more recently by electronic, and others in future undoubtedly by light, but the <u>electrical</u> (usually amplitude) parameters have had similar properties and required the same disciplines for measurement.

Now, automatic systems for test, process control, medical applications, and so forth are using electrical quantities at higher speeds than heretofore. Ten years ago a precision dc, dialable 6- or 7-digit source did not need a settling time specification; today, "programmable" sources have such specifications, since the system architect must know how long it will take for this stimulus to settle to within a given accuracy. In many instances total system speed, hence all-important throughput, dollar payback and/or justification, will be limited by such settling times.

Thus, to precision electrical measurements has been added the temporal parameter. In a manner analogous to the changeover from frequency to time domain work in filter synthesis in the early sixties, measurement must now turn from exclusive attention in the frequency domain, to characterization involving time as well, e.g., settling time to x microvolts in y microseconds is an electrical, analog, amplitude measurement with the time factor added.

The Workshop which this report describes and summarizes, is the means chosen by the Electricity Division to establish direct communication with key elements of the electronics industry among both manufacturers and users, for the purpose of ascertaining the industry's electrical measurement needs, both general and specific. The enthusiasm engendered by the Workshop itself attests to the fact that the time has come for leadership and action: In spite of difficult times and severe cost pressures, 24 outstanding organizations were willing to send top personnel to the 2-day Workshop, disrupting busy schedules, and at considerable financial expense.

This report on the Workshop results must inevitably reflect some of the author's technical biases, developed over the course of 25 years of varied design, management and consulting experience in the fields of electronics, measurements and standards. During that interval the technology has made tremendous advances, so that in many areas it is virtually unrecognizable in comparison with its major jumping-off point directly following the Second World War. Indeed, some of those advances are the direct result of work accomplished at or backed up by programs of the Electricity Division of the NBS, notably during what might be termed the measurement "explosion" of the decade of the sixties.

By the same token, it is hoped that the author's general breadth of design and measurement exposure during those same years of experience, plus long-standing and continuing interactions with the Bureau, have provided a balanced view of the Workshop results in this report. If this has been accomplished, the Division programs resulting from the Workshop can form the basis for new and crucially-important electrical measurement technology for electronics in the forthcoming decade.

It is impossible to convey here the excitement felt by virtually all participants during the Workshop which helped to make the author's task as moderator both rewarding and enjoyable. The excitement was undoubtedly due in part to the professional challenge offered by the opportunity for open, free-swinging exchange among the outstanding group of participating engineers and scientists. But it clearly reflected, as well, the participants' recognition of the large and important work that so critically needs to be done, and their enthusiastic reception of the role of the Electricity Division in grasping the initiative to establish relevant new programs on a priority basis. There was, in short, the excitement resulting from the pervasive feeling of being part of an undertaking that was both significant and effective.

I should like to express my thanks to the Electricity Division and to Dr. Barry N. Taylor in particular, for giving me the opportunity to contribute to this important work. I should also like to add my own personal thanks to the participants and their organizations, as it is they who are truly responsible for the Workshop's success.

Peter Richman
Consulting Engineer

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Mr. Loyle E. Baltz
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Ford Motor Company
Allen Park, MI

Mr. Eduard F. Boeckmann
Chief Engineer
Angstrohm Precision, Inc.
Hagerstown, MD

Mr. Warren C. Collier
Manager, TM 500 Design, Engineering
Tektronix, Inc.
Beaverton, OR

Mr. Thomas J. Coughlin
Product Engineering Manager
Component Systems
General Radio Company
Concord, MA

Mr. Jack D. Dougherty
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Mr. George W. Herron
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Automation Group
National Bureau of Standards
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Mr. Robert H. Verity
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Leeds & Northrup Corporation
North Wales, PA

Mr. William R. Walters
Chief Engineer
Codi Semiconductors
Fairlawn, NJ

Mr. F. Mansfield Young
Director of Engineering
Teradyne, Inc.
Boston, MA

Mr. Ray A. Zuck
Director of Operations
Geometric Data Corporation
Wayne, PA

APPENDIX D

STANDARDS AND CALIBRATION LABORATORIES

CODE: Type of Service

S - Primary standards
C - Calibrations
B - Both
T - Testing

Type of Organization:

C - Corporate laboratory
I - Instrument manufacturing
P - Calibration & metrology lab solely or mostly

No code indicates exact nature of service not known to authors.

Laboratory	Member NCSL	Type of Service Code	Type of Organization Code
AEL, Colmar, PA			
AEL Communications, Lansdale, PA		B	C
AIL Technological, City of Industry, CA		B	P
AVCO Corporation, Charleston, SC	X	B	C
AVCO Corporation, Lycoming Div., Stratford, CT		C	C
AVCO Corporation, Richmond, IN		S	C
Aerojet Nuclear, Idaho Falls, ID	X	B	C
Ailtech Cutler Hammer Co., Farmingdale, NY		C	C
Airtron Div., Litton Systems, Morris Plains, NY		C	C
All Systems, Morristown, NJ			
Allis Chalmers Mfg. Co., Milwaukee, WI	X	B	C
American Electronic Labs, Lansdale, PA		B	P
American Geophysical & Instrumentation, Gardena, CA		B	P
American Instrument Service, Philadelphia, PA		B	P
Ark Electronics, Willow Grove, PA		C	P
B&K Instruments, Cleveland, OH		C	P
BLH Electronics, Waltham, MA		?	?
Ballantine Laboratories, Boonton, NJ		C	I
Ball Brothers Research, Boulder, CO	X	B	C
Bath Iron Works Corporation, Bath, ME	X	C	C
Beckman Instruments, Fullerton, CA	X	B	C
Beech Aircraft Corporation, Wichita, KS	X	B	C
Bell Aerospace Co., Buffalo, NY	X	B	C
Bendix Corporation, Teterboro, NJ	X	S	C
James G. Biddle Co., Plymouth Meeting, PA	X	B	I
Blake Electronics, Inc., Greendale, WI		C	
Boeing, Wichita, KS		C	C
Boeing Aerospace Group, Seattle, WA	X	B	C
Brunswick Engineering, Inc., Northbrook, IL		C	
Burroughs Corporation, Paoli, PA		B	C
Calibration Central, Alexandria, VA	C	C	
Certified Calibration Labs, Inc., Philadelphia, PA	S	C	P
Collins Radio Co., Cedar Rapids, IA	X	B	C
Communications Satellite Corp., Clarksburg, MD	X	B	C
Computer Diode Co., Fairlawn, NJ	X	B	I

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Laboratory	Member NCSL	Type of Service Code	Type of Organization Code
Comtel Corporation, Detroit, MI		C	
Cox & Co., New York, NY	X	B	C
DBA Systems, Melbourne, FL		C	
Dalmo Victor, Belmont, CA	X	B	C
Davidson Optronics, West Covina, CA		C	P
Dayton T. Brown, Inc., Bohemia, NY	X	B	P
Detroit Edison Co., Detroit, MI	X	B	C
Dillon, W. C. & Co., Van Nuys, CA			
Douglas Instrument Lab, Boston, MA		B	P
Dow Chemical Co., Rocky Flats, CO	X	C	C
EG&G, Albuquerque, NM		C	C
EG&G, Las Vegas, NV	X	C	C
E. I. DuPont de Nemours, Aiken, SC	X	B	C
EIL Instruments, Timonium, MD	X	B	P
Electrical Instrument Service, Mt. Vernon, NY	X	B	P
Electrical Science Services, Cambridge, MA		C	
Electrical Testing Labs, Inc., New York, NY	X	B,T	P
Electro Scientific Industries, Portland, OR	X	B	I
Electronic Marketing Associates, Kensington, MD		C	
Eppley Laboratories, Newport, RI		B	I
E-Systems, Dallas, TX	X	B	C
Fairchild Space & Electronics, Germantown, MD		C	C
Fischer/Porter Co., Warminister, PA		C	
John Fluke Mfg. Co., Seattle, WA	X	B	I
Foxboro Co., Foxboro, MA	X	B	C
Gage Corp., Philadelphia, PA	X	C	P
General Dynamics, Groton, CT	X	B	C
General Dynamics, Quincy, MA		C	C
General Dynamics, San Diego, CA	X	B	C
General Electric, Bay St. Louis, MS	X	B	C
General Electric, Dallas, TX		C	C
General Electric, Pittsfield, MA	X	B	C
General Electric, Schenectady, NY	X	B	C
General Electric, Seattle, WA		C	C
General Electric, Syracuse, NY	X	B	C
General Electric Instrumentation, Inglewood, CA		S	C
General Environments Corp., Morton Grove, IL	C	P	
GENRAD, West Concord, MA	X	B	I
Greentron, Inc., Greenville, SC		C	P
Guildline Instruments, Inc., Larchmont, NY	X	S	I
H-B Instrument Co., Philadelphia, PA		C	I
Hamilton Technology, Lancaster, PA		C	C
Harris Intertype, Melbourne, FL	X	B	C
Hercules Inc., Magna, UT	X	C	C
Hewlett-Packard Co., Palo Alto, CA		C	I
Hewlett-Packard, Santa Clara, CA		B	I
Hoffman Engineering Corp., Old Greenwich, CT		C	
Honeywell, Inc., Aerospace Div., St. Petersburg, FL	X	C	P
Honeywell, Inc., Annapolis, MD		C	P
Honeywell, Inc., Burlington, MA		C	P
Honeywell, Inc., Chicago, IL		C	P
Honeywell, Inc., Cleveland, OH		C	P
Honeywell, Inc., Denver, CO	X	B	P
Honeywell, Inc., Detroit, MI		C	P
Honeywell, Inc., Downey, CA		C	P
Honeywell, Inc., Hazelwood, MO		C	P
Honeywell, Inc., Fairborn, OH		C	P
Honeywell, Inc., King of Prussia, PA		C	P
Honeywell, Inc., Minneapolis, MI		B	C

Laboratory	Member NCSL	Type of Service Code	Type of Organization Code
Honeywell, Inc., San Diego, CA		C	C
Honeywell, Inc., Springfield, VA		C	P
Honeywell, Inc., Sunnyvale, CA		C	P
Honeywell, Inc., Westfield, NJ		C	P
Hy-Cal Engineering, Sante Fe Springs, CA		S	P
Hughes Aircraft, Culver City, CA		B	C
Hughes Aircraft, Fullerton, CA		C	C
IIT Research Institute, Chicago, IL	X	B	P
Incal Service Corp., Stanford, CT		C	P
Infinite, Inc., Cape Canaveral, FL		C	P
Inland Testing Labs, Inc., Morton Grove, IL	X	S	P
Instrument Labs Corp., Chicago, IL		C	P
Intergalactic Corporation, Salt Lake City, UT		C	
Julie Research Labs, New York, NY		B	I
KC Calibration Lab, Kansas City, KS		C	
Kahl Scientific Instr. Corp., El Cajon, CA		S	P
Keithley Instruments, Cleveland, OH		B	I
Key Instruments, Gardena, CA		C	P
LTI Research Foundation, Lowell, MA	X	B	P
Lab Instrument Service, Campbell, CA		C	
Lear Siegler, Santa Monica, CA		C	C
Leeds & Northrup, North Wales, PA	X	B	I
Lehighton Electronics, Lehighton, PA		C	
Librascope, Div. of Litton, Glendale, CA		C	C
Lockheed Aircraft Service, Ontario, CA		C	C
Lockheed-California, Burbank, CA	X	B	C
Lockheed Electronics, Houston, TX	X	B	C
Lockheed-Georgia, Marietta, GA		B	C
Lockheed Missiles & Space Co., Sunnyvale, CA	X	B	C
3M Corp., St. Paul, MN	X	B	C
Main Electronics, Wichita, KS		C	P
Mancib Co., Burlington, MA		C	P
Martin Marietta, Denver, CO	X	B	C
Martin Marietta, Marietta, GA	X	B	C
McDonnell Aircraft Co., St. Louis, MO	X	B	C
McDonnell Douglas Astronautics, Long Beach, CA	X	B	C
McDonnell Douglas Astronautics, West Huntington Beach, CA	X	B	C
Micro-Radian Instruments, Seal Beach, CA		C	P
JR Miles Corporation, Elk Grove Village, IL		C	
Montedoro-Whitney, San Luis Obispo, CA		B	P
National Astro Labs, Burbank, CA		B	P
National Camera, Inc., Englewood, CO		C	
New Era Products, Cleveland, OH		C	P
Newport News Ship Building & Drydock, Newport News, VA		C	C
New York Testing Labs, Westbury, NY		C	P
North American Rockwell, Anaheim, CA	X	B	C
North American Rockwell, Rocketdyne Div., McGregor, TX		B	C
Nucleus Corp., Madison Heights, MI		C	P
Ogden Technology Labs, Fullerton, CA		B	P
Optronic Labs, Silver Spring, MD		C	
Ormond Inc., Sante Fe Springs, CA		C	P
PTS Electronics, Inc., Bloomington, IN		C	
Penn Airborne Products, Southampton, PA		B	I
Pioneer/Instrumentation, Cleveland, OH		B	P
QVS Inc., East Orange, NJ		C	
RCA, Gov't Services, Moorestown, NJ		B	C
RCA International Service Corp., Camden, NJ		B	C
RCA International Service Corp., Patrick AFB, FL	X	B	C

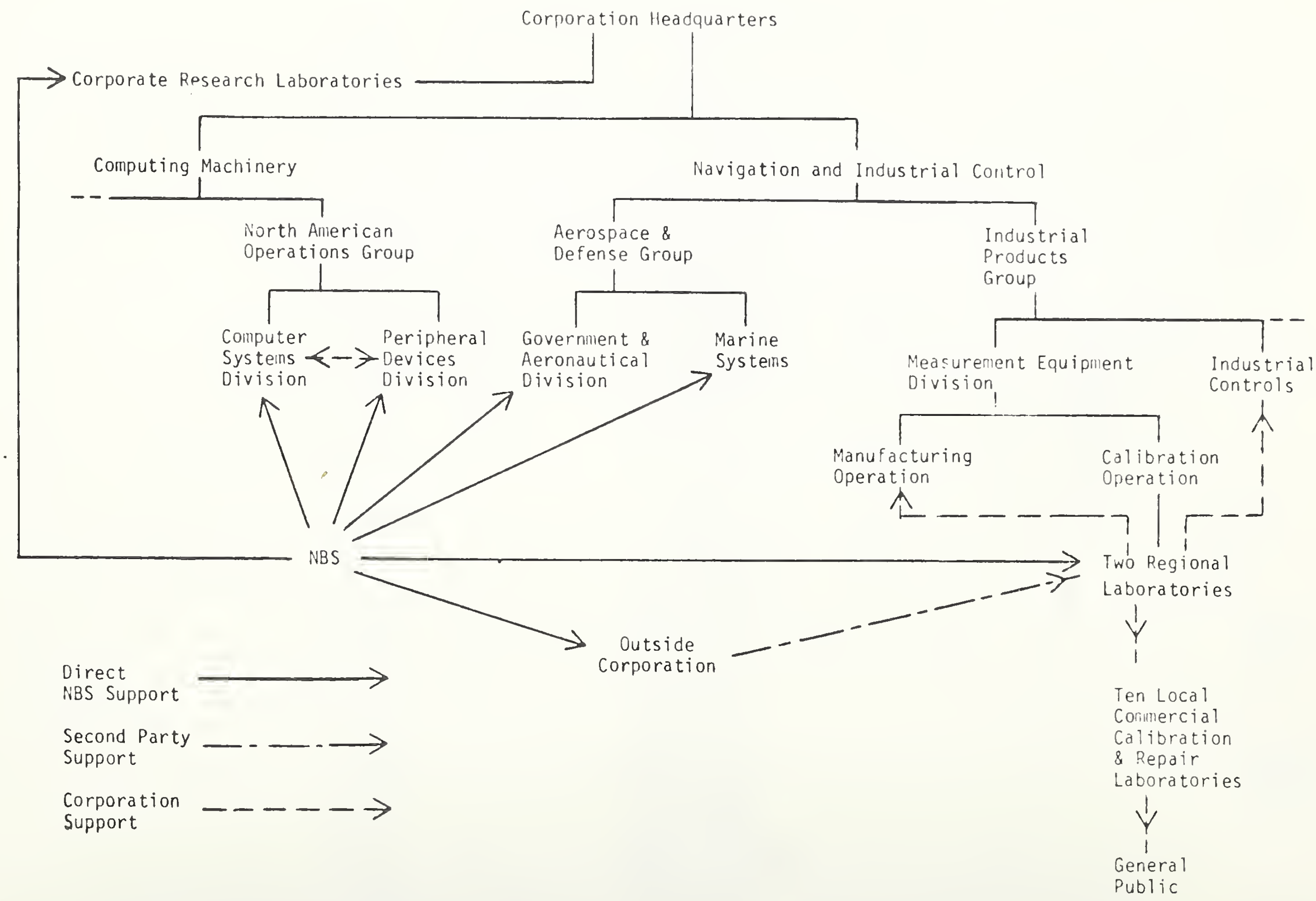
Laboratory	Member NCSL	Type of Service Code	Type of Organization Code
Ram Meter, Inc., Ferndale, MI		C	P
Ramsey Engineering, Anaheim, CA		C	P
Raytheon Submarine Signal, Portsmouth, RI	X	B	C
Reliance Electric Co., Cleveland, OH		C	P
Robertshaw Controls Co., Richmond, VA		C	
Rockwell Engineering Co., Indianapolis, IN		C	P
Rutherford Research Products, Rutherford, NJ		C	P
SSCO Standards Laboratory, Detroit, MI		B	P
Sanders Associates, Nashua, NH	X	B	C
Scientific Leasing Services, Lake Success, NY		C	
Sensitive Research Instruments, Mt. Vernon, NY		C	P
Simpson Electric Co., Elgin, IL		C	
Singer Co., Kearfott Div., Little Falls, ND	X	B	C
Sperry Electronic Tube Div., Gainesville, FL		B	C
Stabro Labs, Salt Lake City, UT		B	P
States Electronic Corp., Blundworth Marine, Linden, NJ		C	C
Sunshine Scientific Instruments, Inc., Philadelphia, PA		B	P
Sweetman Calibration Services, Pennsauken, NJ	X	B	P
Systron Donner, Concord, CA	X	S	C
TRW Systems, Redondo Beach, CA	X	B	C
Taylor Instrument, Process Control Div., Rochester, NY		B	C
Technicians Unlimited, Lexington, MA		C	
Teledyne Brown Engineering, Huntsville, AL		C	C
Teledyne McCormick Selph, Hollister, CA		C	C
Teledyne Systems Co., Northridge, CA	X	B	C
Texas Instruments, Houston, TX		C	P
Thwing-Albert Instrument, Philadelphia, PA		C	P
Transducers, Whittier, CA		C	
UNIVAC, Utica, NY	X	S	C
Union Carbide, Oak Ridge, TN	X	B	C
Varian, Palo Alto, CA	X	S	I
Viking Labs, Sunnyvale, CA		B	C
Westinghouse Electric Co., Baltimore, MD	X	B	C
Westinghouse Electric Co., Pittsburgh, PA	X	B	C
Weston Instruments, Newark, NJ	X	B	I

This listing of calibration and standards laboratories is not to be taken as an endorsement by the National Bureau of Standards of laboratories included, or as an indication of the quality of calibrations available from either listed or unlisted organizations.

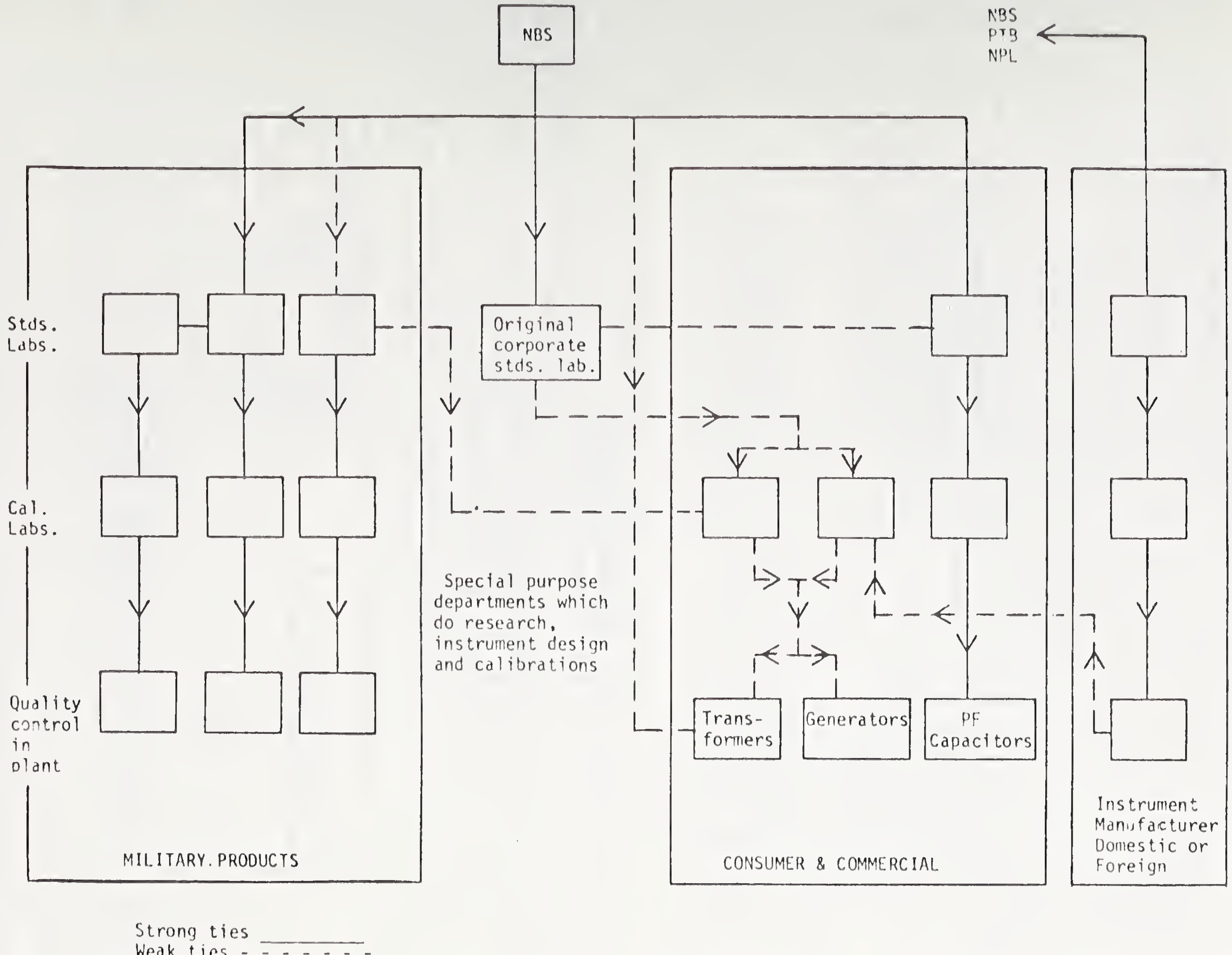
APPENDIX E

TYPICAL MEASUREMENT SUPPORT STRUCTURES

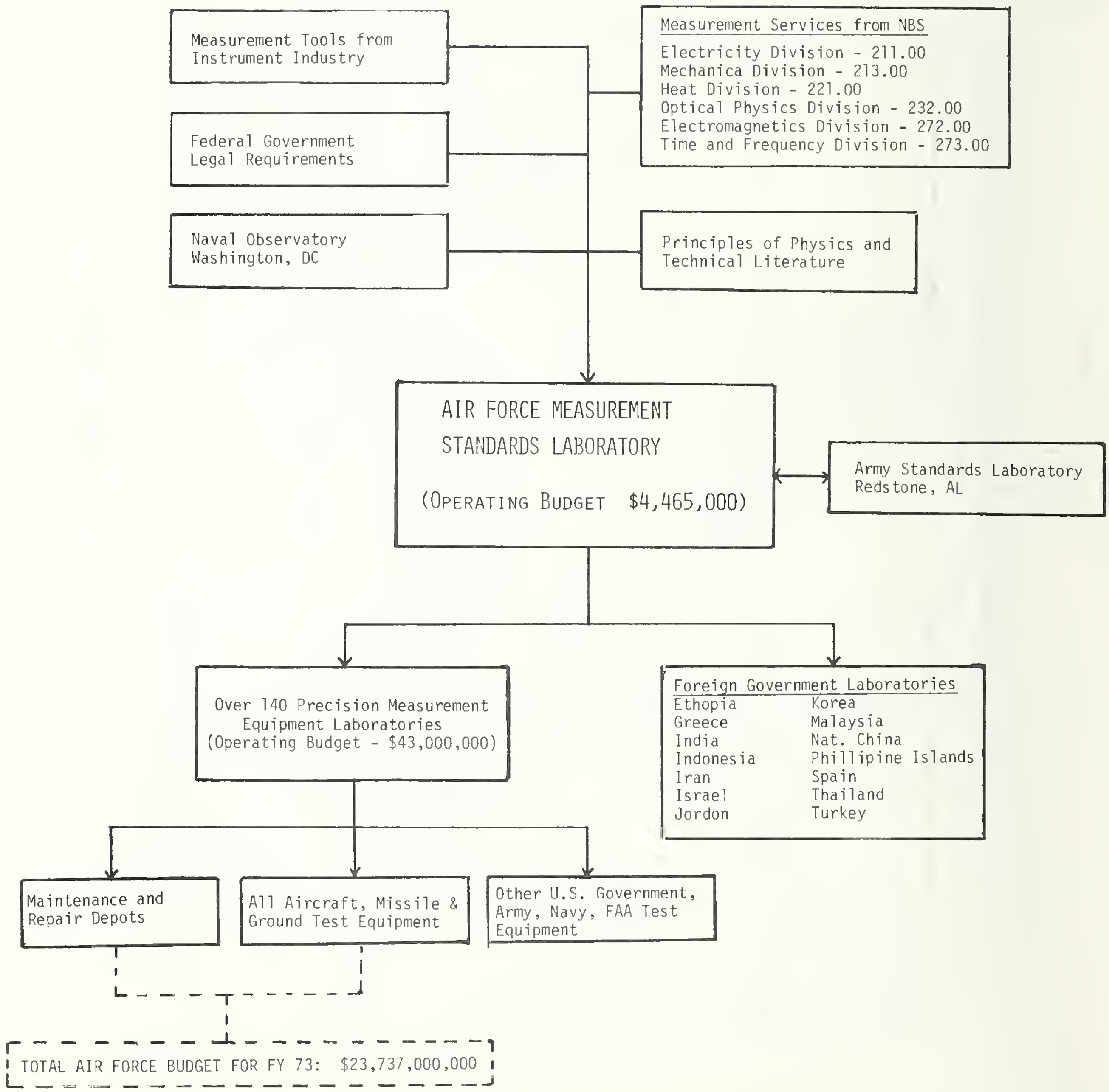
On the following pages are representative functional diagrams of two corporations and their measurement support structures. On the following page is depicted the structure by which the U.S. Air Force, through a network of over 140 calibration facilities, provides world wide measurement support for over $400 million worth of electronic test equipment with which maintenance and operational support for weapons, communications, navigation, guidance and medical systems are supplied.



Typical Corporate
Measurement Support Structure



Typical Corporate
Measurement Support Structure



Air Force Metrology Structure - FY 73

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NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 75-935	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Electricity Division Study of the National Measurement System			5. Publication Date September 1978
			6. Performing Organization Code
7. AUTHOR(S) Norman B. Belecki, Bernadine L. Dunfee, and Oskars Petersons			8. Performing Organ. Report No. NBSIR 75-935
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No.
			11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* Same as No. 9			13. Type of Report & Period Covered Final
			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The National Electrical Measurement System, by which all measurements of electrical quantities are made in the U.S., is reviewed. This overview, based on the results of a four-year study, details the organizational structure of the system; the technical aspects of realizing, maintaining, dissemination and using the units for measurements; and the economic characteristics of its basic industry, the instrumentation industry, and the system's user constituency. Documentary standards and the organizations producing them are discussed, concluding with a survey of presently adopted documents. Its two major components, the electronics subset and the electric power subset, are defined, described, and contrasted. Major technical, management, and logistics problems facing the system are delineated. An in-depth view of the Electricity Division, which supplies the measurement base of the system, is given. Finally, recommendations for technical and management action by NBS in a number of areas are given.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Calibrations; Dissemination of units; Electrical measurements; Electric power measurements; Electrotechnology; Impact of measurements; Measurement technology assessment; National Measurement System; Standards.

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U.S. GOVERNMENT PRINTING OFFICE 1978— 2·1/238/259