NBSIR 75-928

The National Measurement System for Mass, Volume and Density

Paul E. Pontius, James R. Whetstone, and John A. Simpson

National Engineering Laboratory
National Bureau of Standards
Washington, D.C. 20234

Final

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DEPARTMENT OF COMMERCE

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THE NATIONAL MEASUREMENT SYSTEM FOR MASS, VOLUME AND DENSITY

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Mass, a property of all matter, is unique in the sense that the concept is generally deduced from the motion of a body under the influence of an applied force. It is for this reason the mass unit for measurements over the range of objects which can be physically handled is now, and for some time to come will continue to be, embodied in an artifact standard. The mass of one object with respect to another is deduced from a comparison of the gravitational forces acting on the two objects. The additive nature of mass makes it possible to construct appropriate subdivisions and multiples of a single defining artifact. The present mass unit, the International Prototype Kilogram, is one of the Base Units of the International System of units. Access to the unit is provided by Bureau International des Poids and Mesures (Sevres, France) through prototype kilogram replicas of the unit. Prototype Kilograms No. 20 and No. 4 provide such access for the United States, and are in turn the basis for the U.S. practical mass scale as established by the nichrome kilograms N1 and N2.

Volume is a quantity derived from the length unit. It is inseparably coupled with mass. The intent of the founders of the Metric System was that one cubic decimeter of water at maximum density have a mass of one kilogram. The realization was proven to be imperfect, thus introducing for a period of time the liter as a volume unit. (The current unit for volume is the cubic meter). Precise mass measurement requires a knowledge of the displacement volume of the objects being compared. Hydrostatic weighings are used to (a) determine the displacement volume ratio relative to an object with displacement volume established by direct measurement and (b) displacement volume relative to a known density of the fluid.

Density is defined as mass per unit volume. Density is a property of interest for a variety of fluid mixtures. The density of a fluid in conjunction with mass measurement is a means to determine the containment volume of a variety of volumetric standards. Mass and volume are both used to determine quantity of material. Density is usually considered to be a property of a material, however, such extension requires an assumption on the homogenity of the sample measured.

Considering that most of the measurement processes within the mass, volume and density measurement systems are based on economic compromise rather than technological capabilities, it is presumptuous to assume that NBS has any substantial impact on the total system. On the other hand, NBS, by providing a means for access to the unit, is generally considered to be a partner in all measurement activity. Consistency of results commensurate with requirements is a fundamental to all of the activities the system supports. Resolution of inconsistencies, by referral measurements, by suggested process modification, or by basic changes in measurement concept is the essential support to the system provided by NBS.

In spite of the size of the system, it appears to be in almost complete control and operating to the general satisfaction of all concerned. There are several reasons for this: (1) mass standards are intrinsically stable so that the unit once injected into a subsystem remains reasonably consistent; (2) the instruments used are reliable; and (3) the size of large subsystems concerned with voluntary standards, weights and measures activities, government requirements, etc., result in inertia with respect to change. Through the mechanism of Measurement Assurance Programs, NBS or any other interested party, can test the effectiveness of a given subsystem relative to the intended use of the measurement results. The same medium provides a means for a running audit of the subsystem to insure that stability is not lost.

With the advent of the NBS-2 kilogram comparator the precision of measurement has reached the point where factors affecting the short term stability of the defining artifact can be studied. These factors include cleaning procedures, moisture films and environmental contamination. Problems associated with the air density algorithm, e.g., oversimplification and non-uniformity, introduce small offsets in the practical mass scales of the various countries. These offsets, too small to be of concern in most weighing operations, do not affect the consistency of practical measurements in a given country. Resolution of the problem, however, is important in support of work on fundamental physical constants.

There are certain identifiable constituencies within the system which rely exclusively on NBS services. Support to the State Weights and Measures activities, coordinated by the NBS Office of Weights and Measures, extends to about 84,000,000 weighings in supermarket chains alone, which in part supports a $145,100,000 a year industry which provides the needed weighing devices. The petroleum industry has a worldwide investment of $1,800,000,000 in volume measurement facilities at 650,000 sites, manned by 50,000 full time personnel. Each "barrel" is measured on the average of 12 times between the well head and the consumer, with either custody transfer or accountability between each pair of measurements. All measurements on local or imported crude and products are based on NBS calibration of metal volumetric provers. In the beverage industry, approximately $2,500,000 is expended annually for density measurements in the production of $15,400,000,000 of products. NBS is providing support in the development of procedures for both custody transfer and accountability of nuclear material. The Mass Measurement Assurance Program provides direct support to the Department of Defense measurement systems, measurement systems within the nuclear and aerospace industries, and to manufacturers of precise weighing equipment.

Problems in the interface between the Mass and Volume Section and the rest of the measurement system are, in general, matters of judgment. The section, recognizing the service roll of measurement, has worked diligently to establish and maintain a line of communication with the individual users (a non-coherent constituency). Such an approach requires not only an understanding of measurement process limitations but also a clear definition of what is to be expected from the measurement effort. The latter requirement is the most difficult, and where it has been possible to define acceptable limits relative to a particular undertaking there has been visible evidence of success, e.g., savings to the Food and Drug Administration relative to the calibration of glassware, the adoption of measurement assurance procedures within the nuclear weapons complex, and the efforts supporting accountability and safeguarding of nuclear materials. Assistance provided to large numbers of users through consultation generally relates to specific problems, the resolution of which has no visibility. Generally, most of these problems relate to specifying what the measurement is supposed to accomplish and there are those who expect NBS to address his particular problem, however ill defined.

On the other hand, there are pressures to work through an interface (identifiable constituency) both from within NBS and from other sources. Working through an interface tends to isolate NBS from practical measurement problems. Interfacing through a system of facilities which are primarily regulatory raises the question as to whether such a system can provide advice and guidance with regard to methods and procedures without compromising its regulatory function. The legalization of all measurements, as proposed by the International Organization for Legal Metrology, diverts attention from the measurement result to traceability of the unit. In some instances, the consumer of measurement data is relieved from the burden of proving that the results are adequate for the intended purpose. In other instances, there is an added burden of not only proving that the measurements are not only adequate but also legal.

The above listed problems not withstanding; the discharge of NBS responsibilities in the area of mass, volume and density, is judged to be satisfactory. Except for the maintenance of certain staff skills, the level of effort now displayed results in slow but steady progress. The nature of the services provided and the role of the section will change as its aging staff moves into retirement. The course of activities for the future includes support to the system as it exists at the time, and a continuing effort to improve the efficiency of measurement.

THE NATIONAL MEASUREMENT SYSTEM FOR MASS, VOLUME AND DENSITY

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National Bureau of Standards

1. INTRODUCTION

Weighings for purposes of trade were made at least as far back in time as the Early Bronze Age and a well developed system of standards and enforcement of standards was in effect in Egypt by the second dynasty. The use of the balance--as a symbol of fairness and justice--dates from the same mists of antiquity [1]. While it was common knowledge that early governments used one set of weights in the collection of goods for taxes and another to disperse goods for services, by simply interchanging the loads on the balance pans, it was easy to demonstrate that there was nothing wrong with the balance. In normal commerce, other than the usual haggling over the details of the transaction, the measurement process worked well. However, with the first technological advance which made weighings rapid and convenient, the steelyard thought to be introduced by the Romans, the situation changed. The buyer was at the complete mercy of the seller who could alter the instrument at will, changing either the sliding poise, or the lever ratio. The widespread usage of the steelyard in commerce was the genesis of regulatory activities relating to weights and weighing devices. It was the diversity of local units, staunchly defended by the tradesmen, that ultimately led to the development of the metric system of measurement units.

Mass, in the context of mass measurement, is based on physical laws formulated by Newton [2], thus relative to the history of weighing, and even the metric system, the concept of mass is a recent one. Because of the size of the solar system, Newton could consider the planets and their satellites as points in the vacuum of space [3]. The concept of mass was essential to the formulation of his laws of motion. As a consequence, mass cannot be measured directly in the normally encountered environment.

For example, a balance, contrary to popular opinion, is a force comparison device which cannot separate the gravitational force acting on the object from the buoyant effects of the atmosphere [4]. While one can compare these forces to a very high precision, an algorithm must be employed to separate the two effects. This algorithm must incorporate knowledge of the volume or density of the objects of interest as well as the density of the surrounding environment.

The qualities of mass, volume, and density are related by the following definition:

$$\text{MASS} = \text{VOLUME} \times \text{DENSITY}$$

One can determine one of these quantities if the other two are known, e.g., the mass of petroleum contained in a tanker can be determined from measurements of tank volumes and petroleum density.

Maintenance of the unit of mass is, by the Treaty of the Metre, the responsibility of the Bureau Internationale des Poids et Mesures (BIPM). The responsibility for maintenance of the base unit for mass and the units for volume and density in the United States is one of the oldest and most basic missions of NBS. It remains a unique responsibility since the mass unit is the only Systeme Internationale (SI) unit which in principle is not independently reproducible. Of the two Prototype Kilograms designated No. 4 and No. 20, received by the U.S. under the Treaty of the Metre, Prototype Kilogram No. 20 is the de facto United States' unit of mass [5]. In reality, K4 and K20 are merely a mechanism for transferring a defined unit from one mass measurement system to another.

The derived unit of volume is now expressed as length cubed. High precision measurements of artifact displacement, or containment, volumes are determined from length measurements. Such measurements are complex and rarely done, e.g., the work of Cook [6,7] in measuring the density of mercury and that of Bowman, Schoonover and Carroll in measuring the density of single crystal silicon [8]. Practical measurements of displacement volumes use Archimedes Principle, e.g., hydrostatic weighing in a fluid of known density.

Practical volumetric measures are vessels whose volume is defined by weighing the vessel filled and empty, using a liquid of known density. This operation inextricably ties volume measurements to mass and density. Where weighing operations are impossible, such as in determining the capacity of large volume tanks, direct dimensional measurements ("strapping") are used [9]. In these cases, the errors normally encountered in the length measurements are very small relative to the total volume of the tank.

The derived unit of density is currently expressed as kilograms per cubic meter [10]. (In this case the SI unit is so large that it has little practical meaning.) By far, the majority of density measurements are made for determination of the characteristics of substances in the liquid phase. A variety of arbitrary units are used, each associated with a particular class of liquid. The simplicity and precision of the hydrometer is a practical means of quality control for any products produced or marketed in liquid form, ranging from milk to alcohol-water mixtures and from petroleum and its products to paints and acids.

Derived units involving force, e.g., direct force measurements, pressure measurements, electric field strength measurements, are directly tied to mass measurement since mass is one of the base SI units. Each of these areas is covered in other surveys, nonetheless, the consistency within and between these seemingly diverse fields is directly related to the characterization and dissemination of the mass unit.

Measurements of mass, volume, and density are undoubtedly the most pervasive measurements performed in the world. Weighing operations are involved in activities ranging from teaching addition in the elementary grades to establishing the mass of a testing device for use in determining the mass and center of gravity of space vehicles and mass determination of objects used in current NBS measurements of the universal gravitational constant, G. In present day commerce, almost all commodities are priced by weight, as are materials more precious than gold and cheaper than dirt. Most physical and chemical processes are mass based. Chemical reactions, as well as the energy of nuclear reactions, depend on mass ratios. Moreover, techniques exist for conveniently performing weighings over a range of 10^{12}; literally, almost nothing is too large or too small to be weighed or to be similarly described through the related properties, volume and density.

The almost infinite number of measurements of mass, volume, and density in the United States tie to the Mass and Volume Section of NBS in many different ways. In some cases the relation is established by legal, or contractual, requirements. In other cases, the relation is either a matter of necessity or of convenience. In some cases the link between the U.S. Prototype Kilogram and the point of judgment as to the acceptability of a given measurement relative to a specified requirement is through a hierarchy of calibration laboratories. In other cases the link is as short as is practicable. Each route has its own unique characteristics. The ultimate goal in any case is to obtain a consistency of measurement compatible with the manner in which the measurement is to be used [11].

2. STRUCTURE OF THE MEASUREMENT SYSTEM

The commonality of certain elements in specific measurement processes provides a logical basis for ordering groups of measurement processes into systems and subsystems. To illustrate the ways in which the system is "tied" together, figure 1 is a diagram of the factors which affect the design and operation of a specific measurement process. The task requirements, which arise from the desire for success, or the consequences of failure, are the basis for the details of the process. These requirements, as perceived at the measurement level, establish the specific process and procedural details. In operation, there is a value judgment for each measurement--accept, scrap or rework items, or remeasure. In the end, the item and result pass on to others and in combination with many other elements, i.e. results from other measurement processes, contractual requirements, entrepreneurial judgments, etc., constitute the completion of the task. Economic factors, success/failure ratio, changes in the consequences of failure, and changing technology are all "feedback" factors contributing to refinement of process detail.

The one element common to all mass, volume and density measurement processes is the conceptual basis for the measurement. This element, however, is more devisive that adhesive relative to the total system. For example, as the task requirements, either real or perceived, approach the limit of measurement capabilities, each step in figure 1 must be treated explicitly--not only relative to the specific process but also relative to the other elements contributing to the accomplishment of the task. Those who work in this area become, by necessity, "understanding" oriented. In contrast, when the requirements are modest with respect to capabilities, many of the steps can be treated implicitly and those who work in this area become "procedure" oriented. In the first instance, the interest is in "how much," i.e. the mass of an object, the volume of a tank, or the density of a material. In the latter instance, the interest is in how much one is in error if he assumes that the mass of an adjusted weight is 1 kilogram, or the capacity of a "certified" prover is 1 gallon, and so on.

The most visible common element is the need for access to a consistent set of metrics.

Another common element, which to date has no identifiable bureaucratic structure, relates to the availability of adequate instrumentation. Finally there is a commonality in the basis for the value judgment, particularly where there are many processes engaged in the same or similar tasks, and where the measurement requirements are modest. The identifiable bureaucratic infrastructures relate to providing access to consistent metrics adequate for the task at hand, and to the value judgments for similar measurements (voluntary standards).

The infrastructure related to the metric is shown in figure 2. All who have need have

Figure 1

INFRASTRUCTURE OF THE MEASUREMENT PROCESS

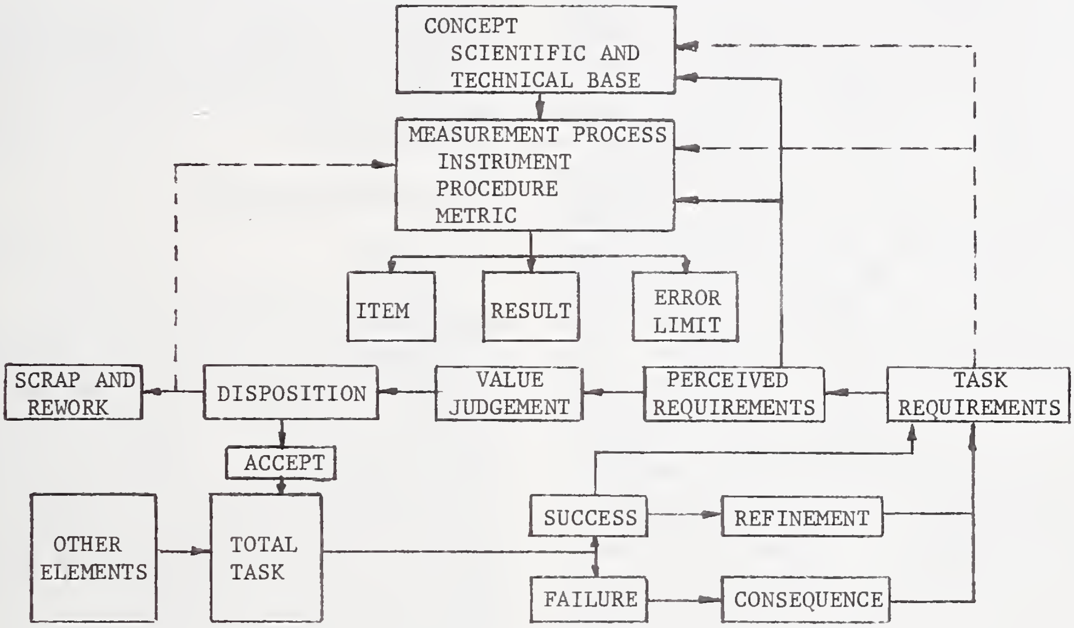
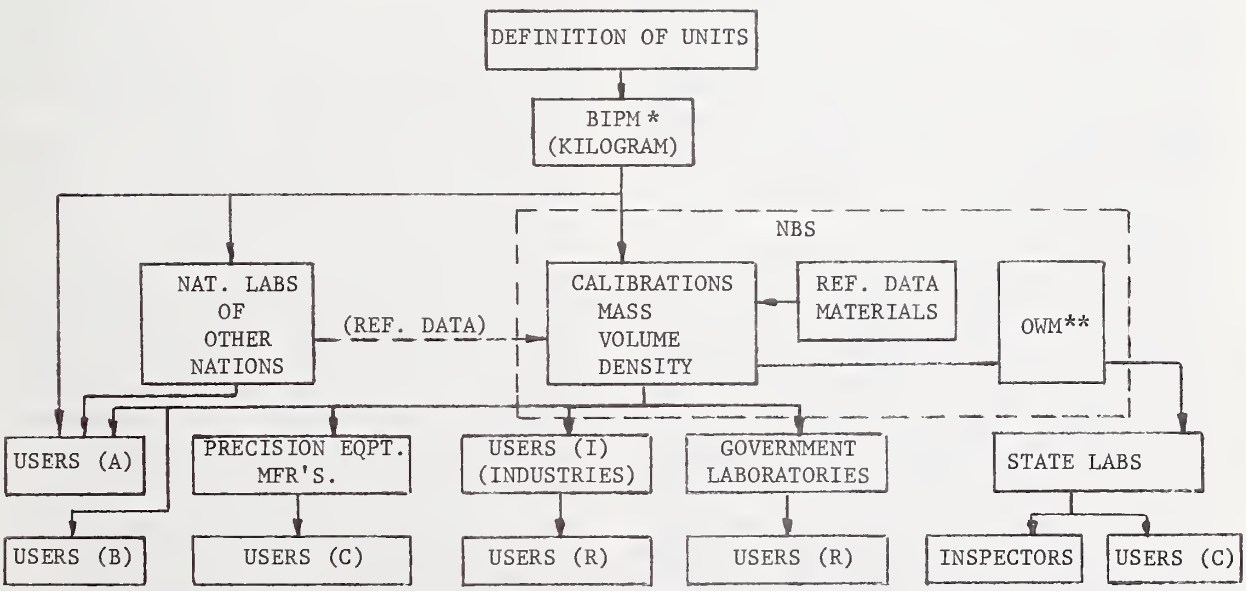


Figure 2

INFRASTRUCTURE OF THE METRIC



* BIPM = International Bureau of Weights and Measures, Sevres, France

** OWM = NBS Office of Weights and Measures access to adequate mass standards, either from NBS and similar laboratories of other nations, and in some cases, directly from BIPM, or from other sources served by the echelon shown. The first level dissemination from NBS provides access to those with real needs (USERS (A)), or perceived needs (USERS (B)), which require direct access to national standards. Precision equipment manufacturers are also served. These in turn provide instruments and standards which are themselves adequate for USERS (C). The industrial organizations served in turn provide services for a restricted set of users (USERS (R)), generally limited to groups within the particular organizations. Government laboratories, usually organized in hierarchial echelon systems, also provide access to a restricted set of users. Finally, through the Office of Weights and Measures, the state laboratories provide services for their inspections and in most cases to unrestricted users, USERS (C). It should be noted that both USERS (B) and USERS (C) include equipment manufacturers serving measurement areas in which the requirements are modest.

The infrastructure associated with value judgments; i.e. voluntary standards, regulations, etc., is considerably more complex. The task is to establish a consensus agreement between the user-supplier, or the regulator-regulated, as to what constitutes an adequate measurement under a specific set of conditions. The procedural steps leading to a voluntary standard are shown in figure 3. The time span from start to general acceptance is often in excess of 10 years. If the standard is in response to a regulatory requirement, the regulator may reject the entire effort at any time. Obviously, once a standard becomes an accepted practice, it is extremely difficult to make substantial changes in spite of the fact that most standardizing organizations require periodic review. The standardizing organizations, with interest in mass, volume and density measurements are shown in table 1.

The structures described in figures 1, 2, and 3 are frameworks within which one can discuss various aspects of mass, volume, and density measurement. The actual measurement system is far more complex. Unlike measurement systems which originated around the turn of this century or later, measurements of mass, volume and density started with the dawn of technology. These measurements are necessary to the accomplishment of about every human endeavor, be it by an individual, a profession, or by a society. Fundamental to these accomplishments are measurement processes that work well enough for the intended purposes. Where the resulting processes are adequate, regardless of being ill conceived, there is little to be gained by imposing change. On the other hand, technological progress may eventually dictate requirements beyond the capabilities of currently accepted practices, at which time the old processes must be discarded and a new and more appropriate one devised. Thus, because of the diversity of requirements at any point in history there are (a) subsystems which are stable with formal infrastructures; (b) existing processes which, for various reasons, are undergoing change with resulting pressures on existing infrastructures; and (c) processes being developed for emerging requirements which are not as yet sufficiently stable to permit the development of a formal infrastructure.

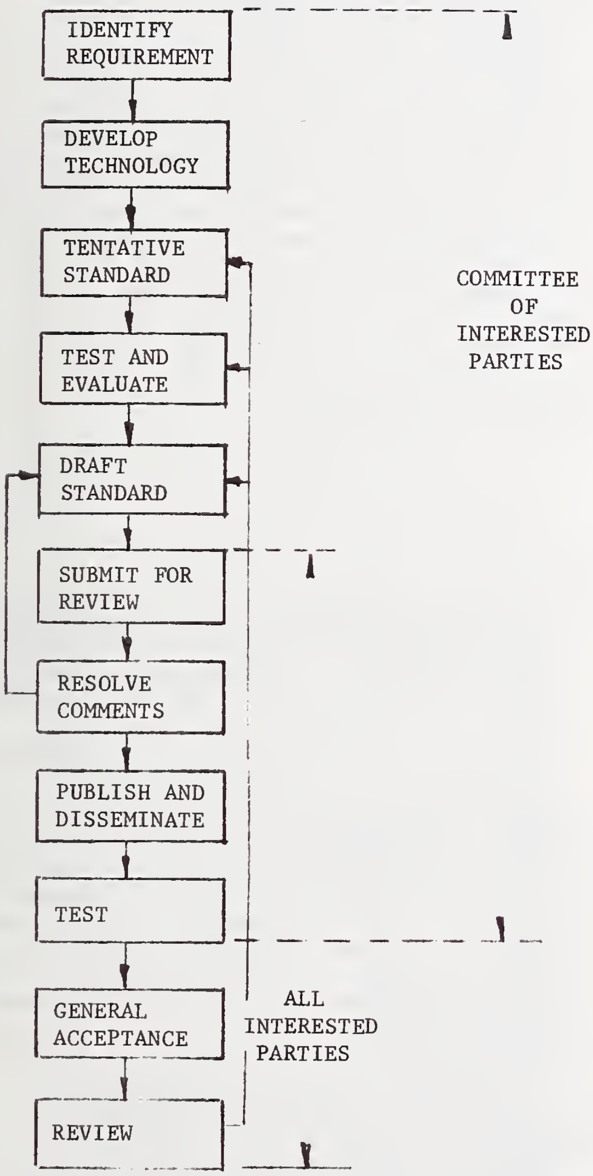
2.1 Conceptual System

2.1.1 Mass

It is very difficult to construct a conceptual mass measurement system which would be acceptable at all levels of interest. From the beginning, and even now, most weighings are associated with determining quantity of material. Highly developed weighing devices were widely used long before the reasons why such instruments were successful were understood. The concept of mass does not exist without motion. Few, however, would interpret the simple act of placing a weight on a balance pan as motion. Mass and force are inseparable, but an intellectual separation has been maintained by definitions, e.g. mass is measured by a balance; force is measured with a spring. While it is only necessary for a conceptual system to be logically correct, there are good reasons for it to also reflect reality. Few are motivated to pursue measurement detail beyond an understanding of some conceptual system. Decisions are then made on the basis of this understanding. If the concept as perceived is in error, then the decision may also be in error.

The mass of a body is revealed by a body's resistance to change in state of motion, i.e. inertia, or by the fact that a force of attraction exists between any two bodies, that force being proportional to the product of their masses and inversely proportional to the square of the distance between their mass centers, i.e. gravitation. For all practical purposes, the same property of a body is responsible for both effects, thus consistent measurements systems can be constructed using either effect. Mass measurements on, or near the surface of, the earth are based on gravitational effects. Body mass changes of astronauts in orbit were measured with systems based on inertial effects [12]. For a conceptual mass measurement system, it is sufficient to state simply that mass is one property of any object.

Figure 3
INFRASTRUCTURE OF THE
VOLUNTARY STANDARD PROCESS



The traditional concept of mass equality, "Two bodies have equal mass if, when placed on the opposite pans of a "perfect" equal arm balance, result in the balance arms being horizontal," or paraphrases thereof, has been a serious retardant to the understanding of mass, and mass measurement, and the development of instrumentation. If one accepts that mass is a unique property of an object, then, for the purpose of mass measurement, the object can be considered as a mass point located at the mass center of the object. For two such mass points, if the attractive gravitational forces at the same location in the earth's gravity field are equal, then the two points have equal mass properties. If the response of the two points to the application of a given force is the same, the points also have equal mass properties.

For mass measurements in the earth's gravity field, any force measurement device with sufficient resolution, be it a traditional two pan balance, a nonsymmetric one pan balance, an elastic device, a pressure device, or whatever, is a candidate for a mass measuring instrument. Over the past ten years, the traditional equal arm balance has lost its position of prominence, even at the highest level of mass measurement, that of providing access to the International Prototype Kilogram [13]. There are now a variety of high technology weighing devices which are convenient to use and are adequate for practically all requirements.

To complete the conceptual measurement system, one must be able to extend or subdivide the unit, i.e. one needs a definition for addition. For a collection of objects fixed relative to each other, there is a unique point at which the total mass of the collection can be considered to be concentrated. In terms of measurement, this is just another mass point, differing only in quantity. It remains only to have the force sensor respond to the gravitational force acting at this point. Simply stated, the mass of two objects together on a balance pan is the sum of the masses of the individual objects. In reality, considerable care is exercised in the design, construction, and operation of weighing devices to assure that with a single object, or a collection of objects on the "pan," so to speak, the effective mass center of the "pan" load has a fixed position relative to the force sensor and the direction of the gravitational field.

Considering an object, or collection of objects, as a mass point in the concept introduces ambiguities in the realization of the measurement. When these discrepancies are important relative to the intended

Table 1. Standardizing Organizations with Interest in Mass, Volume and Density

Organization	Classification	Area of Interest
International		
Treaty of the Meter (BIPM)	Treaty	Units
International Standards Organization (ISO)	Suppliers	Marketing
International Organization for Legal Metrology (OIML)	Treaty	Legal Metrology
Government and National		
Department of Defense (DoD)	Government	Procurement
General Services Administration (GSA)	Government	Procurement
Nuclear Regulatory Commission (NRC)	Government	Material Control
American Society for Testing Materials (ASTM)	(1)	Procedures, Materials,
American National Standards Institute (ANSI)	(1)	Instruments, Artifacts
Professional		
National Conference of Weights and Measures (NCWM)	(2)	Artifacts, Instruments, Procedures
National Conference of Standards Laboratories (NCSL)	(2)	Procedures, Administration
American Petroleum Institute (API)	Suppliers	Petroleum Products
Scientific Apparatus Manufacturers Association (SAMA)	Suppliers	Apparatus
Institute for Nuclear Materials Management (INMM)	Suppliers	Nuclear Materials Control

(1) Requires equal participation between users and suppliers
(2) Users and suppliers participate

usage of the result, a treatment of the appropriate ambiguities must be included in the definition of equality. The major ambiguities are associated with the displacement volumes, air density, surface finish, and the response of the surface of the objects to changes in environment, i.e., corrosion, moisture layers, etc. In some instances, the difference in the position of the mass centers of the objects being compared, relative to the mass center of the earth must also be considered.

2.1.2 Volume

The concept of volume is the quantity of three dimensional space enclosed by a closed boundary surface. Therefore, its dimensions, as a derived unit, are those of length raised to the third power. Volume is an additive quantity. The major ambiguities of concern in the realization of the measurement are associated with definition of the closed boundary surface and temperature. For each material, volumetric changes with temperature change are related to length changes with temperatures for that material (usually expressed as volumetric coefficient of expansion).

Displacement volumes can be computed from direct measures of the exterior dimensions of solid objects. However, unless the objects are of very uniform geometry, the results are relatively crude. When this method is used, the geometry of the objects is generally limited (cube, cylinder or sphere) with surface finish adequate for length measurements by interferometry. Volume determinations by length measurement are usually limited to two classes of measurement: those associated with determining the density of various reference liquids, e.g. water and mercury, or those associated with very large volumes, e.g. large objects and liquid storage tanks.

Precise displacement volumes of a variety of forms can be obtained by Archimedes' Principle, e.g., hydrostatic weighing in a fluid of known density. Volumetric coefficients of expansion enter in two places: for the object and for the density of the fluid. The surfaces of the object must be compatible with the fluid so that the boundaries remain clearly defined without causing the mass of the object or the density of the fluid to change. One of the largest ambiguities in this method is associated with air bubbles which are entrapped on the surface of the submerged object which, in turn, cause apparent changes in the mass of the object. The method is also subject to the normal ambiguities associated with mass measurement. Generally, the method is limited by the availability of equipment and handling problems associated with the object.

The largest number of volume measurements are associated with determining the amount of liquid which is "contained" in, or can be "delivered" from, a variety of appropriate vessels, i.e., pipets, burets, flasks, metal containers or capacity standards, process tanks, etc. When the container design is such that it can be weighed in the filled condition, the containment volume is determined by gravimetric methods. The container is first weighed in an empty condition, then filled to an appropriate index with a liquid of known density and reweighed. The volume of the liquid, determined from the definition of density, is assumed to be the volume of the container. The method is subject to all of the ambiguities associated with mass and volume measurements, as described above. For "delivered" volume, there is an ambiguity associated with the tendency of the liquid to cling to the walls of the container during drainage. In this case, the container is filled and drained for a specific time interval before the first weighing. With proper attention to the ambiguities, one can establish the volumes of large containers by transfer methods, e.g., a repetitive operation consisting of filling a container of known volume to an appropriate index, and emptying it into the larger container.

2.1.3 Density

Density is defined as mass per unit volume. It is not a measurement unit in the same sense as mass and volume. It is a unit generally used to characterize a material, be it gas, liquid or solid. In certain cases density may be a measure of mass distribution within the boundaries of the enclosed volume, e.g. certain gas and gas mixtures, certain pure liquids, and certain solids. In many cases density is merely a useful characteristic of an object.

Because of large numbers of ambiguities which are involved in both mass measurement, and direct measurement of volume using a length metric, the most precise density work has been limited to the characterization of specific reference materials: water, because of its prominence in the establishment of the metric unit of mass and its availability as a reference material; mercury, for use in pressure measurement; and most recently, single crystal silicon. Density work with regard to a reference material has an additional complexity over and above those associated with measurement: that of the uniformity of the reference material over time and as obtained from various sources.

2.2 Basic Technical Infrastructure

Mass

The accepted standard mass unit is the mass of the International Prototype Kilogram, a platinum-iridium cylinder of height very nearly equal to its diameter. The mass of this object is exactly one kilogram by definition. There are no environmental restrictions associated with the definition. In the comparison of the International Prototype Kilogram with its replicas, the ambiguities mentioned above are not large, provided that sufficient time is allowed for the surfaces to come into equilibrium with the environment since the objects are made from the same material with nearly the same surface finish.

The acceptance of the International Prototype Kilogram as the standard of mass did not end the confusion associated with mass, weight and force. In 1901, the 3rd General Conference on Weights and Measures (CGPM) declared:

1) "The kilogram is the unit of mass; it is equal to the mass of the International Prototype Kilogram;"
2) "The word weight denotes a quantity of the same nature as force; the weight of a body is the product of its mass and the acceleration due to gravity."

This second statement, a deviation from the general policy of the CGPM of defining only units but not quantities, demonstrates the wisdom of this policy.

The 11th CGPM, in 1960, established the derived unit for force, the Newton, which is defined as the product of mass and acceleration. This action, in essence, relegates the word "weight" to mean an object which has a mass property of interest. In reality the words weight, mass, and force are still syntactically confused. The degree to which the populace, as well as those directly interested in mass and force measurements, accept the Newton remains to be seen.

In this country, the most common metrics for mass measurement are the avoirdupois pound, with a growing use of decimal subdivisions, and the kilogram, with the usual subdivisions. Traditional subdivisions of the pound are required by legislation to be used in some areas, e.g., the Troy pound and ounce are used in precious metals trade; grains, in coinage. All now have been defined, directly or indirectly, relative to the kilogram. There are no inconsistencies between the various metrics.

In determining the mass of an unknown object, the metric can be introduced in one of two ways; by direct comparison with an appropriate summation of mass standards, relying on the instrument indicating system to subdivide the smallest practical standard, or by direct measurement using a device which has been designed to indicate either mass units directly or some mass related quantity of interest, or both, e.g. the grocery store pricing scale. The choice of method depends upon the end usage of the measurement results.

In the comparative mode, the constancy of the metric is determined by the available summation of mass standards. The uncertainty of the result is a function of the uncertainty of the mass value assigned to the standards, the precision of the instrument, the care exercised in making the measurement, and the attention given to significant ambiguities. In the direct reading mode, the constancy of the metric is assigned to the instrument. The uncertainty of the result is then a function of both the long term stability of the instrument and its precision, as well as the uncertainty of the mass scale as embodied in the instrument. The instrument design usually includes some compensation for significant ambiguities. It remains for the user, however, to ascertain that such treatment is indeed appropriate for his particular measurement. In practically all cases, commercially available instruments are designed to be used as direct reading devices. Most instruments, however, can be used in either mode of operation either as is, or with minor alterations, if the instrument indicating system has not been arbitrarily rounded.

The most confusing technical problem concerns the basis for stating mass values. In addition to confusion between mass, weight and force as mentioned above, there are at least three "mass scales" in common use. To understand the origin of these scales, consider the case in which a standard of known mass is compared with two "unknowns," one made from the same material as the standard, one made from a different material. In comparing the like materials of essentially equal mass, the buoyant effect becomes a second order correction, and the value transferred to the unknown is on the same basis as the value assigned to the standards. Where the materials are different, the buoyant effect must be reconciled in some manner. The practice was started long ago where the value assigned to the unknown was called "apparent mass," and was assigned on the basis of the observed differences. Later, the precision of the "apparent mass" scale was preserved by normalizing the data to obtain the value one would expect if the unknown had been compared with a hypothetic standard of stated density in a specific environment. The oldest "apparent mass" scale used in this country is based on a standard of 7.8 g/cm^3 at 0°C and an air density of 1.2 mg/cm^3. The newest scale, originating in Europe and Japan, is based on a standard of density 8.0 g/cm^3 at 20°C and an air density of 1.2 mg/cm^3. The systematic difference between the two scales is observable on many instruments. Finally, there is the "Newtonian" mass scale, e.g. "true mass" or "mass in vaccuo," for which the International Prototype Kilogram is the defining artifact.

Volume

The founders of the metric system, in an attempt to establish a reproducible mass unit, defined a mass unit, the gram, to be the mass of one cubic centimeter of pure water at the temperature of maximum density. On the basis of this definition, and the newly established length unit, the meter, the Kilogram of the Archives was constructed using arbitrary mass units as embodied in the Pile of Charlemagne [14]. Using Archimedes' Principle, and objects with measured displacement volumes in terms of the meter, the summation of arbitrary mass units which would be equivalent to one kilogram was established. It then remained to construct and adjust the newly established kilogram to be equal in mass to the appropriate summation of arbitrary mass units. This work was a substantial scientific effort, with careful attention to the ambiguity associated with the buoyant effect of the air. There was no way to check the realization however, since the available platinum-iridium alloy used in the construction of the Kilogram of the Archives was too porous to permit a hydrostatic determination of the displacement volume. It was generally accepted, however, that the kilogram was equivalent in mass to that of one cubic decimeter of water at its maximum density point [15].

A later group of platinum-iridium kilograms, from which the International Prototype Kilogram was selected on the basis of being most nearly identical in mass to the Kilogram of the Archives, was of sufficient quality to permit hydrostatic determination of displacement volume. It was then evident that the intended realization was not achieved. In 1903, the unit of volume was defined by the third CGPM as follows: "The unit of volume, for determinations of high precision, is the volume occupied by a mass of one kilogram of pure water, at its maximum density and under normal atmospheric pressure; this volume is termed the litre."[16] No reference is made to the unit of length. Careful measurements had shown that the mass of one cubic decimeter of water at its maximum density point differs from the mass of the kilogram by 27 milligrams. As measurement precision has increased, the confusion between the cubic centimeter and the milliliter has done likewise.

The eleventh CGPM in 1960 requested a resolution of this controversy which subsequently occurred at the twelfth CGPM in which the definition given in 1901 was abrogated, the recommendation made "that the name 'liter' should not be employed to give the results of high accuracy volume measurements, but that high accuracy measurements be expressed in the SI units, i.e., in cubic meters or cubic decimeters."

For liquid measure, the most common metrics are cubic decimeter (usually called liter in spite of the above recommendation) and the U.S. gallon, which has a defined relationship to the SI length unit.

Density

During the era encompassing the third CGPM, about 1900, the thermal coefficient of expansion of normal (to be defined) water was measured [17,18]; and in 1937, Tilton and Taylor at NBS [19] published tables (expressed in grams per milliliter) of the relative densities of water as a function of temperature from a formula they constructed to fit the early data. Around 1910, BIPM [20,21,22] had measured the true volume (in cubic centimeters) of a milliliter by hydrostatically weighing objects of directly measured volumes in normal water. "Normal" water is now defined as that having a "normal" or "average" isotopic abundance ratio.

Modern workers [23,24] have shown that the isotopic abundance ratio in samples of water drawn from various locations on earth may vary enough to result in density differences of as much as 5 or more parts per million. Without knowledge of the isotopic abundance ratio, we are left with an uncertainty of this amount in the accepted density of a particular sample of water. Additionally, there is an even larger source of uncertainty. The vapor pressures of the various isotopic forms of water are significantly different [25], so that distillation to remove impurities or boiling to eliminate dissolved gasses can further upset the isotopic abundance ratio from its "normal" value. Density differences as great as 20 ppm have been found [26] between the first and last fractions of a distillation.

Uncertainties in the density of "pure" or "normal" water, still under study, limit its use as a reference material in high accuracy measurements. Water, however, is an adequate reference material for a wide variety of measurement activities. The most recent fit of the original data has been done by Wagenbreth and Blanke [27]. In this work the data has been adjusted to the International Practical Temperature Scale of 1968 (IPTS-68), and the density values, expressed in SI units (kilograms per cubic meter) are tabulated for the temperature range 0° to 40°. Density values, as given in this work, are used at NBS for all volume measurements in which water is used. In some cases, the values can be adjusted for use with normal tap water.

The problem of uniformity of the reference fluid was handled in a different way by Cooke in his work with mercury. In essence, the final results apply to a large quantity of mercury obtained by mixing samples from a variety of sources. The mix was then subdivided, with smaller quantities being furnished to national laboratories interested in high accuracy pressure measurements.

Following the demonstrated ability to compare densities of silicon crystals at the 1 X 10^6 level [28], Bowman, Schoonover, and Carroll [29] have established the density of single crystal silicon artifacts with measurement uncertainty on the order of 1 ppm. In this work, the volume of a group of steel spheres was determined by interferometric measurement. Spheres were selected because manufacturing processes have now been perfected to the point that nearly perfect geometry is readily obtained. Working with the buoyant forces in a fluid of arbitrary density, one can determine the volume of other objects relative to the measured volume of the spheres, the result being independent of the mass unit. This work suggests that the natural density of single crystal silicon may be more constant than obtainable with water in any form. Artifacts of known density in combination with mass measurements and Archimedes' Principle, can be used to characterize either fluids of interest or other objects. Crystal samples have been furnished to other laboratories, including BIPM.

In contrast to the high technology work briefly described above, most practical density measurements are made to characterize a wide variety of fluids, again a problem of interest since man discovered the pleasures of alcohol. The resulting measurement system, revised and improved over the centuries, is a simple, practical solution to a very complex problem. This complexity arises from the fact that where solutions are involved, volumes are not additive. Further, the changes in density of the solution with temperature cannot generally be predicted from the characteristics of the solution components.

Based on Archimedes' Principle, a hydrometer floats in the solution at a level where the buoyant force acting on the submerged portion of the instrument balances the gravitational force. The sensitivity of the instrument depends on the ratio of the stem cross section area to the submerged volume. A reading scale in the stem can be graduated in any units which are related to the density of the fluid. Further, by selecting the density of some arbitrary fluid at a particular temperature as unity, the instrument is not dependent on any system of measurement units. Since distilled water is a widely used dilutant, it is the basis for a variety of "density" scales. Figure 4 illustrates some of the more common metrics currently in use.

The starting point for hydrometer calibration is the selection and preparation of the reference fluids. In the case of simple solutions, for example, a series of solutions of known dilution are prepared from pure materials. For more complex fluids, density is determined by weighing using weighted glass plummets of known displacement volume, or picnometers of known containment volume. These solutions are used to establish appropriate scales on reference hydrometers. Corrections for temperature effects are essential. Sets of reference hydrometers for the common metrics are maintained at the various national laboratories. The reference standards are used to calibrate "master" hydrometers for manufacturers and certain classes of users. The "master" hydrometers are an essential part of the manufacturing process. It is not generally possible to control the physical dimensions of the hydrometer to a degree commensurate with the sensitivity of the instrument. For each precision instrument, the scale must be established relative to an appropriate "master" hydrometer as one step in the manufacturing process. The finished instrument may then be checked against another "master" hydrometer, either by the manufacturer or the user, or it may be submitted to a national laboratory for calibration relative to the appropriate reference standard.

Recent developments include a method to establish reference hydrometers without using reference fluids, provided that the surface tensions and thermal characteristics of the fluid are well known, and provided that the desired scale is defined relative to the SI unit for density.[30] The most important development is the availability of a new type of instrumentation for density measurement based on the inertial properties of mass, described in Section 2.2.2.1.

2.2.1 Documentary Standards System

We define documentary standards to include all documents which are formulated for the purpose of providing solutions to constantly reoccurring routine problems. This includes recommendations, test methods and procedures, and specifications, both hardware and performance. All standards are, in a sense, after-the-fact documents, and as such reflect an acceptable consensus decision with respect to some particular problem. Standards provide a degree of order which in many cases produce economic savings to both the producer and the user. Perhaps more important, standards provide a means to address the legal problems associated with supply and demand, e.g. the specific desires of the customer, the limits of control by the regulator, the limits of guarantee or warrantee by the producer, and some form of proof that "due care" was exercised to comply with appropriate restraints.

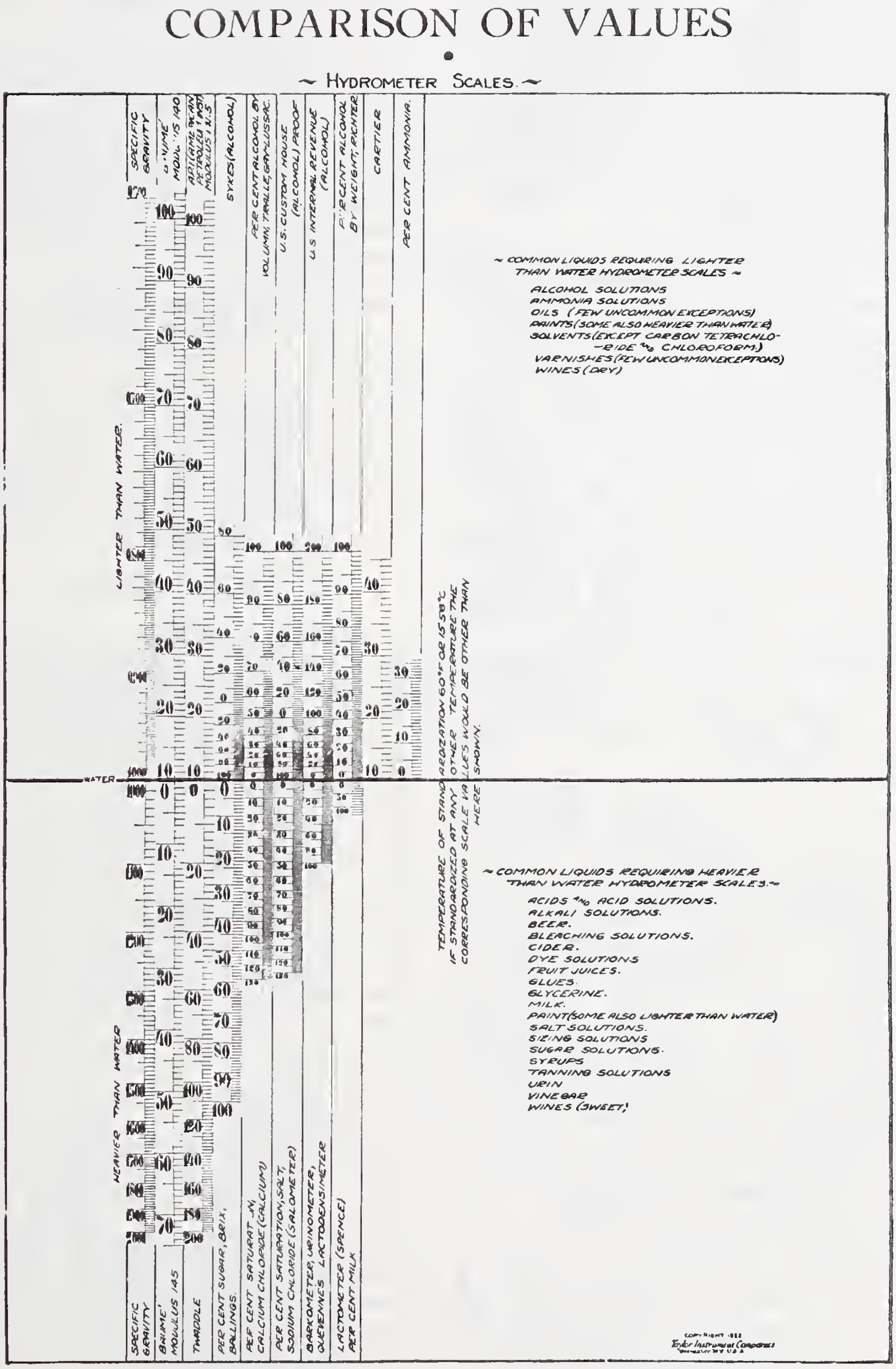
2.2.1.1 Standardization Institutions

The first of these is the apparatus set up by the Treaty of the Metre of 1875. This structure has two levels, diplomatic and technical. Nations who are signatories of the Convention of the Metre are represented on the General Conference for Weights and Measures (CGPM). This body, composed of national delegates, elects the International Committee for Weights and Measures (CIPM) and formalizes the international adoption of recommendations. These recommendations in essence promote uniformity in communications by defining the various base units, in this case the kilogram and the meter, and the various derived units.

It should be emphasized that the organization established by the Treaty of the Metre is concerned only with the realization of the units. The utilization of the units, so defined, is left to others.

International Bureau of Weights and Measures (BIPM) is the laboratory arm of CIPM. From its location just outside of Paris, it serves as secretariat to the advisory committees, maintains the prototype kilogram and periodically intercompares the National Prototype Kilograms belonging to the member nations.

Figure 4
PRACTICAL HYDROMETER SCALES



A second international treaty organization is the International Organization for Legal Metrology (OIML). Its objectives are:

(1) to determine the general principles of legal metrology;

(2) to establish model draft laws and regulations for scientific and measuring instruments and their use; and

(3) to determine necessary and adequate characteristics and standards to which measuring instruments must conform in order for them to be approved by member states and for their use to be recommended internationally.

Actions of the Conference on Legal Metrology are in the form of recommendations and are not legally binding, but member nations are morally obliged to implement decisions of the Conference as far as possible [31].

A nontreaty international standards organization of importance is the International Organization for Standardization (ISO). The American National Standards Institute (ANSI) is the United States member of the International Organization for Standardization, which now consists of the national standards bodies of 52 countries. The United States' viewpoints to be presented in the technical work of the ISO are developed either through the interested sectional committee or through a competent committee of another organization or, if there are none of these available, through a committee specially organized as a USA Advisory Committee for the ISO Technical Committee.

The work of the ISO technical committees results eventually in ISO Recommendations which may be embodied in the national standards of the ISO's Member-Bodies. ISO recommendations, like all voluntary standards, may be in the form of either detailed "how to" specifications or overall performance specifications, e.g., "standard" test for determining the density of crude oil or a listing of agreed upon ranges for hydrometers.

ANSI and the American Society for Testing and Materials are the two largest of over 500 organizations in the United States who consider the preparation of standards to be a major or important part of their reasons for being [32]. The field of expertise found in both the ASTM and ANSI type of organization is best described by ASTM's managing director: "Actually, the Society has only one area of expertise and that is a full knowledge of management systems for the development of consensus standards" [33]. A great deal of care is taken to ensure user participation in any committee to avoid antitrust action.

Voluntary standards organizations work through a committee structure whose membership is composed of representatives of users united in a common endeavor, or the manufacturers and users of a product or technique. In the latter case, it is generally true that manufacturers' input is very strong unless the area of interest concerns a large number of users.

The Federal Government within its procurement process generates specifications which become, because of the size of the government market, de facto national standards. Other Federal Government agencies, such as the Department of Defense and the various regulatory agencies produce standards which impact all aspects of measurement.

State and local governments also produce standards of varying degrees of impact. By far the most important of these, within the context of this document, are the weights and measures laws which are currently issued by 775 separate jurisdictions. While the legal responsibility is at the state level, national coordination is obtained through the National Conference of Weights and Measures, sponsored by NBS through the Office of Weights and Measures.

2.2.1.2 Survey of Documentary Standards

CGPM resolutions define the metrics for mass and length, and the terminology for the SI base and derived measurement units. Resolutions are universally adopted by the 93 signatories of the Conventions. Efforts to provide access to these measurement units generate a literature base associated with the "how to" of measurement, e.g., instrumentation design and development, constancy of the unit, and the performance of the measurement process over time and in the various environments in which measurements must be made. This literature base is a major resource for measurement application. The community which is concerned with the "how to" of measurement is not generally restricted by either proprietary or legal limitations.

The application of the "how to" of measurement to resolve specific measurement problems generates standards which can be categorized according to the nature of the specific problem. For routine problems with wide application, e.g., instrument performance specifications and the adjustment tolerances for different classes of mass standards, or of interest to large sections of the populace, e.g., weights and measures activities, the resulting standards are readily accessible to all who have interest. Ease of access, in turn, results in such standards inadvertently becoming a part of the "how to" literature base. The "how to" of measurement will be discussed further in section 2.2.3.

The largest number of standards relating to application are the "in house" standards of the producers of goods and services. In order to limit liability with respect to contract compliance, warrantee or guarantee, such standards are not widely circulated. In many cases there is a concerted effort to protect the proprietary nature of these standards within a given organization, with circulation based on the "need to know." While standards of this type are the basis for eventual consensus standards, the existence of a consensus standard does not preempt the use of the "in house" standard. Product performance, established and maintained by "in house" standards, may be defended in a legal sense on the basis of consensus standards.

The basic differences between the OIML and the voluntary and government standards are related to the means of deciding what constitutes "due care" in a legal sense. OIML is an effort to define "due care" at a national level through the control of measurement detail. OIML recommendations pertaining to artifacts and measuring devices specify the placement of a metrological control mark upon the article in question. That is every article of that type must bear the "mark." Obtaining the "mark" for a product requires adherence to the specifications of the instrument or artifact engineering design contained in the pertinent recommendations.

For example, a case in point is that of a U.S. manufacturer of weights attempting to market his product in a nation subscribing to OIML recommendations [34]. A prototype approval was required before any weights could be sold. Submission of a typical set of weights resulted in rejection based upon the dimensions of the weights rather than on the suitability of the weights for the specific application.

Further, the 59th National Conference of Weights and Measures passed a resolution pertaining to OIML in which it defined its view of the "moral obligation" involved in the treaty. That resolution specified that the NCWM was not morally obligated to implement any OIML recommendation, i.e., a model weights and measures law, which had not been approved by the NCWM after review and acceptance and only then if the U.S. had cast an affirmative vote for the model regulation in the International Conference of Legal Metrology.

The U.S. Advisory Panel who reviewed the first 19 recommendations found 18 technically unacceptable. The ultimate impact on U.S. industry is a cause of concern due to the potential, and to a degree existing, use as nontariff barriers to trade.

Voluntary standards organizations, in essence, establish "due care" at the producer or the producer/user level. By mutual consent, voluntary standards dealing with materials are generated by the American Society for Testing and Materials (ASTM), and those dealing with devices by the American National Standards Institute (ANSI). There is close cooperation between the two institutions and their standards are similar in nature. ANSI has an additional role relating to ISO. ANSI represents the United States' views in the international voluntary standards effort. Both ANSI and ASTM standards are subject to periodic review.

The role of voluntary standards in American industry is complex and generally not well understood. Voluntary standards are "how to" documents for a variety of specific tasks. The standards are essentially defense mechanisms. In most cases, the issuance of a standard is contingent on a unanimous affirmative vote by the reviewing body. The time interval between concept and approval is on the order of 5 years, with mandatory review intervals of 3 to 5 years. After issuance there is another time interval, also measured in years, during which the standard is implemented by the various users. As a consequence, voluntary standards serve stability rather than viability. Nonetheless, the collections of voluntary standards are used by many as authoritative "how to" standards for measurement.

Professional societies, such as the Society of Automotive Engineers, the American Society of Mechanical Engineers, the Institute for Nuclear Materials Management acting through ANSI, develop and issue standards as do some 360 trade associations. There are at least 20,000 such standards, accessible via NBS SP 329, "An Index of U.S. Voluntary Engineering Standards." An ASTM subcommittee on balances has reviewed all of the ASTM specifications to identify those in which mass measurement was limiting. As expected, in an excess of 20 volumes of specifications, there were no mass measurement requirements which could not be satisfied with available instruments and procedures. In many cases, however, the specifications did not reflect a knowledge of the convenience and economy associated with modern methods and instruments.

Federal Standards, issued by the General Services Administration for use by the government in the purchase of consumer goods, represent a different approach to the "due care" problem. These standards represent an arbitrated resolution of differences between user requirements and vendor capabilities, with specific attention to the factors used to differentiate between an acceptable and a nonacceptable product, i.e., carefully address the legal aspects of "due care." These standards are subject to periodic review. There are approximately 28 such standards relating to mass, volume and density. In the case of volumetric glassware, the size of the government market relative to the total market is such that these specifications are essentially industry specifications, with obvious benefits to the nongovernment user.

The Department of Defense Standards relating to the procurement of weapons systems have an important role in American technology. Weapons procurement involves high technology design, development and production, usually where there is no precedent for design, or where performance specifications are far more stringent than those associated with normal commercial products. Currently such procurement is based on a vendor responsibility concept. In this framework, the procurement procedures must address the problem of what constitutes "due care" on the part of the vendor in the course of carrying out the contract.

The resulting system is set up under the basic documents which affect all areas of measurement:

MIL-Q-9858A "Quality Program Requirements"
MIL-C-45662A "Calibration System Requirements"
MIL-I-45208A "Inspection System Requirements"
DSAM 451553 "Evaluation of a Contractor's Inspection System."

The implementation of these documents has resulted in the establishment of a system for measurement control, the operation of which is a contractual requirement, and the inspection of which is carried out by the contract administrator. In excess of 65% of the total calibration activity of NBS directly supports the resulting systems. It should be emphasized that the system is, in view of the procuring agency, a minimal effort necessary to production of acceptable goods, i.e., a definition of "due care." No attempt is made to resolve problems where the required measurement effort has no relation to the quality of the product or where the output of the system is inadequate for the task at hand.

Weights and measures activities, a state, and to some degree a local, function, are basically concerned with the legality of mass, volume and density measurement within the context of trade and the enforcement of regulatory requirements originating at the state or local level. The principal universal documentary standard is Handbook 44, "Specifications, Tolerances and Other Technical Requirements for Commercial Weighing and Measuring Devices." This loose leaf style handbook, periodically revised, is technically the output of the National Conference of Weights and Measures (NCWM). The Office of Weights and Measures of NBS acts as the Secretariat of the NCWM, providing guidance and coordinating various activities. HB44 Has been adopted by all 50 states and incorporated into their weights and measures laws. In addition, 28 states have chosen to adopt uniform weights and measures laws following a model law prepared by NBS and approved by NCWM.

2.2.2 Instrumentation Systems

Broadly speaking, the instruments for measurement of mass, volume and density consist of a wide variety of measuring devices, artifacts, and procedures. Drastic changes in all of these categories have occurred over the past few decades. The precision balance industry has changed from the isolation of a tightly controlled craft to a high production, high technology industry with worldwide sales and service. A few foreign firms satisfy essentially all of the market demands. These same firms, concentrating on the problem of making good measurements rapidly and conveniently, have had an impact on all types of weighing devices. The market for weight sets has essentially disappeared, with only one small company in this country devoting part of its efforts to supplying conventional weight sets, and perhaps a few supplying special sets to weights and measures officials. The use of volumetric glassware, particularly in clinical laboratories, has been replaced by a variety of completely automated test equipment. New instrumentation has been developed for determining densities of fluids. Weighings which were previously done in the market are now being done with weighing devices incorporated in complete packaging systems. Procedures, which were carefully designed to maximize the performance of the older instruments, are no longer applicable.

The above changes have been made economically feasible by concentrating the design and manufacturing effort on the areas in which there is a large market, i.e., from a few grams to a few kilograms. There is only one firm in this country, and perhaps in the world, that markets a 30kg capacity instrument of other than traditional design. Only two companies in the world offer custom built kilogram balances with performance in the microgram range. One in this country offers an instrument based on NBS design for about $75 000, and one in Japan, for about $125 000. Equal arm balances with 5 000 lb capacity have been custom built; they are not available commercially. Most large capacity weighing devices are designed for use as commercial weighing devices, i.e., in accordance with Handbook 44, or other appropriate specification. The nature of the industry is such that a large amount of capital investment is required to design, develop, market, and service a new instrument. As a consequence, manufacturers are very reluctant to supply special equipment to limited markets. Performance claims are generally limited to that obtainable by simplified procedure in relatively poor environments.

Two other recent developments have had a large influence on the instrumentation system: the availability of stainless steel for use in mass standards, and the ability to characterize an individual measurement process, and groups of similar processes. The stability of stainless steel weights, e.g., constancy of mass values, is superior to brass in any form, and perhaps even superior to the platinum-iridium alloy of the prototype kilograms. Careful material control associated with the "built in" weights is important to the success of modern instruments. Computer analysis of large sets of data provides quantitative parameters descriptive of actual instrument performance which in turn guides the development of equipment and procedures.

The most important development of the last decade, generally made possible by electronic advances, is a change in the way in which the instrument indication is determined. Traditionally, changes in the angular position of the beam, as the balance is subjected to different "pan" loads, have been used to indicate differences in mass. In increasing numbers of instruments, the beam is driven to a prescribed "null" position by applying an auxiliary force to the beam through a servo system. The current in the "feedback" loop of the servo is then a measure of the mass difference. There are a number of advantages: the use of flexural elements instead of knife edges, rapid operation, and a signal which can be read directly by a computer.

2.2.2.1 Measurement Tools and Techniques

Measurement tools and techniques are largely determined by the way in which the result is to be used. Two sources of ambiguity must be considered, the response of the instrument to changes in environment and the ambiguities associated with the concept. The sophistication and, to a large degree, the cost of the instrument depends on the degree to which the manufacturer has minimized these effects by design. Depending on the materials to be weighed, ambiguities associated with the concept must be considered at the part in 5 000 to 10 000 level. Beyond this point, the instrument indication may or may not be an appropriate measure of the mass of the object or material being weighed. Most weighing instruments are intended to be used as direct reading devices, and as such, are adequate for all requirements where the accepted uncertainty of the result is determined by factors which are not related to the measurement process, e.g., the grocery store pricing scales. This creates a competitive market in which speed, convenience, and maintenance costs, and perhaps certain regulatory requirements, are important factors.

As the limits for acceptable uncertainty approach the magnitude of the ambiguities associated with the process, one must either restrict the magnitude of the process ambiguities, e.g., impose environmental controls and limit the class of objects to be weighed, or one must adopt more sophisticated procedures and methods for data analysis. Specifying one particular weight material, for example, extends the speed and convenience of the pricing scale into the calibration laboratory which is concerned only with the maintenance of the unit. Such action, however, does not necessarily account for ambiguities in the assignment of mass values to other materials. With few exceptions, everyone must use commercially available equipment for mass measurement. Therefore, one must resort to procedures and techniques to make adequate measurements for requirements which are beyond the performance claims of the manufacturer.

The instrument indication is in essence an amplification of the mass difference between the object in question and a "tare" setting. The prerequisite for changing the mode of operation of the instrument from a direct reading mode to a comparative mode is that the indicating system not be intentionally rounded to obscure random-like variability as the sensitivity is increased.

In a comparative mode of operation, with appropriate procedures and attention to environmental conditions, one can achieve the maximum instrument performance. The convenience of direct reading, however, is generally sacrificed. In a comparative mode, the constancy of the unit is shifted from the instrument to a stable artifact.

The significant ambiguities are accounted for by attention to environmental factors, and by treating the ambiguities associated with the concept in the data analysis. Where requirements are stringent, it may be necessary to use supplementary measurement data to determine the displacement volumes of the objects of interest, and to determine the density of the air in the vicinity of the instrument.

The most readily identifiable artifacts in mass measurement are the weights or weight sets which provide local access to the measurement unit. In those nations which are members of the Treaty of the Metre, a national laboratory has the task of transferring the unit as embodied in the appropriate prototype kilogram to a more practical weight material. This work, in essence, substantially reduces the magnitude of the ambiguities associated with the concept in providing the nation with access to the unit. Errors in the initial transfer, however, become systematic offsets of the practical mass scales of the various nations.

There are in effect two systems for the dissemination of the unit with reference to the practical artifact standard. Starting with an artifact with defined value, an equal arm balance, and a mass of material slightly in excess of that of the artifact, one can carefully remove material from the "unknown", until a comparison indicates a "null" condition. At this point, one could declare the mass of the two objects to be "identical." As one increases the sensitivity of the balance, at some point it becomes impractical to make further adjustments. The residual difference is then determined from the balance indicating scale. One can now announce the results of the work in one of two ways: the mass of the adjusted object does not differ from the defined mass of the standard in excess of some appropriate amount, e.g., difference expressed as a percentage error; or, the mass of the object relative to the mass of the standard is a particular value, usually expressed as a nominal value plus a correction, the sum of which is the assigned mass of the object. For example, the CGPM, in distributing the prototype kilogram, announced that maximum difference in mass between the prototypes and the defining artifact did not exceed 1 mg. The reports of calibration from BIPM in contrast, state mass values relative to the defining artifact with uncertainties on the order of a few micrograms. The relative importance of these two points of view, one emphasizing the closeness to the nominal value and the other value relative to the defined value, has changed drastically over the last few decades.

For centuries, precision weighings were made by comparing the mass of the object of interest to the mass of a summation of known weights with an equal arm balance. The necessary weight sets were provided through a hierarchy structure of mass standards. The adjustment problem was solved by using two piece weights, the weight body with an appropriate cavity, and a cover or seal for that cavity. In the adjustment process, small pieces of material were added to achieve equality with the known standard according to prescribed limits of adjustment, and the cavity was sealed. The mark on the seal was, and in some cases still is, a symbol which verified the authenticity of the adjustments. Such weights were also, and still are, used to verify the performance of direct reading commercial weighing devices. The structure was simple, and easily understood--to make a better measurement all one needed was a set of weights from a higher level in the hierarchy, e.g., weights which had been adjusted closer to the prescribed nominal value.

Modern weighing devices remove the choice of weight sets from the user. As before, the user assembles an appropriate summation of weights to obtain an "on scale" condition using the appropriate controls on the instrument and then relies on the indication to subdivide the mass of the smallest internal weight. The instrument manufacturer has taken the responsibility for the construction and adjustment of the reference standards. The weight materials are chosen on the basis of stability. Using techniques such as electropolishing, weight adjustments can be made on a production basis with deviations from nominal essentially limited only by the uncertainty of the values assigned to appropriate reference standards. The instrument case provides clean, dust-free, and essentially nonaccessible storage. In at least one case, instrument assembly is done in a "clean room" environment. The design philosophy is in essence to remove the responsibility for the detail measurement procedures from the user with a well engineered instrument. The instrument cost is considerably more than a traditional equal arm balance and a set of weights, however, in terms of cost per measurement, the traditional methods are obsolete.

The change in emphasis from the closeness of adjustment to actual value is not without problems. Everyone whose concept of mass measurement was formulated before the last decade, including the scientific community, views mass measurement as a hierarchy of mass standards. The most prevalent manner of expressing measurement error is relative error, e.g. in error so many parts per million or percentage. While this may be a convenient or valid way to express error in some cases, the error in mass measurement is not quantity proportional. A part in a billion measurements can be made at the kilogram level, but not at the gram or milligram level. Further, long standing regulations and specifications which are the basis for a number of inspection systems cannot cope with instruments which are "better" than the available hierarchy standards.

With one exception, volume and density measurement is essentially mass measurement instrumentation applied to a different set of artifacts, e.g. a wide variety of volumetric containers, hydrostatic weighings to determine displacement volumes or fluid density, picnometers, etc. One characteristic of interest is the coefficient of expansion of fluids over a rather wide range of temperatures. Traditionally, a picnometer (a special glass container of known contained volume) is filled and sealed in a temperature controlled bath.[35] After sealing, the picnometer is cooled to a temperature compatible with the weighing device. From the weighing data and the characteristics of the picnometer, one can determine the temperature-density characteristics of the fluid. The method is tedious and time consuming. A very successful instrument is now available which reduces the task to simple routine. The instrument, using the inertial properties of mass, relates the response of a quartz tube, filled with fluid at a specified temperature, to an oscillating force field, to the density of the fluid. The instrument, in essence a "density comparator," can be used over a range of temperature. When well characterized fluids are used for calibration, near state-of-the-art precision can be obtained and density determination can be made in a few minutes.

From the previous discussions in this section, it should be clear that a wide variety of techniques for taking and analyzing the data are used. The degree of complexity of these techniques and procedures is directly related to the manner in which the result is to be used. One such technique, now called Measurement Assurance Programs, was developed in the mass measurement area.[36] This technique addresses the problem of how one obtains the assurance that the measurement results are valid when forced to utilize the maximum capabilities of a particular measurement process. Using redundancy of measurement, "check standards", i.e. objects similar in nature to those which are measured routinely but which remain as a part of the process, and statistical analysis, one concentrates on characterizing a particular measurement process. Performance indices are developed which reflect the influence of major perturbations on the process, and which are valid prediction limits for uncertainty of measurement results over the range of variables for a given process. The programs, once established, provide a continuous monitoring of process performance. The validity of each measurement is checked relative to past process performance.

2.2.2.2 The Instrumentation Industry

Weighing instrumentation can be considered in two classes; Laboratory Precision Balances and Commercial Scales and Balances. The nature of the two industries is significantly different.

The laboratory precision balance industry is primarily foreign, centered in Europe and Japan. The individual companies, while few in number, are large, some with worldwide sales and service organizations. Total sales figures are carefully concealed, however, it is estimated that one European firm has captured approximately 70% of the world market. Marketing in the United States is through wholly-owned subsidiaries, or through agreements with American firms. Many of the balances in the NBS Mass Laboratory, and all of the balances furnished to the State Laboratories, with the exception of the 30 Kg balances, are foreign made. The restrictive nature of the various states weights and measures regulation has generally blocked these firms from the Commercial Scales and Balances field.

The American industry devoted to laboratory precision balances is a group of small companies. The equipment is usually marketed through laboratory supply houses or manufacturers representatives. Few have nationwide sales and service organizations. Most, however, operate short courses in service for journeymen who operate general balance and scale repair organizations. The industry has been somewhat protected by various "Buy American" clauses which are used occasionally in certain government contracts.

In contrast, the Commercial Scales and Balances industry in this country is large, with a number of firms having nationwide and international sales and service organizations. In general, the industry has been conservative and very conscious of the limitations associated with the various weights and measures regulations. A wide variety of equipment is available for both single weighings and large complex systems, e.g., packing systems, counting systems, etc. Pressures from many sources, including marketing, prepackaging, and to a certain extent the foreign precision balance industry, seem to have generated some recent innovations evident in most grocery markets.

Volumetric glassware is produced by large firms who generally market by the case to large users and various scientific apparatus supply houses. Special apparatus for which there is no large market is produced by small companies. The grade of the glassware is established by compliance with specification requirements, some of which are performance specifications and some of which are detail specifications. The size of the market is established in part by the breakage rate in use and by the cost of cleaning after use. Throw-away plastic apparatus is a significant competitor.

Hydrometers are generally made by small companies, usually in conjunction with liquid-in-glass thermometers. Again the grade is established by specification compliance, and as with all glassware, breakage is a factor which tends to support the industry. Hydrometers are not usually general purpose instruments, but related to specific uses, e.g., the tax structure for alcoholic beverages, the petroleum industry, the sugar industry, etc. As a consequence, the market is generally governed by specific industry actions.

Metal volumetric containers, such as used for testing liquid and gas metering devices and for calibrating process tanks, are produced by one or two small companies. Most of the market undoubtedly consists of replacing damaged devices. Large companies which produced such items in the past have now either sold that portion of the business or just stopped production. Again there is an interface with regulatory requirements which to some extent dictates the equipment details.

Table 2 provides an estimate of the size of the American industrial effort relating to mass, volume, and density measurements as compared to the larger category Engineering and Scientific Instruments (SIC 3811).

Table 3 provides an estimate of the number of devices in use for commercial weighing and an approximate cost per device. Currently available precision weighing devices with capacities from a few grams to a few kilograms cost from $3 000 to $10 000 and custom built precision instruments from $20 000 to $125 000. Weighing systems which are a part of a total system usually require a large capital investment.

Table 4 is an estimate of the number of devices which are used by state weights and measures officials, an activity which represents only one hierarchy system - that associated with equity in trade. The systems established within the Department of Defense and by Department of Defense procurement procedure are orders of magnitude larger. Large mass standards, totaling in excess of 3 million pounds, are installed in various deadweight machines used to calibrate force measuring devices. There is no estimate of the total number of artifacts which are used in the industrial or scientific community.

2.2.3 Reference Data

Reference data are defined to include all information or data which are taken from the literature under the assumption that it is applicable to the task at hand. Such data, in general, are presented in a format which is convenient to use. The format, however, usually reflects judgments on the part of the author which are rarely discussed in detail. The ability to judge the validity of the data relative to a particular usage is, in many cases, beyond the capabilities of the user either because of insufficient background on the part of the user, or lack of detail discussion relative to the limitations of the data, or lack of time. In many instances the validity of the data is determined by the reputation of the author. Difficulties arise, however, when the judgments of the author are not appropriate to the task at hand.

Perhaps the largest body of reference data are related to the "how to" of mass, volume and density measurements. Concepts of measurement are introduced in the elementary grades and amplified in the high school and early college sciences. The concepts are applied to practical measurement tasks in text books and test procedures throughout science and industry. For example, authoritative treatises on analytical chemistry contains chapters or sections devoted to measurement detail [37, 38], weights and measures officials receive formal instruction, defense department personnel are formally trained in calibration procedures. Many industries conduct formal training in the measurement techniques appropriate to their products. The result is a great confidence throughout the populace in the ability to make mass, volume and density measurements. In reality, however, this confidence is limited by the level of understanding of the person who undertakes the task of instructing the "how to" of measurement.

Tabular data on the density of both dry and moist air are available in various metrological literature, such as the Smithsonian Tables [39]. For requirements beyond the accuracy of these tables, air density is usually computed using supplemental measurements of pressure, temperature, and relative humidity, and appropriate formulas. There are sources of reference data which are adequate for mass measurement. When such data are not adequate for the materials under study, appropriate data are determined by separate

Table 2

Code	Description	1972	Value of Shipments (million of dollars) 1971	1970	1969	1967	1963	1958
3811--	Engineering and scientific instruments		1110.5	1215.9	1115.3	1049.0	722.1	758.6]
3811371	Laboratory precision balances		6.8			6.5	6.5	3.7
3829321	Hydrometers, glass, all types	8.1	4.6					
3229423	Scientific and Lab Glassware	92.5	64.1					
3229425	Industrial and Technical Glassware	62.4	47.3					
3576--	Scales and balances, except laboratory		138.3	152.7	169.4	131.4	90.02	70.99
3576011	Railroad track and motor truck scales		16.9			18.8	12.2	6.5
3576021	Bench and portable industrial scales		10.8			8.9	6.3	7.0
3576023	Floor scales (including built-in)		6.3			6.9	3.8	3.0
3576025	Predetermined weighing and check weighing scales		11.9			9.9	8.7	
3576027	Automatic bulk weighing		10.2			10.6	6.0	
3576029	Miscellaneous industrial scales		14.7			18.7	10.2	7.2
3576031	Computing scales		19.9				12.1	11.6
3576035	Miscellaneous computing scales		3.3				2.5	1.3
3576041	Bathroom scales		17.5			13.8	11.0	10.9
3576043	Person weighing scales		2.1			1.8	1.1	1.3
3576048	Miscellaneous kitchen, baby scales		2.3				1.2	1.4
3576051	Mailing and parcel post scales		3.9			3.2	2.9	2.0
3576082	Accessories and attachments		3.2			2.3	2.6	
3576084	Parts for scales and balances		9.1			8.6	6.0	
3576000	Miscellaneous household scales and balances		6.1				3.44	2.2

a number of published formulas, all of which are adequate for some level of measurement. There is evidence that a fundamental lack of knowledge concerning the density of moist air is one limiting factor on the transfer of mass value from an object made of a dense material to an object made of a light material, e.g., platinum-iridium alloy to stainless steel, or single crystal silicon. [40]

Coefficients of expansion of metals are of primary importance in length measurement and in many scientific and industrial applications As a consequence, there are many experiments which in turn become a part of the reference data base.

Water, and particularly distilled water, is a reference material which is used for many purposes in addition to volume and density measurements. Tabular data regarding the density of water at various temperatures are available from many sources, practically all of which are based on measurements made in the early 1900's. Changes in the definition of the unit for volume and in the temperature scale are not contained in the older references. As mentioned

Table 3

Type of Device	Total Number of Devices in Use	Number of Devices Produced in 1969	Retail Prices for New Devices (Average)
Drum computing scales	298,600	13,393	$275-525
Fan computing scales	74,800	3,073	$150-425
Projection scales	50,000	--	$800
Prepackaging computer scales	29,000	3,985	$3,200-5,600
Package checking	48,500	7,511	$225-243
Railroad track scales: Load Cell	574	36	$16,000-30,000
Railroad track scales: Mechanical	7,000	31	$17,000-40,000
Motor truck scales: Load Cell	121	29	$3,000-7,000
Motor truck scales: Mechanical	54,500	1,939	$3,000-10,000
Other Platform Scales: Load Cell and Mechanical	282,894	22,810	$225-20,000
Beam Scales which have capacities 100-1250 lbs.	4,720		
Drum type computing and automatic meter scales	3,320		
Fan type computing scales	36,000		
10 ton capacity vehicle	50		
16 oz. beam scales	205,000		
500 lb. parcel post scales	220		

Table 4

Type of Equipment	Total Number in Use	Type of Equipment	Total Number in Use
Weight sets		Test measures and provers	
Cube weight sets (1/16 oz to 2 lb)	841	1 gallon	1,312
Decimal pound weight kits (0.001 lb to 0.3 lb)	455	5 gallon	2,793
		50 gallon	251
Decimal ounce weight kits (0.01 oz to 0.5 oz)	127	100 gallon	380
		100 gallon (stainless steel)	5
8 lb test weight kits	163		
Small individual mass standards		500 gallon	58
50 lb mass standard	36,647	1000 gallon	24
25 lb mass standard	191	Miscellaneous test measures and provers	300
Miscellaneous mass standard	140		
Scales, balances, etc.			
Over and under 5 lb			
Package checking	726		
10 lb field balance	305		
Miscellaneous scales and balances	272		
Platform scales	97		
Large mass standards			
500 lb mass standard	1,143		
1000 lb mass standard	2,628		
2500 lb mass standard	122		
5000 lb mass standard	37		
Miscellaneous mass standard	7		
2500 lb dollies calibrated	36		
5000 lb dollies calibrated	4		
Miscellaneous moving dollies calibrated	16		

before, NBS uses and recommends the tables of Wagenbreth and Blanke [27].

Limitations on the density of water as a reference material are associated with the isotopic content. Menache [41] and Emmet and Miller [42] find that particular continental waters vary in density as much as 10 ppm because of isotopic composition. Information on the variation at one place with time indicates a change of less than 1 ppm. The distillation process, however, may alter the isotopic content of the waters. These limitations were in essence the reason for developing a solid object density reference material (single crystal silicon) to be described in section 2.2.4.

2.2.4 Reference Materials

Reference materials, that is, objects or materials which have been characterized by careful measurement, are made available to others for use in local measurement processes. In one sense calibrated mass and volume artifacts, considered to be one of the instruments for mass measurement, could be classified as reference materials. The remainder of the reference materials is associated with density measurements, primarily the density of certain fluids.

Cook of the National Physical Laboratory (NPL) studied the density of mercury. This work included mercuries from various sources as well as a mixture. In one study density was determined by the hydrostatic weighing method using a tungsten carbide cube, with displacement volume computed from measured dimensions. In the second study density was determined on the basis of the mass of mercury contained in a cubic volume constructed of optically flat quartz plates, the computed volume being based on interferometric length measurements. The announced volume from the density of mercury, uncertain by about 1 ppm, applies to the mixture. Sufficient quantities of the mixture were furnished to various national laboratories for use in precise pressure measurement.

Early work of Bowman, Schoonover and Carroll using an instrument based on the principles of the Cartesian Diver, demonstrated the ability to compare the densities of small single crystal silicon artifacts to a precision of 0.1 ppm. [43]. This work suggested the possibility of using single crystal silicon as a density reference. Bowman et al. [8] determined the density of selected large single crystal artifacts by first computing the volume of a pair of steel spheres from interferometric measurements of diameter. The volumetric ratio method, which is essentially a hydrostatic weighing but independent of the mass unit and the density of the fluid, was used to establish the displacement volumes of the crystals. The uncertainty of the announced density for these artifacts is on the order of 1 ppm, the major components of which seem to be associated with phase shift at the surface of the steel sphere in the interferometric measurements of their diameters and perhaps the air density algorithm used to establish the mass of the silicon. All of the characterized samples are on long term loan or have been requested for loan by various national laboratories. Since the material is brittle it must be handled carefully. Care must also be exercised in the preparation of the material for hydrostatic weighing. There are plans to characterize a larger quantity of this material and make it available through the Standard Reference Material program of NBS.

Oceanographers interested in relative changes have established a reference material designated Standard Mean Ocean Water (SMOW). SMOW is taken from depths of 500 to 2,000 meters in open ocean areas where no direct dilution by continental runoff or glacial melt water can occur. Large bodies of data are based on SMOW from a particular location, however, samples from other areas taken at various times are adjusted to agree with the established characteristics of SMOW. Density is only one of the characteristics of interest. Samples of SMOW are available to oceanographers and available from several sources.

2.2.5 Science and People

Mass, volume and density measurements, together with length measurements, are somewhat unique in the history of civilization. Practical instruments for the measurement of these quantities were essential to emergence of the arts and crafts from the earliest agrarian societies. Practical instruments were essential to transition from barter to commerce in the form that we know it today, first intertribal, then between communities, and later between nations. Finally, practical instruments for the measurement of these quantities were for centuries the most precise instruments available which could be used by philosophers and scientists for testing theories relating to natural phenomena. The only common factor between these diverse areas is the instrument, a situation which resulted in growth of one of the most secretive crafts in the history of technology - that devoted to the development and manufacture of precision balances.

The characteristics of the three groups of users, broadly designated as (1) the producers of goods and services, (2) the regulators, and (3) the scientists, are such that there is little intragroup communication of significance. Producers of goods and services are profit oriented, that is, primarily concerned with establishing and maintaining a market for a product or a service. Their success depends upon ingenuity in the application of science and technology in resolving practical problems relating to the particular product or product line. Competition, supported by antitrust regulation, makes it necessary to protect this ingenuity.

Professional engineering society meeting agendas rarely include plant visits and even then competitors must register separately. Plant access is always restricted, except in certain very large basic-type industries, e.g., steel plants, automotive assembly plants, large power plants, etc., with frequent interdepartmental restrictions. Except for companies which conduct non-product related research, communication within the area of producing goods and services and with the other two areas designated above, is generally limited to elements which are common to the group, such as problems relating to the definition of "due care," e.g., test procedures, specifications, and "out of the ordinary" contractual requirements. For the average professional the peer group structure, if such exists, is related to these common elements.

In contrast, the scientific community is entirely different. Generally, it is not profit oriented. It is more or less dedicated to the advancement of knowledge rather than the application of knowledge to the solution of practical problems. The established review procedures associated with most scientific literatures emphasize the peer groups. The individual scientist in turn relies on the quality of the literature of his field and concentrates on contribution to that literature base. In the design and construction of apparatus he concentrates on minimizing the influence of measurement variables which mask the property of interest. By exercising care in the definition of the problem he is usually able to achieve his goal supported in part by open discussion with interested colleagues, laboratory visits, and participation in one or more established peer group activities.

The member of the regulatory group is not interested in either the advancement of knowledge or the application of that knowledge. He is concerned with the actions which define a measurement relative to established laws and, in certain areas, to ascertain that measurements are made accordingly. He has essentially no interaction with the scientific area. He does influence the producers of goods and services in two ways. In commercial transactions involving the exchange of certain materials, contracts can be challenged, in which case one defense is evidence that the measurements were legally correct. As a protection against fraudulent and liability charges relating to the goods and services produced, the producers of such must conform to the legal interpretation of what constitutes "due care." In these matters if one has a choice between a defense based on the justification of new procedures, or on the precedence of old established procedures, the path of wisdom is usually the latter.

These three groups have coexisted for the last few centuries, relying on the guilds to produce the necessary balances and weighing devices. Events in the early 1800's resulted in an attempt to impose an additional common factor - the adoption of a uniform set of measurement units. The units for mass and volume were to be based on natural phenomena rather than replicas of existing artifacts. The scientists of the time could not agree on the basis for the length unit, e.g., the length of a pendulum of a specified period or a fraction of circumference of the earth as measured along a particular meridian. The metric system, as developed in France, is based on the latter, with the mass unit based on the maximum density of pure water. As a result of a fire England was faced with the problem of replacing the accepted mass unit. The resulting action, a reconstruction of the destroyed artifact, established the pound as the mass unit for the English speaking countries. This action favored the producers of goods and services. Both the construction of the metric units for mass and length and the reconstruction of the pound were major scientific efforts.

With the completion of the artifacts the dissemination mechanism in essence created a new discipline - metrology. The metrologist was concerned with the conservation and dissemination of the unit. The metrologist utilized material from many sources in the accomplishment of his assigned tasks. Scientists on occasion had found it necessary to improve mass measurements in order to accomplish particular tasks. Using such literature, together with some engineering and a lot of good judgment, the metrologist was able to make substantive contributions to the literature with regard to improving balance performance. He was, however, never really a part of any particular discipline. His closest relationship was with the scientific field. Scientists quickly adopted the metric units whereas the technologists were and still are reluctant to change. The metrologist also realized that solution to many of his problems must come from the scientific field, but he was frustrated by an inability to define his "real world" problems in a manner which would attract the necessary talent. His problems could not compete with the exploding new field of modern physics. He was not a part of the regulatory system, but, by his position, he was the highest authority for decision. He was not a producer of goods and services so that his judgments relative to dissemination were not always consistent with users intentions. He was almost never challenged, either because of his authoritative position or because usage requirements had not caught up with measurement capabilities.

As with all other facets of the concept of mass, volume, and density measurements, the science and people aspects have also experienced substantial change over the last few decades. There are many factors which have contributed to the change. Engineering curricula were changed drastically in the late 1940's and early 1950's. New disciplines were established to bridge the gap between science and engineering, e.g., engineering science and engineering physics. The constancy of artifact mass units, a problem which plagued the metrologist, essentially disappeared with the adoption of stainless steel. Computer technology took over much of the routine drudgery of lengthy hand computations associated with precise measurement, and for the first time it was possible for the people involved in measurement to actually think about what they were doing. Statistical techniques were developed to characterize a total measurement process in the environment in which it had to be used. At the same time emerging measurement requirements, first associated with the space age and later with environmental protection, were beyond the capabilities of currently used measurement methods and established mechanisms for inspection. As a consequence the perceived role of the NBS mass and volume section changed.

It was recognized that the data base and methods of analysis used in characterizing the processes used for maintaining and disseminating the mass unit could also be used in other ways, and further, the principles used had wide applicability in many measurement areas. It became possible to formulate both the problems associated with precise mass measurement and the suggestions for those with practical mass measurement problems in such a manner as to attract the interest of the scientific community and industry as well. The emerging synergistic relationship is faced with many difficulties, mostly associated with past practices, however, it seems to be growing steadily.

2.3 Realized Measurement Capabilities

Any measurement result is the product of a particular measurement process. The quality of the results is generally expressed by a quantitative statement regarding the area of doubt, or uncertainty, associated with the result. The magnitude of the uncertainty depends on two factors; the quality of the reference standards, and the details of the particular measurement process. A necessary condition imposed on the measurement process is that the magnitude of the uncertainty be acceptable relative to the manner in which the result is to be used. Satisfying only this condition is not always sufficient. Other imposed conditions are related to compliance with contractual requirements and conformance with accepted practices, both of which may or may not be of importance relative to the intended usage. In most cases realized measurement capabilities are not limited by either the available standards or equipment but rather by insufficient knowledge concerning the performance of the process and concerning adequate acceptable limits relative to the end use of the result.

2.3.1 Quality of Reference Standards

The reference standards for the mass unit are the artifacts, or mechanisms, which give the local measurement processes access to the unit and multiples or fractions thereof. In size, reference standards range from fractions of a milligram (small pieces of quartz fiber which must be handled with a manipulator and a microscope) to large 50,000 lb stainless steel discs, as used in the NBS force generators. The quality of this array must be judged from two viewpoints, constancy relative to the precision of measurement at a particular level, and constancy relative to the intended usage. In most cases, the latter viewpoint is the most important.

The precision of measurement at the prototype kilogram level (on the order of .001 mg) is now such that changes in mass can be observed which reflect the response of the material to the immediate environment.[44] Cyclic changes seem to correlate with changes in pressure and relative humidity. Constant rate increases are attributed to contaminants in the atmosphere. Both of these are surface effects, perhaps related to the catalytic properties of platinum. These changes are significant relative to the highest precision of measurement (10 to 20 standard deviations). Kilograms made from stainless steel do not appear to vary as much as the platinum iridium kilograms. Such changes are negligible relative to the precision of most kilogram capacity balances (on the order of .05 mg).

Before the general availability of stainless steel, most weights used in precise weighings were made of brass. Constancy of mass was then a continuing problem. First with the quality of the brass, then with atmospheric corrosion, and finally with coating materials and the material used for adjustment. Lacquer coatings were hygroscopic. Plating discontinuities and plating solution residue caused variability. Oxidation of adjusting material caused problems. NBS Circular 547 delineated the detail requirements for weights which would be accepted for calibration. Strict inspection and rejection at NBS resulted in improved stability. With the increasing use of stainless steel, and the recent changes in instrument design, constancy relative to most usage requirements is no longer a problem.

Reference mass standards are available in a variety of forms. Both regulatory and competitive pressures have resulted in a hierarchial structure in which the quality of a mass standard is judged on the basis of its form and the difference between the mass of the weight and its assigned nominal value--the adjustment tolerance. The highest order weights have the smallest adjustment tolerances, and in general, are more carefully constructed. The various levels are frequently designated as primary, secondary, tertiary, quarternary and so on down to the level of weights which are considered adequate for testing commercial weighing devices. The hierarchial structure exists primarily to satisfy the legal requirements for the calibration of weights, i.e. the comparison of weight with a similar weight from a higher echelon.

There are in excess of a dozen different classes of weights, ordered by construction detail and adjustment tolerance, the most common being Class C--Commercial Test Weights. Table 5 shows the adjustment tolerance limits originally established in 1918. This tolerance structure has been extended to include weights up to 10,000 lbs. It is of interest to note the influence of the crafts in the listing of the customary units, many of which are still in use but now defined relative to the kilogram. (1 lb Avoirdupois, the equivalent of 16 oz or 7,000 grains, is defined as 0.45359237 kg; 1 apothecaries' oz is 480 grains; 1 apothecaries' dram is 60 grains; 1 apothecaries' scruple is 20 grains; 1 oz troy is 480 grains; 1 pennyweight is 24 grains; and one carot is 200 mg.) To complete the picture, the class C weights are typical of those used to test commercial weighing devices to verify compliance with performance specifications shown in Table 6.

A different hierarchy of adjustment tolerances is used for laboratory mass measurements. The commercial tolerance structure tacitly assumes that the ambiguities associated with the concept and the precision of the instruments are negligible relative to the size of the tolerance. The tolerance structure associated with precision weights is frequently so small that both of the above factors must be considered in detail to verify compliance. This leads to a considerable degree of confusion in the interpretation of calibration results. One school of thought advocates strict control of weight materials and designs in order to maintain the simplicity of hierarchial structure relative to weight sets, generally at the expense of the user. The competing school of thought, believing that one should be able to assign a mass value to any object reasonably stable in mass properties, advocates the abolishment of the hierarchy beyond the requirements of commercial weighing.

In summary, mass standards are available which are sufficiently stable in mass for all known requirements. This fact is generally down graded in the manner in which the mass value is assigned to the standards. The variety of adjustment tolerance structures is confusing to those who must obtain standards with reference to a particular usage. An ASTM subcommittee has been working on the task of unifying and simplifying the various specifications. While this document is now nearing completion, the growing acceptance of the direct reading instruments has greatly reduced the priority initially attached to the task. The problem, however, remains in areas which utilize a hierarchy of mass standards. For an increasing number of users, the reference mass standards are the "built-in" weights in the modern balances. These weights are of good quality and are carefully adjusted to well within the established tolerances. Generally it is not possible to calibrate such instruments in the traditional manner, i.e. the use of hierarchy standards.

Reference standards for glass volumetric apparatus consists of volumetric and measurement pipets, volumetric flasks and

TABLE 5.—Tolerances for Class C—Commercial Test Weights

[The maximum error allowable on each weight is given in the columns headed "Tolerance"]

Metric		Customary										Carats	
		Avoirdupois		Grains		Apothecary		Ounces troy		Pennyweights			
Denomination	Tolerance	Denomination	Tolerance	Denomination	Tolerance	Denomination	Tolerance	Denomination	Tolerance	Denomination	Tolerance	Denomination	Tolerance
kg	mg	lb.	gr.	gr.	gr.	oz. ap.	gr.	oz. t.	gr.	dwt.	gr.	c	mg
20	600	50	10	10 000	1	12	1	1000	10	10 000	10	2500	70
10	400	25	6	5000	1	10	1	500	10	5000	5	2000	60
5	250	20	6	2000	0.5	6	0.5	400	5	4000	5	1000	40
2	150	10	4	1000	0.3	5	0.5	300	5	3000	3	500	30
1	100	8	3	500	0.2	4	0.5	200	5	2000	3	200	20
g		5	3	200	0.15	3	0.4	100	3	1000	2	100	10
500	70	4	2	100	0.10	2	0.3	50	2	500	1.5	50	7
200	40	3	2	50	0.05	1	0.2	40	1.5	400	1.0	20	5
100	30	2	1.5	20	0.03	dr. ap.		30	1.5	300	1.0	10	3
50	20	1	1.0	10	0.02	6	0.2	20	1.0	200	1.0	5	2
20	10	oz		5	0.015	5	0.2	10	1.0	100	0.5	2	1
10	7	10	1.0	2	0.010	4	0.2	5	0.5	50	0.4	1	0.7
5	5	8	0.5	1	0.005	3	0.1	4	0.5	40	0.3	0.5	0.5
2	3	5	0.5	0.5	0.005	2	0.1	3	0.4	30	0.3	0.2	0.3
1	2	4	0.5	0.2	0.0025	1	0.05	2	0.3	20	0.2	0.1	0.2
mg		2	0.3	0.1	0.0020	s. ap.		1	0.2	10	0.2	0.05	0.15
500	1.5	1	0.2	0.05	0.0015	2	0.05	0.5	0.2	5	0.1	0.02	0.10
200	0.7	1/2	0.2	0.02	0.0015	1	0.03	0.4	0.15	4	0.1	0.01	0.05
100	0.5	1/4	0.1	0.01	0.0015			0.3	0.10	3	0.05		
50	0.35	1/8	0.05					0.2	0.10	2	0.05		
20	0.20	1/16	0.05					0.1	0.05	1	0.03		
10	0.15	1/32	0.05					0.05	0.03				
5	0.10	1/64	0.02					0.04	0.025				
2	0.05							0.03	0.025				
1	0.04							0.02	0.020				
								0.01	0.015				
								0.005	0.010				
								0.004	0.008				
								0.003	0.007				
								0.002	0.005				
								0.001	0.005				

straight precision burets. Perhaps the major factors differentiating the quality of such glassware are related to the index mark which defines the contained volume--the quality of the mark, its location, and permanence. The user must set the level of the miniscus to coincide with the plane established by the index by adding or removing small quantities of liquid. He is interested in the quantity of liquid in the vessel when this condition has been satisfied. In the case of precision glassware, the location of the index is established by actual test. In the case of burets, there may be several test points which are subdivided linearly in the marking process. The reference standards are the basis of a variety of glassware which is graded according to the quality of the marking, and the difference between the actual volume contained relative to a particular index and the nominal volume. The useful life of all glassware, including the reference standards depends on breakage and the cost of cleaning.

The present manufacturing processes produce glassware which is in accordance with current specifications. These specifications generally contain both performance and detail requirements. The sales groups favor the detail requirements but when basic manufacturing methods are changed, the ware produced may no longer comply with specifications. This situation is usually resolved by a concentrated effort to change the specification. For example, changing from an etched and filled index to a "fired on" index requires a change in Handbook 44 if the ware is to be acceptable to the state weights and measures officials.

Precision volumetric glassware is basic to the current methods for the preparation of solutions in "wet" chemistry and clinical pathology. Testing of this apparatus for compliance with specifications or for adequacy relative to a particular requirement is now within the capability of most users with one exception. A legal measurement as defined by the regulators requires an artifact which has been calibrated by higher authority. The calibration efforts of NBS exist essentially to support the states weights and measures operations with only occasional requests for calibrations relative to a particular end use. For example, some calibration work directly supports manufacturers quality control systems.

Metal capacity standards, e.g. "slicker plate" containers, cubic foot bottles and provers, are used either singly or in combination to test flow metering devices, or in the calibration of large tanks. The devices are compromises between the properties one would like to have in a standard,

TABLE 6--TYPICAL BASIC TOLERANCES FOR SCALES INDICATING OR RECORDING IN AVOIRDUPOIS UNITS
(Edited, for complete table see NBS Handbook 44, pages 19, 20, 21)

Test load		Maintenance tolerances			Acceptance tolerances		
From	To*						
Ounces avdp.		Grains	Ounces	Pounds	Grains	Ounces	Pounds
0	2	2	------	------	1	------	------
2	4	4	------	------	2	------	------
4	8	8	------	------	4	------	------
8	16	16	------	------	8	------	------
Pounds avdp.							
1	2	25	1/16	0.004	13	1/32	0.002
2	4	------	1/8	.008	------	1/16	.004
4	7	------	3/16	.012	------	3/32	.006
7	10	------	1/4	.016	------	1/8	.008
50	75	------	1	.062	------	1/2	.031
75	100	------	1 1/2	.094	------	3/4	.047
100	150	------	2	.125	------	1	.062
800	1,000	------	14	.875	------	7	.438
1,000 and over		0.1 percent of test load			0.05 percent of test load		

* but not including

BASIC TOLERANCES FOR SPECIAL SCALES INDICATING OR RECORDING IN AVOIRDUPOIS UNITS

Type scale	Maintenance tolerances	Acceptance tolerances
Prescription	0.1 percent of test load	0.1 percent of test load
Jewelers	0.05 percent of test load	0.05 percent of test load
Cream and moisture Test (18 gm load)	0.5 grain	0.3 grain
Animal, livestock, crane, axle-load, hopper (other than grain) and vehicle	0.2 percent of test load	0.1 percent of test load
Railway track scales		
static	0.2 percent of test load	0.1 percent of test load
uncoupled in-motion	0.2 percent of test load	0.2 percent of test load
Wheel load weighers	3.0 percent of test load	2.0 percent of test load
Railway coupled in-motion (100 car test train)	Acceptance and Maintenance Tolerances a) Difference between motion weight and static weight of train shall not exceed 0.2 percent. b) Difference between motion weight and static weight on 100 car weights shall not exceed. 1) 0.2 percent on 30 cars 2) 0.5 percent on 5 cars 3) 1.0 percent on any car	

and the ability to handle the standard in use. "Slicker plate" standards use a flat glass plate on a flat surface of the container to define the contained volume. Such artifacts are usually of heavy construction and are limited in size to at most a few gallons. Capacity standards are of lighter construction, the location of the liquid level in the neck being inferred from the liquid level in a parallel glass tube with reference to an appropriate linear scale mounted on the vessel. The calibration may consist of determining the volume relative to the scale reading, or the adjustment of the scale to a position appropriate to a nominal volume and then determine the "over" and "under" amounts relative to appropriate scale graduations. There is no formal hierarchy of capacity standards. The manufacturers, of which there are only a few, can furnish calibrated standards adequate for most requirements. In some specific uses, such as in the petroleum industry, the items are routinely sent to NBS for calibration.

Reference standards for density measurements include picnometers, reference fluids, solid objects of measured density, and calibrated hydrometers. Hydrometer sensitivity to change in density is determined by the ratio of the cross sectional area of the stem to the displacement volume of the bulb, and, consequently, the instruments are fragile. A high quality hydrometer has a hand marked scale permanently enclosed and anchored in the stem. The calibration is for a given liquid at a specified temperature. Corrections are necessary for other liquids (surface tension correction) and other temperatures.

2.3.2 The Measurement Process

A measurement process includes the instrument, and all of the measurement details including preparation of material, making the observations, supplementing data, data analysis, and interpretation. The NBS measurement processes for mass, volume and density are sufficiently well characterized that the uncertainty statements are based on quantitative values for random and systematic error which are based on large collections of data reflecting both current and past performance. Typical measurement uncertainties are shown in Table 7.

It has been the intent to completely describe the various measurement processes in the literature to demonstrate the measurement capabilities which can be achieved with currently available instrumentation and procedures. This is not to suggest that all measurements should be made according to these published techniques but rather to identify the magnitude of variability from various sources which the user must evaluate relative to the manner in which he intends to use his result. Ultimately, the uncertainty associated with his result is based on three factors, the systematic error introduced into his process by NBS calibrated standards, and the systematic error and random error associated with his process. If one or both of the latter factors are the predominant terms in his uncertainty, technically there is little need for direct contact with NBS. For example, the Class C tolerance for 1 kg from Table 5 is 100 mg.

TABLE 7--TYPICAL MEASUREMENT UNCERTAINTIES

Mass	
Level	Uncertainty
50 000 lb	± .2 lb
50 lb	± .000 03 lb
1 kg	± .11 mg
1 g	± .003 mg
1 mg	± .000 5 mg
Large Capacity Measures	
Test Tank 3 000 liters*	± 1 liter
100 gal prover	± .000 20 gal
30 gal prover	± .000 33 gal
5 gal "Slicker Plate"	± .000 31 gal
Displacement Volume	
Aluminum Kg	360 ± .000 5 cm
Volumetric Glassware	
1 Liter Flask	± .1 cm
50 ml Buret	± .01 cm
10 ml Buret	± .005 cm
25 ml to 50 ml Transfer Pipet	± .01 cm
Hydrometers	
API Scale Range 10 to 21 in .1 API	± .92 API
Specific Gravity Scale Division .0005	± .0001
Alcoholometer 56-72 %vol. in .1% Divisions	± .02%

*The recommended SI unit for volume is m^3. In practice, however, the term "liter" is used for one cubic decimeter, and milliliter (ml) for one cm^3.

The uncertainty associated with a calibration of the same weight from Table 7 is .11 mg. If compliance with Class C is adequate for his intended usage, the esthetics of an NBS calibration is a costly luxury. Nonetheless, for reasons associated with compliance or conformance, it may be necessary for the user to have standards calibrated periodically at NBS.

2.4 Dissemination and Enforcement Network

There are a number of networks more or less loosely interlocked. By virtue of the embodiment of the mass unit in artifact standards, NBS is the focal point of the network concerned with the dissemination of the unit. The dissemination of methods, or the "how to" of measurement has in the past been the literature of the various disciplines, i.e. chemistry, clinical pathology, etc. The most widely recognized enforcement network is that associated with equity in trade, a responsibility delegated to the individual states. Other enforcement networks have been established by various segments of the government such as the Department of Defense, the Internal Revenue Service, the Nuclear Regulatory Commission and others. A different type of enforcement network is that associated with voluntary or consensus standards, mostly concerned with the "how to" of measurement. With the emergence of the concept of measurement as a production process, a concept which concentrates on the adequacy of field measurements relative to the intended usage, the role of the Mass and Volume Section relative to these various networks is quite complex.

2.4.1 Central Standards Authorities

The units, as defined by the Convention of the Metre and the Committee Generale dis Poids and Mesures, were declared legally permissible in the U.S. by Congressional action in 1866. This action was followed in 1893 by the Mendenhall Order in which the Secretary of the Treasury announced that the International prototype standards for mass and length would be regarded as fundamental standards. The practical mass unit in the U.S. is embodied in a pair of nichrome kilograms. In the dissemination of the unit, the Mass and Volume section is not concerned with the conformance of the reference mass standards to any specification requirement for construction or adjustment tolerance. The perceived role of the Mass and Volume section is to establish mass values for any object sufficiently stable in mass to warrant the calibration effort. The calibrated objects, in turn, provide fixed reference points on a hypothetical mass scale such that others can adjust working weights to whatever tolerance desired.

A second class of de facto central standard authorities have been established by various levels of the Federal Government. Of these, the two of largest impact are the Federal Procurement Specification, as issued by the General Services Administration, and the regulations of the Department of Defense, previously mentioned. In the former case, GSA acts as a mediator between the federal user and the supplier to obtain products which are adequate for the intended use. Federal specifications, unlike voluntary standards, address the quality control aspects of procurement and clearly delineate the basis on which a product will be accepted or rejected. The DoD regulations with regard to measurements also stem from the generic problem of quality control with respect to military procurement.

2.4.2 State and Local Offices of Weights and Measures

One of the largest central authorities is the National Conference of Weights and Measures, an organization of state and local weights and measures officials. The historical tie between NBS and NCWM is long standing. The Constitution of the United States, Article I, Section 8, empowers Congress ". . . . to fix the standards of weights and measures." Congress has chosen to allow the individual states to perform this function. However, as early as 1836, Congress, in a joint resolution, directed the Treasury to fabricate standards for customhouses and states and to establish an Office of Weights. In 1901, this office was designated as the National Bureau of Standards. As the nation grew, a need was felt for a closer coordination of the state activities and the National Bureau of Standards met with state officials to discuss "protecting the public against short weight or measure." A dialogue developed which is now carried out through the agency of the National Conference of Weights and Measures.

A typical state Office of Weights and Measures is a unit in the state Department of Agriculture although it may be under the Department of Law and Public Safety (New Jersey), Department of Labor (Rhode Island), Department of Commerce (Arkansas), or elsewhere. It is headed by an appointed state official and has a staff of inspectors which varies according to the size of the state by at most a few dozen.

Within the state, various local jurisdictions may also have weights and measures authority. In all, there are a total of 775 offices and a total of approximately 3000 officials. Besides controlling the weights and measures activities of retail trade, depending on the state's industry, anhydrous ammonia (fertilizer) or lumber or grain may be of official interest. Recently, under both the Fair Packaging and Labeling Act of 1966 and the general use of consumerism, these offices are increasingly involved in consumer protection in areas remote from classical weights and measures activities.

In 1965 Congress appropriated funds to equip state laboratories with standards whose values were known with uncertainties smaller than those needed to support the tolerances mentioned in section 2.3. This program, managed by the NBS Office of Weights and Measures but calling on other NBS resources, has to date delivered 42 of the 53 sets of artifacts and instruments needed by U.S. states, territories, and the District of Columbia.

Provisions of this law call for the states as a prerequisite for the award to supply a suitable laboratory and trained metrologists. In the absence of educational facilities noted before, a training program has been established to provide initial and continuing education for weights and measures officials and technicians. Only the State of California has a comprehensive in-state program and less than 6 states have a full time training officer, although some twenty states have a program of some sort.

The state weights and measures offices provide a calibration service for mass which is accessible to the general user community in addition to performing such services for their own inspection operations. The NBS interfaces with this system only through contact with certain users who have tried these services with inadequate results. The impression is that the service is seldom used where the uncertainty of the measurement must be known. The service is a convenient way to comply with certain imposed requirements, however, with few exceptions, the facilities are not oriented to end use problems.

2.4.3 Standards and Testing Laboratories and Services

Weight and balance manufacturers offer calibration services, i.e. tests for compliance with or adjustment to comply with, tolerance specifications for both weight sets and weights internal to certain balances, with reports which are acceptable for most requirements. The world's largest supplier of precision balances (by far in excess of 50% of the market) relies on NBS for the maintenance of their standards. Maintenance and test of weighing equipment is usually done by separate organizational units in large facilities, or by service contracts with reputable repair service organizations, e.g., those made available by the instrument manufacturer. Metal volumetric apparatus manufacturers, of which there are only a few, provide both refurbishing services and calibration services.

The production of precision glassware is controlled at the manufacturing level by the same methods as used in NBS calibration. The manufacturer guarantees compliance with federal specifications. These specifications, in turn, can be used by anyone in the procurement of apparatus. GSA has established procedures to monitor the quality of the products. Considering the normal breakage rate and the increasing use of "throw away" apparatus, there is little motivation for testing services to calibrate apparatus.

Attempts to interest independent testing laboratories in providing calibration services, particularly with regard to hydrometers, have not been successful. These laboratories are primarily concerned with performing specification tests according to procedures prescribed by ASTM, The American Concrete Institute, The American Welding Society, etc. Either the volume of work is too small relative to the cost of establishing a service, or the nature of the industry using the instruments is such that the risk is too large with respect to the profits. Of approximately 130 members of the American Council of Independent Laboratories, less than ten list weighing as a particular specialty.

There are a few companies, some worldwide, who provide calibration services to the petroleum industry. The services, consisting of meter and tank calibrations, contract directly with the oil companies. It is presumed that these companies exist because of the necessity of the oil companies to meet various regulatory requirements, in which case it is less expensive to contract for the services than to establish their own service organizations. By far, most of the large oil and pipeline companies have their own service organizations.

The primary function of the echelon calibration laboratories of the Department of Defense (DoD) is to provide calibration and testing facilities to the various branches of the department. With few exceptions, e.g. government owned equipment and certain support to defense contractors, these services are not generally available to the user community at large. Cooperation with local weights and measures officials, and with local industry is largely dependent upon the work load and the attitude of the local command. Similar services are provided to the National Aeronautics and Space Administration contractors through a series of contract operated facilities. All of the top echelon laboratories in these two networks are participants in the Mass Measurement Assurance Program.

2.4.4 Regulatory Agencies

Regulatory agencies are concerned with the application of measurement technology to certain specific measurements. Generally, the uncertainty associated with the measurement result is only one factor in judging the adequacy of the measurement. Regulatory agencies view measurements in one of two ways. One view typical of the older agencies is defensive in nature. In this view, in the event of prosecution, the use of NBS calibrated standards is considered to be a means to divert attention from the measurement detail, i.e. the adequacy of the measurement is established by "traceability" of the unit. Requirements established by the newer regulatory agencies tend to emphasize the uncertainty of the measurement result relative to the manner in which the result is to be used, i.e. the adequacy of the measurement is established by "traceability" of the measurement. In this case the adequacy of the measurement result is established by careful analysis of the entire process including standards, methods, control of systematic errors, etc. In these cases NBS involvement is primarily consultation. The standards may or may not be NBS calibrated.

State weights and measures regulations are typical of the former viewpoint mentioned above. Regulatory agencies which are concerned with limiting concentrations of harmful substances, such as the Environmental Protection Agency and the Nuclear Regulatory Commission, are examples of the latter viewpoint. The Nuclear Regulatory agencies have worked closely with the Mass and Volume Section since special nuclear materials accounting procedures require and use both mass and volume measurements using state-of-the-art techniques.

The Mass and Volume Section has been aggressive in encouraging the regulatory agencies to change from a "traceability of the unit" concept of measurement to a "traceability of the measurement" concept. The following examples are illustrative of the nature of the transition.

The recognition of adequacy relative to the manner in which the result is to be used is illustrated by the work with the Internal Revenue Service's Division of Alcohol, Tobacco and Firearms Control. The function is the control of the use of ethyl alcohol. All legal ethyl alcohol is manufactured under bond. No matter what the use of this alcohol, be it beverage, medicinal, cosmetics, or any other purpose, it is taxed at the time of withdrawal from bond on the basis of equivalent 100 proof gallons (i.e. a 100 proof mixture is a fifty percent mixture with water). The determination of proof at the time of withdrawal is a consensus between the IRS, the supplier and the purchaser. The measurements are made with "proof" hydrometers. From the IRS viewpoint, the required precision of measurement is established by the proof increments in the tax tables. Modification of these procedures are used in the case of wine and similar alcoholic beverages. There is a mechanism for tax rebate where ethyl alcohol is not used as a beverage. Over the years under the guidance of NBS, IRS has established a calibration service adequate to support these activities. On occasion NBS acts as a consultant in regard to techniques and basic data. The producers and purchasers of the material, however, rely on the NBS hydrometer calibration services.

Finally, the work on voluntary standards relative to the nuclear industry (Institute for Nuclear Materials Management and the Nuclear Regulatory Commission) is an example of an area where perceived measurement requirements are beyond the capabilities of traditional weights and measures regulatory procedures. In this case NBS has been involved in helping both the regulated and the regulator to (1) quantify the requirement and (2) understand the concept of measurement as a production process and measurement assurance and (3) ways and means to improve measurement techniques in both mass and volume measurements.

2.5 Organizational Input-Output Matrix

In an attempt to more clearly define the morphology of this measurement system, we have created an Input-Output Measurements Transactions Matrix. This matrix presents in compact form all we have been able to deduce about the interconnections in our system and it justifies careful study.

Along the upper and left hand border of the matrix you will find twenty-five organizations or groups which have been identified as potential users or suppliers of measurement data in the field of mass, volume, and density. Many of these are both users and suppliers. In their role as suppliers, they appear on the left, as users along the top border.

By survey, by interview, by a retrospective study of NBS calibration records, and by the experience of the authors, the interactions between these elements of the system were estimated and quantified according to the code at the bottom. The interactions were examined for magnitude, derivative of the magnitude, and importance to the system's well-being. Particular care was exercised to maintain a uniform scale of values, particularly relative magnitudes. It is realized that this scale reflects a degree of subjective judgment even though utilizing the individual opinions of several knowledgeable people independently.

First, as a supplier of measurement information, we note, not surprisingly since our charge is measurement, that NBS interacts strongly with most of the other elements. Only a few industries are blank. These are industries where mass, volume, and density measurements are not frequently made. Our interactions with the knowledge community, for example, is strong, stable, important and moderately successful.

NBS as a rule seems to listen fairly well to what people have to say. Except for the knowledge community and the upper echelons of the standards bodies, these transactions are largely assessments of perceived needs.

3. IMPACT, STATUS AND TRENDS OF MEASUREMENT SYSTEM

The national measurement system for mass, volume and density, being defined as the totality of all such measurement processes from the defining standards to the point of ultimate usage, is so vast that further subdivision is necessary before one can address impact, status and trends. One can identify three subsystems on the basis of the manner in which the results are used, one relating to the determination of quantity of material; one relating to matters concerning regulation and quality control; and one relating to properties of objects or materials. While these systems are not completely independent, the structures reflect practical boundary conditions associated with the desired result. Within this structure, the impact, status and trends of the subsystem can only be discussed relative to the desired result. All mass, volume and density measurements are merely one of many elements involved in a variety of specific endeavors. In at least two of the above subsystems success is not limited by the precision of measurement, but rather by social and economic judgments.

3.1 Impact of Measurements

3.1.1 Applications

Every legal exchange of material, be it at the local market or in the world trade arena, has two elements, the price and the quantity of material. The same is also true in the exchange of products except where the product is marketed as a unit. As a consequence, there is at least one, and in some cases many, determinations of quantity for each transaction, and the cost of measurement is a part of the cost of doing business. Order in the marketplace is contingent on the acceptance of uniform measurement procedures. The major constraints on the resulting measurement processes are the cost of measurement relative to the cost of the material, the constancy of the mass, or volume, of the material over the interval between shipment and receipt, and the ability to make adequate measurements in the environments associated with custody exchange. In all cases the measurements must be within the capabilities of the available personnel and be defendable in court, that is, in accordance with a consensus agreement and relative to an acceptable artifact standard. Direct NBS involvement with this subsystem is providing access to artifact standards which are accepted as authoritative. Indirect involvement by NBS is associated with the availability of instrumentation and measurement methods.

The subsystem concerned with quantity measurements is very large and diverse. It includes those activities in which the end product is formulated by recipe, including the preparation of solutions in the chemistry laboratory to the bulk production of paints, acids, beverages and other liquid

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR MASS, VOLUME, & DENSITY

SUPPLIERS \ USERS	1 KNOWLEDGE COMMUNITY (Science, Education, Prof. Soc. & Publ.)	2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	3 DOCUMENTARY STANDARDS ORGANIZATIONS	4 INSTRUMENTATION INDUSTRY (SIC Major Gp 38)	5 NBS	6 OTHER U.S. NATIONAL STANDARDS AUTHORITIES	7 STATE & LOCAL OFFICES OF WEIGHTS & MEASURES (OWM's)	8 STANDARDS & TESTING LABORATORIES AND SERVICES	9 REGULATORY AGENCIES (excl. OWM's)	10 DEPARTMENT OF DEFENSE (excl. Stds. Labs)	11 CIVILIAN FEDERAL GOVT AGENCIES (exc. Stds Labs & Reg.Ag.)	12 STATE & LOCAL GOV'T AGENCIES (exc. OWM's & Reg. Ag.)	13 INDUSTRIAL TRADE ASSOCIATIONS	14 AGRICULTURE, FORESTRY FISHING; MINING (SIC Div. A & B)	15 CONSTRUCTION (SIC Div. C)	16 FOOD/TEXTILE/LBR/PAPER/LEATHER/ETC. (SIC 20-26, 31)	17 CHEM/PETROL/RUBBER/STONE/CLAY/GLASS... (SIC 28-30, 32)	18 PRIMARY & FAB. METAL PRODUCTS (SIC 33-34, 391)	19 MACHINERY EXCEPT ELECTRICAL (SIC Major Gp 35)	20 ELECTRIC AND ELECTRONIC EQPMT (SIC Major Gp 36)	21 TRANSPORTATION EQUIPMENT (SIC Major Gp 37)	22 TRANSPORTATION & PUBLIC UTILITIES (SIC Div. E)	23 TRADE/INS/FIN/REAL EST/PERS SVCS/PRINT (SIC F-H, bal I, 27)	24 HEALTH SERVICES (SIC Major Gp 80)	25 GENERAL PUBLIC
1 KNOWLEDGE COMMUNITY (Science, Education, Prof. Soc. & Publ.)	1 · 2	3 2 2	2 3 1 2 ·	2 2 2 N ·	4 1 3 2 ·			1	2 2 1 2 ·	2 2 3 N ·	1			1			2 1 2		2 2 1					2 1 1 2 ·	
2 INTERNATIONAL METROLOGICAL ORGANIZATIONS	1	4 3 3 2 ·	3 3 3 2 ·	2 4 2 4 ·	3 2 3 4 ·		2 4 1 4 ·												2 4 2 4 ·						
3 DOCUMENTARY STANDARDIZATION ORGANIZATIONS	1	3 1 4 2 ·	2 1 2 2 ·	3 1 3 2 ·	2 · 3 3 ·		3 1 2	4 · 3	1	1 1 1 1 ·	1		1	X		2 · 1	2 · 1		3 1 3 2 ·		1	1	2	2 · 1	1
4 INSTRUMENTATION INDUSTRY (SIC Major Gp 38)	1 · 2	2 2 1 3 ·	2 1 2	1 · 3	2 1 3 2 ·		2 · 1 2 ·	2 · 3 2 ·	2 · 2 2 ·	2 · 2 2 ·	1 · 2	1		1 · 1		2 · 3 2 ·	2 · 2 2 ·	1	2	1	2	1	3 · 1	3 · 3	2
5 NBS	4 1 4	4 1 4 3 ·	2 1 3	2 1 2 1 ·	4 2 3		4 1 4 2 ·	2 · 2	3 1 3	1 · 2 N ·	2 · 1		2 · 1 1 ·	2 · 2 1 ·		2 · 1	2 · 2 1 ·	1	2 · 2 1 ·					1 · 2 N ·	
6 OTHER U.S. NATIONAL STANDARDS AUTHORITIES																									
7 STATE & LOCAL OFFICES OF WEIGHTS & MEASURES (OWM's)		2 2 1 1 ·	2 1 2 1 ·	3 1 2 2 R	4 1 4 · R		4 · 3	2 1 2	1	1		3 1 3 1 ·		2	1	3 1 4 2 ·	1		3 1 3 2 R		1	3	4 · 4 1 ·		4 1 3 1 ·
8 STANDARDS & TESTING LABORATORIES AND SERVICES			1 · 1	1 · 2 · R	2 · 2 · R			2 · 2		3	1 · 3	1		1			1	2	1 · R	1	1		1	2 · 2 1 ·	
9 REGULATORY AGENCIES (excl. OWM's)			1	1 · R				1 · R	3				1 · R	1 · R		3 1 3 1 R	3 1 2 · R	1 · R	1 · R		3 1 2 1 R	3 1 3 1 R	2 · R	3 1 2 1 R	1 · R
10 DEPARTMENT OF DEFENSE (excl. Stds. Labs)	1		1 1 1 1 ·	2 1 2 N R			1 · R	3 · R		1 · 3							1 · R	1 · R	2 1 3 N ·		1 · R		1 · R	1 · R	
11 CIVILIAN FEDERAL GOV'T AGENCIES (excl. Stds. Labs & Reg. Ag.)	2 1 1 N ·	2 2 2 2 ·	1	2 · 1 · R	2 · 2 · R			3 · R			1 1 3	1 · R			1 · R	1 · R	1 · R	1 · R	2 · 1		1 · R		1 · R	1 · R	1
12 STATE & LOCAL GOVERNMENT AGENCIES (exc. OWM's & Reg. Ag.)							2 · R	1 · R				3			1 · R			1 · R	1 · R			1 · R	1 · R		
13 INDUSTRIAL TRADE ASSOCIATIONS		2 2 1 2 ·	2 1 3 1 ·		2 1 2 · R			2 1 2 · R	2 2 3 1 ·				1 · 2 1 ·			2			3				3		1
14 AGRICULTURE, FORESTRY FISHING; MINING (SIC Div. A & B)	1		2 · 2		3 · 1 · R		2 · R	1 · R				1	1	1	1 · R	X	4	4	1 · R		1 · R	? · R	2		2
15 CONSTRUCTION (SIC Div. C)				1 · R			1 · R	1 · R		1	1	2		1	1	1	1	1 · R				2	1		
16 FOOD/TOB/TEXTILE/APPAREL/LBR/FURN/PAPER/LEATHER (SIC 20-26, 31)			1	1 · R			1 · R	2 · 1 · R	2 · 1	1	1		2 · 1	1		1			2 · R			1	3	1	3
17 CHEM/PETROL/RUBBER/PLASTICS/STONE/CLAY/GLASS (SIC 28-30, 32)	1	2 2 1 2 ·	2 · 2	1 · R	3 · 2 1 R			2 · R	1	2	1		2 · 1	3	3	1	2 · 4	1 · R	1 · R	1	1 · R	2	1	3	2
18 PRIMARY & FAB. METAL PRODUCTS (SIC 33-34, 391)			1				1	1 · R	1	2	1	1		1	1	1	1	3	1			1	2		1
19 MACHINERY, EXCEPT ELECTRICAL (SIC Major Gp 35)	1	2	3	3	3 · R		2	2	1	2	2	1		1	2	2	2	1	1	1	2	1	1	2	4
20 ELECTRIC AND ELECTRONIC EQPMT (SIC Major Gp 36)								1 · R												2					1
21 TRANSPORTATION EQUIPMENT (SIC Major Gp 37)			2 · 2					1 · R	2 2 2 2 ·	1	1	1	2 1 2 1 R	1	1		1		1 · R		2	2 · 2 1 ·	1		2
22 TRANSPORTATION & PUBLIC UTILITIES (SIC Div. E)			1	1 · R			3 · R		2	1	1	2		1	2	2	2	2	2	1	3	1	2 1 3	1	2 1 3
23 TRADE/INS/FIN/REAL EST/PERS SVCS/PRINT-PUB (SIC F-H, bal. I, 27)			2	3 · R			1 · R		1	1	1	2	3 · R	2	2 · R	1 · R	1 · R	1	3 · R	1	1	2	4	1	4 2 4 1 ·
24 HEALTH SERVICES (SIC Major Gp 80)	1			2 · 2					3 1 2 1 ·	1	2 1 1						1 · R						2 · R	4	4 1 2 1 ·
25 GENERAL PUBLIC				1 · R			3 1 3 1 R		3 1 2 1 R			1 · R	1 · R	1 · R				1 · R	1 · R	1 · R	1 · R	1 · 2 · R	1 · 4 1 R	1 · 1 1 ·	1 · 4 1 ·

KEY TO MATRIX ENTRIES

C - IMPORTANCE OF TRANSACTIONS

1 = Purely convenience
2 = Strongly desirable
3 = No real alternatives
4 = Essential

D - (IN)ADEQUACY OF SERVICES

0 = No improvements needed
1 = Could be improved
2 = Marginal
3 = Serious deficiencies
4 = Out of control

USERS

C	D
A	
B	R

B - RATE OF CHANGE

N = Declining
0 = Stable
2 = Growing
4 = Growing explosively

A - MAGNITUDE OF TRANSACTIONS

0 = Trivial
1 = Minor
2 = Moderate
3 = Important
4 = Major

R = Flow of requirements info dominates

? = Unknown, X = Not studied, Blank = 0

products. These measurements are subject to essentially the same constraints as those associated with the exchange of goods, except that the cost of measurement is established relative to the quality and market value of the end product. The NBS role, however, is essentially the same.

The subsystem associated with quality control and regulation is also a diverse subsystem with a different set of constraints. A characteristic of such measurements is that the measurement effort is defensive rather than productive. The concern is generally whether the measurements are adequate for the purpose, or whether the product does or will conform to the appropriate specification. Decisions concerning the details of the measurement process are relative to risk. The generation of the elements of the subsystem arise from social pressures, the need for product acceptance, the need for national defense, and the health and welfare of the nation. Three subelements, discussed below, illustrate the NBS role with regard to this subsystem.

Perhaps the oldest of the elements is that associated with weights and measures--the states weights and measures activities. Constraints on the system are those associated with the legality of measurement, the need for viability, the need for simplicity, i.e. parties involved must understand the detail, and the resulting procedures must be within the capabilities of the available personnel. The net results in a labor intensive system which operates most effectively at the consumer level, and with great difficulty in interactions with capital intensive organizations. NBS has supported this system by providing well calibrated reference standards for mass and volume, and good instrumentation. By and large, this equipment supports an echelon of field standards.

A second element associated with quality control is the system established by the Department of Defense. One of the unique characteristics of this element is that the established system at any given time must be capable of immediate expansion, thus it is very similar to the weights and measures elements, with echelons of calibration laboratories. Each laboratory maintains standards of mass and a measurement capability appropriate to the echelon, partly to support the various commands, and partly in anticipation of immediate expansion. Visibility is in the form of calibration intervals and inspection "marks." One can argue the cost effectiveness of such a system, however, in the event of rapid expansion, a simple inspection system based on manufacturer's specification which can be maintained with minimum training is better than nothing. A more complex system, based on the premise that completely trained metrologists will be available, would tend to collapse from the lack of adequate manpower. There are other ramifications, previously discussed relating to "due care." The element is large, and through inertia, the features have been adopted in other disciplines, i.e. American College of Clinical Pathology.

The third element consists of the measurement processes associated with regulation other than weights and measures. Some of these systems, those associated normally with compliance, have features from both the weights and measures, and the military systems. All are concerned with legality of measurement. The one component with which the Mass and Volume Section has the most direct input is associated with the control of nuclear material. In this case, the source of detail specification is the regulated facility. The regulator, usually the Nuclear Regulatory Commission, generally provides only guidelines and goals. In the process of establishing a facility, detailed procedures are submitted for review and approval. The collection of approved procedures eventually becomes the operation manual. The role of the inspector is that of enforcing compliance with the approved procedures. This approach is also being considered in regulations concerning the introduction of pollutants into the atmosphere. In this element, the people being regulated have considerably more interest in measurement detail. The decisions, however, are theirs relative to the economics of measurement, including the maintenance of the system, and the announced goals established by the regulator. Generally, the desired precision of measurement is somewhat beyond that associated with either weights measures and military procurement with respect to mass and volume.

The last subsystem, those concerned with the properties of objects or materials, is also a large diverse system. The elements of this system are mostly concerned with adequacy of the result of measurement relative to a particular requirement, that is, the uncertainty associated with the measurement result as compared to functional limits related to the task at hand. In essence these are the processes associated with the product which in turn are monitored by the various quality control and regulatory systems, if such exist. These measurement processes range from those associated with the constancy of the defining mass unit, to the determination of the density of dislocation free single crystal silicon, to the support of force and pressure measurements. Some of these processes are concerned with properties of special materials, such as the density of crude oil and refined petroleum products, the results being the basis of measurement systems relating to both regulation and commerce. Measurement processes in this element are usually free of all constraints other than that of producing adequate results in the most economical manner.

3.1.2 Economic Impacts

3.1.2.1 Processes Relating to Quantities of Material

In a free economy one factor contributing to the stability of the marketplace is the ability to make adequate measurements of quantity. The system that has evolved places NBS in the role of higher authority with regard to measurement standards while generally reserving the right for decisions with regard to measurement detail. Considering the intricacies of the judgment factors this perhaps is as it should be. There are adequate techniques for the measurements which have to be made. The dollar volume associated with exchange of material is a significant fraction of the gross national product. Yet direct NBS interaction is minuscule. On the other hand, this subsystem is not receptive to attempts to establish self-sufficiency. Change in the cost of materials or changes in regulatory requirements are the major motivating factors for improvement. It is clear that NBS visibility is desired, and on occasion aggressively pursued, yet direct economic benefits remain intangible.

3.1.2.2 Processes Associated With Quality Control and Regulation

In both cases, the investment in measurement processes is associated with the entrepreneur's assessment of risk and not by the available precision of measurement. This follows from the fact that neither function exists until such time that there are facilities capable of production of parts or products more or less adequate for the introduced usage. Professional Quality Control people and inspectors are not generally trained metrologists. In both cases the assessment of the effectiveness of the efforts are measured in terms of compliance with the established plan rather than the effectiveness of the effort relative to what the effort is expected to accomplish. In the interface between the producer and the consumer, and between the regulator and the regulated, the visibility of NBS seems to be highly desired, particularly in the form of calibrated standards. On occasion, NBS calibration is used to resolve disputes in lieu of other legal action. As before, the cost of the NBS services provided is minuscule relative to the value of the goods subject to quality control and regulation. Again, this subsystem is not receptive to efforts directed toward establishing self-sufficiency. Aggressive attempts to improve the utilization of both methods and instrumentation have not only been resisted but met with animosity. In contrast to the previous subsystem, it is felt that this area would welcome NBS expansion of routine calibrations, not from the standpoint of product improvement, but from the resulting simplification of paperwork requirements.

3.1.2.3 Processes Associated With Properties of Objects or Materials

The processes in which mass, as an intrinsic property of a material or an object is of interest require the ultimate in mass measurement capabilities, e.g., the constancy of the defining artifacts and the density of single crystal silicon. These processes are without exception within the scientific community and in support of specific scientific goals, e.g., the determination of Avagadro's Number, the realization of certain electrical quantities, the gas constant, the universal gravitational constant and the like. While a substantial part of the total effort in mass, volume and density measurements at NBS has been in support of these efforts, the direct economic impact resulting from this effort cannot be measured at this point in time. This does not mean that these efforts are totally devoid of such benefit. The emergence of new procedures and reference materials as a result of this work reduces the cost of certain types of measurements, e.g., the "solid object" density standard. In the course of this work, the efforts devoted to understanding the philosophies of measurement, in addition to development of procedures, have the greatest potential for economic impact on the entire measurement community.

3.1.3 Social Impacts

The greatest impact of the Mass, Volume, and Density system to the average citizen lies in the area of retail trade. Thanks to a functioning weights and measures enforcement system, the citizen in his daily life can rest assured that he can base his purchasing decisions on posted price-per-unit quantity. It is not necessary to search for the gas station giving the largest gallon and prepackaged foods can be bought without qualm. Yet, this state of affairs is not without cost. In 1972-73, the State of California reported litigation costs of over $100,000 in a single "short weight" case. In the same year, the State of New Jersey reported 1,321 citizen complaints of which 1,183 were successfully prosecuted with $54,750 in penalties assessed. The State of West Virginia reports over $60,000 recovered for consumers. Most of the populace have some knowledge of the general concepts of these measurements, and a large percentage are involved in some degree through such things as keeping track of body weight, procuring supplies and materials, and formulating various recipes. Marketing practices have changed substantially over the past two decades, however, and with the preponderance of prepared and prepacked foods, pricing scales interfaced with computers, etc., the populace must rely largely on the system to look after his interests. Systems, on the other hand, tend to be inflexible, bureaucratic and not generally sensitive to individual problems. Achieving and maintaining order in the marketplaces through a bureaucratic structure is not without cost. The degree of uniformity in available products and prices across the country is one of the characteristics noted by many foreign visitors.

Sizable as these numbers are, they are a vanishingly small fraction of total sales. It is impossible to overstate the benign influence of the weights and measures activity on social order. In an era where alienation from government is rampant, the citizen can see, if only by the seals on the scales in the supermarket and on the gas pumps, that his local government is protecting his interests.

The rest of the system impacts only lightly on the citizen. He does have an interest in the health services delivery system and his spokesmen are expressing a legitimate concern over the adequacy of the laboratory work. These tests, upon which a great deal of diagnosis is based, depend on elaborate automatic volume measuring equipment whose accuracy is largely unproved. Efforts are now under way to examine this part of the system.

A second social impact which influences measurements relates to inflexibility of large bureaucratic structures which are designed to address certain specific problems. Such structures are generally established on the basis of a set of conditions at some point in time. Continually changing technology, marketing procedures and the like may result in more effective ways to achieve the desired result, or may make obsolete the problems which originally established the bureaucracy. In these cases, the advantages of changing the system must be compared with the disadvantages associated with disrupting the work force. Generally, if the measurements are not vital and if the costs are accepted as a part of business, the work force is preserved. Because mass, volume and density measurements are so widely used, and because the measurement techniques are not difficult, there are a number of areas where present practices are continued as the result of a social decision rather than a technological one.

3.2 Status and Trends of the System

The precision of measurement has now reached a point where the ability to transfer the unit to other objects is limited by the characteristics of the defining artifact and the characteristics of the weighing environment. The longevity of the present defining artifact is contingent on the resolution of these problems. In terms of the national measurement system, the questions are largely academic.

One cannot seriously doubt that the national measurement system is producing results adequate for the requirements as perceived. Problems which are brought to NBS are seldom associated with the ability to measure but with (A) inadequate definition of the measurement requirement relative to the task at hand and (B) inadequate understanding of the measurement process details. These problems are equally prevalent in science, industry and commerce. For modest measurement requirements, these factors do not necessarily affect the adequacy of the result relative to its intended use. The efficiency of the measurement effort, however, decreases significantly, e.g. more measurement effort is expended than the task requires, or measurements are made which are unrelated to the basic task.

The parts of the system which are satisfied with the measurement results currently obtained are essentially static. In many cases, there is little motivation for change. Where measurements are reasonably important relative to the task at hand the trend is to eliminate or at least reduce operator judgment, e.g. digital indications, sometimes with computer interfacing, and completely automated processes such as in the packaging industry.

One factor which will influence the direction of the system is the political-economic pressures for increased governmental intervention in the area of standardization and enforcement of standards. These forces, typified by the International Organization for Legal Metrology, would bring a very large fraction of the measurement system under surveillance. The legalization of measurement has two basic limitations. In those situations where adequate results cannot be obtained by "legal" means, the system will have to be circumvented. The laboratories supporting legal metrology (e.g. state weights and measures offices) cannot provide guidance without getting into a conflict-of-interest situation. That is, the regulator cannot provide measurement guidance without assuming responsibility for the adequacy of the result if, at some later time, he must pass judgment on the legality of the resulting measurement process.

4. SURVEY OF NBS SERVICES

4.1 The Past

A brief history of the Mass and Volume Section is presented in Appendix B. For a discussion of the past NBS services in the area of mass, volume and density measurements, there are two time periods of importance, one extending from the establishment of NBS to approximately 1960, and one from 1960 to the present. In the earlier period, services provided were essentially calibration of weights for manufacturers, and for the states' weights and measures organizations. A considerable effort was made in the formulation of specifications for mass standards. A quasi-regulatory function was generated by limiting items acceptable for calibration to those which complied with the specification. These specifications reflected the metrologist view of "what the user should have" rather than a careful assessment of what was actually needed.

Work in the latter part of the period, i.e. studies of the response of a balance to thermal air currents, the development of a 50 lb balance for the states' laboratories, and the initial work on high precision kilogram balances, was instrumental in causing the change in service provided. Typical of this era was the acceptance of the validity of a measurement based on the reputation of the person who made the measurement and, in the interest of not being wrong, error estimates were conservative. This was also a period in which the charges for calibration were not retained by NBS, but returned to the Treasury. As a consequence, calibration was routinized with frequent waiver of fees on the basis of need. There was essentially no communication between NBS and the ultimate user of the calibrated items.

The latter era started with the general acceptance of the then new constant load single pan balance. This gave the user a precision of measurement equal to, and in some cases better than, that available at NBS. Conservative individual estimates of the area of doubt associated with calibration results were no longer acceptable. This in essence, forced a re-evaluation of the services provided by NBS.

Changes in services evolved around the idea that in a given facility, a measurement process is essentially a production process. While the objects after measurement and the results pass on to others, the measurement process remains and in a sense is a capital investment. One can utilize statistical techniques to evaluate the process, and to establish quantitative parameters which describe its performance. These parameters are the basis for realistic uncertainty statements and in turn are the basis for judgments concerning the adequacy of the results relative to the intended usage, the need for process improvement, and perhaps most important, provide a means to monitor the performance of the process independent of individual judgments.

In the 1960's methods and procedures were developed in accordance with the "new approach" for all of the calibration services provided. The most completely developed system is in the area of mass measurement with extension into a number of measurement facilities through the Mass Measurement Assurance Program. The next most developed system is in the area of capacity standards, primarily to bring the NBS processes into a state of control and to extend the techniques into the area of application. In the area of hydrometer calibration and the calibration of volumetric glassware, measurement methods were developed incorporating the desired features but little was done to incorporate the methods into the calibration procedures. In these areas the calibration work load is small, and the new procedures were substantially different from current practices. It was felt that the new procedures would not really benefit the users of hydrometers or volumetric glassware.

4.2 The Present--Scope of NBS Services

The variety of services available from NBS which support the National Measurement System range from providing access to the mass unit and the calibration of appropriate artifacts, to providing guidance to that section of the system associated with "equity in the marketplace" and to providing consultation to all who ask for assistance. The calibration services of the Mass and Volume Section, and the relation between the Office of Weights and Measures and the National Conference of Weights and Measures are the services most widely recognized and easiest to characterize in terms of services provided and user clientele. The consultation services, supported in part by NBS funding, and by "other agency" funding, are the most difficult to characterize. Consultations range from informal conversations relative to selection of equipment, procedural difficulties, and problem definition, process design, development of procedures and the refinement of reference data. The following sections cover the direct services provided by NBS. The indirect, or consultation services, are described in 4.3.2

4.2.1 Description of NBS Services

There are two organizations within NBS which contribute to the measurement system.

The Mass and Volume Section is particularly careful about the interface with the users of the calibration services. In most cases and particularly in the case of new users, each user is contacted by telephone to determine what is needed and when. The conversation is acknowledged by a formal document stating the estimated delivery date, the approximate cost, and special requirements, if any.

There are no clearly identifiable organizational units within the section. While some staff members are more knowledgeable in some areas than others, most can do any of the tasks that the section performs, subject to limitations due to the physical strength necessary to handle some of the larger equipment.

The calibration activities of the Mass and Volume Section offer the following services essentially "at cost" to the user:

4.2.1.1 Mass Measurement

(1) For those who desire to do the calibration of subdivision or multiples of the unit themselves, NBS will establish mass values for suitable pairs of starting standards, e.g., kilograms or pounds, with uncertainties commensurate with the requirement, and limited only by the amount of effort and the uncertainty of the reference kilograms, N1 or N2.
(2) For those who do not have the facilities or for some other reason do not elect to do their own "work downs" or "build ups," NBS will calibrate ordered sets of weights from 30 kg or 50 lb to 1 mg or the appropriate equivalent. Weights less than 1 mg require special balances (quartz fiber) and handling techniques (working in the field of a microscope) and a continuous maintenance of both skill and equipment which cannot be economically done at NBS. Where such weights are required, e.g., for work with small quantities of short life isotopes, the NBS will calibrate suitable "starting standards" as in (1) above, and suggest suitable procedures for "working down" at the user's facility.
(3) NBS will assign mass values and in some cases adjust to specified nominal values, to large objects from 50 lb to 50 000 lb. (The adjustment to nominal value is with reference to force machines, and the requirement that the suspended weight exert a specified force in a given gravimetric field.) The adjustment of large weights is a matter of convenience, considering the handling problems and shipping costs. NBS will not normally adjust weights below 50 lb.
(4) The section will assign mass values and associated uncertainties to any object from 1 mg to 1 kg, provided that the object is sufficiently stable in mass to warrant the measurement, and provided that the displacement volume is such that the object can be handled with existing equipment.
(5) The section will make weighings of convenience on any object up to 50 lb or 30 kg at no charge provided that there is no reasonable alternate source.
(6) Where repetitive measurements are required by other staff members, the section will instruct, and supervise measurements made by others on section equipment.

4.2.1.2 Volumetric Measurements--Glassware

(1) The section will calibrate the standard items of volumetric glassware, made in accordance with the GSA specifications, under the provision that the requirements of the specific work demands such a calibration. The user is advised that the calibration applies only to fluids similar in character to water.
(2) The section will, on occasion, assist large agencies, e.g., Food and Drug Administration, in monitoring the quality of the products purchased by testing samples chosen

at random from a given lot. The agency makes the decision regarding the disposition of the lot in accordance with the rules in the GSA specifications.
(3) The section will accept lots of pipets which are used by the manufacturer in the maintenance of a quality control system. (One method of testing such a system is to put a "known" pipet in the inspection line with the "unknowns.")

4.2.1.3 Metal Volumetric Standards

(1) The section will determine the contained or delivered volume, and calibrate the indicating scale on all standard size provers. The section will not normally adjust, or seal, the location of the reading scale with respect to the prover body. These items go directly to the user, with no intermediate steps. The user in turn makes an effort to monitor the consistency of the section's work.
(2) The section will calibrate .1 and 1 cubic foot bottles, which also go directly to the user.
(3) The section will calibrate slicker plate standards. Adjustment, if required, must be done by the manufacturer.
(4) The section will conduct a standardizing test, and adjust as necessary, Stillman standards, e.g., bell provers of 1 cubic foot capacity. This is currently done with a single purpose test apparatus, and gradual decrease of requests does not warrant further refinement. (Most items of this type are calibrated by "strapping," e.g., determining the displacement volume from direct linear measurement.)
(5) The section will calibrate either to contain or to deliver, any metal container provided that it is sufficiently rigid to be handled in the filled condition, that it can be leveled, and that the end point is sufficiently well defined to warrant the calibration; and further, provided that the effort is necessary to the manner in which the vessel will be used. (This is of course limited by the capacity of the existing equipment.)
(6) The section will accept tests of various apparatus provided that the results of the test are not proprietary, and subject to the condition that the results will benefit a large number of users.

4.2.1.4 Density Measurements

(1) The section will accept hydrometers for calibration which are of such quality, both in manufacture and precision, to warrant the calibration effort, and provided that the items will be used as manufacturers' standards, or directly by the user. The section will not accept certain types of hydrometers where the hydrometer scale is not directly related, or relatable, to density, e.g., lactometers.
(2) The section will calibrate solid density standards for use in specific measurements.
(3) The section will determine, or consult with, or assist, in the construction of apparatus for determining the density of a wide variety of small objects, e.g., gradient columns, special floats and the like.
(4) The section will determine the density of fluids within the capabilities of the existing equipment, and provided that the fluids do not require special handling procedures beyond that available in the normal laboratory.

4.2.1.5 Mass Measurement Assurance Program

The Measurement Assurance Program, as operated by the section, has not been sold in an aggressive manner. Participation is voluntary, and prior to making the decision, the prospective participant is told quite clearly that it requires a lot of work. If on the basis of his analysis he requires either (1) the maximum performance of his measurement processes to satisfy the requirements of his specific task, or (2) the benefits in the form of reduced measurement effort by virtue of the quantitative knowledge of descriptors of his measurement process, he is then encouraged to participate. Approximately six months is required to make the MAP operational in the normal mass measurement facility. Beyond that, the frequency of usage is up to him. If he has the necessary supporting facilities, he may elect to run the program himself with only minimal connection with the section. In other cases, the section may provide all of the supporting effort. Periodically, the knowledge of his process performance parameters is updated. (At this time all of the present participants have been updated at least once.) Currently some of the users are hierarchy laboratories, others are in support of certain direct measurement requirements. Some do almost everything themselves, and others rely on the section for continuous support.

4.2.1.6 Office of Weights and Measures

The second operational unit is the Office of Weights and Measures. The role of OWM is to provide leadership and those technical resources that will assure accuracy of the quantities and quantity representations in all commercial transactions for all buyers and sellers in the United States, and to promote a uniform national weights and measures system.

In fulfilling its mission, the Office of Weights and Measures engages in a wide range of activities all of which are essentially funded by NBS. Foremost is the assistance offered to the States in the following areas:

Laws and Regulations:

The development of model weights and measures laws and technical regulations for the States and local jurisdictions.

The evaluation and updating of laws and regulations at the request of the States.

Standards and Laboratories:

The development and dissemination of design and performance specifications for capacity for use as State and local reference, laboratory, and field standards, and the encouragement of manufacturers to make available standards that conform to such specifications. The conduct of the New State Standards Project, which provides for the issuance of new laboratory standards and instruments and modernization of State weights and measures laboratories. Consultation and recommendations on laboratory facilities, organization, instruments, and technical procedures. The calibration of secondary standards for the States and industry.

Testing and Equipment and Procedures:

The design of testing equipment and the development of testing procedures for weighing and measuring devices.

The conduct of the master railway track scale test project and the testing of commercial track scales operated by the railroads and other industries located throughout the nation.

Measurement Studies:

The identification, analysis, and solution of technical problems in the measurement area of commerce.

The study, including field investigations, of weighing and measuring equipment, the preparation of specifications and performance tolerances, and the establishment of standard practices involving the use of such equipment.

The examination of prototype commercial weighing and measuring devices and equipment submitted by manufacturers for conformance with National Bureau of Standards requirements.

Packaging Practices:

Market surveying to determine the weights, measures, and quantities in which commodities are packaged for retail sale, and the extent to which voluntary product standards are being adhered to by industry.

Determining the relationship between numbers of package quantities available at retail and its effect on consumer ability to make a value comparison.

Distributing published standards and regulations resulting from the Fair Packaging and Labeling Act, providing information and assistance to State officials, and generally promoting uniformity in Federal and State regulation of the labeling of packaged consumer commodities.

Providing advice and counsel to the packaging industry on means and methods for achieving the aims of the Fair Packaging and Labeling Act.

Technical Training

The conduct of formal and informal technical training sessions for weights and measures officials, laboratory technologists, and industry representatives.

Information Dissemination:

The preparation and dissemination, in conveniently usable form, of data on weights and measures units, systems, and equivalents, to satisfy the particular needs of the Federal Government, State and local governments, educational institutions, business and industry, and the general public, including the development and maintenance of archival and reference collections of published material.

The development, the preparation, the publication, and the dissemination of appropriate information on standards, testing equipment, technical procedures, technical investigations, and standard practices.

Conferences and Meetings:

The plan and conduct of an annual National Conference on Weights and Measures, including all secretariat functions to the Conference and its standing committees.

4.2.2 Users of NBS Services

The principal user community of the Office of Weights and Measures is the State and local weights and measures officials. A small, but important, additional service of this NBS group is their prototype approval program. This program allows manufacturers of measuring devices used in trade to obtain approval certifying that the device satisfies the requirements of Handbook 44. Such certification is accepted by many jurisdictions in lieu of their own inspection. The program is small (about 40 inspections per year) but growing.

The Mass and Volume Section, on the other hand, has a much more diffuse clientele. The most serious customers are those who subscribe to our Measurement Assurance Program (MAP). There are currently 18 facilities participating in the MAP program.

The nonclientele group contains all of those whose measurements are now adequate for the intended purpose, or at least thought to be by the user.

In order to establish a profile for the users of NBS services, the customers over a four-year period were categorized according to nature of their business using the Standard Industrial Classification (SIC) codes. While it was not possible to categorize all of the customers according to this method of classification (87% for Mass, 67% for Volume, and 61% for density), Figures 5 through 8 show the frequency of requests from various categories over the period of the study.

4.2.3 Alternate Sources

Technically the user's decision to accept or reject an alternate source for calibration should be based on the uncertainty of the calibration relative to the task at hand. Generally, if the user's process cannot detect the small differences between like objects which are clearly identifiable in the calibration process, the user cannot utilize the full benefits of the calibration. Practically, many decisions with regard to source of calibration are based on political or economic factors rather than technical requirements.

With access to the defining unit, and with the world's most precise balance, NBS-2, BIPM provides the highest level calibrations. The uncertainty of the results are limited by the instability of the defining artifact. BIPM has provided calibrations for selected artifacts to be used in redefining certain electrical units, i.e. the ampere and the faraday. BIPM has provided calibration services at the kilogram level for at least one foreign balance manufacturer. While BIPM is not in a position to provide general access to the defining artifact, the precedent has been established with regard to providing support for certain types of activities.

While all national laboratories are acceptable alternate sources for calibrations with regard to military specifications, most national laboratories limit their services to organizations within the territorial boundaries of their governments. On occasion users may obtain calibrations from other national laboratories using local organizations as "fronts." In the area of mass measurements the results are used as "informal international audits" rather than sources of calibration.

The higher order calibrations provided by NBS reflect the uncertainties from three separate measurement processes, the defining artifact to the prototype kilograms, the prototype kilograms to the nichrome kilograms, and the nichrome kilograms to the artifacts being calibrated. Of these three processes only the latter has been completely characterized. With the exception of a small group of measurements which were made when NBS-2 was still at NBS, essentially no calibrations have been made relative to the prototype kilograms. This has primarily been due to a lack of equipment and to uncertainties associated with the air density algorithm. Present calibrations are on the basis that the historical values assigned to the nichrome kilograms are exact.

The uncertainties assigned to the various pairs of kilograms of the Mass Measurement Assurance Program participants are on this basis, thus these laboratories are capable of providing an alternate source for most of their requirements which formerly were sent to NBS, as well as for others if they desire. (An "informal international audit" shows that the practical mass scale as disseminated by NPL and by NBS may be offset by one part in ten million. This is attributed to problems associated with the air density algorithm.) Since the consistency of the work of each of these laboratories has been evaluated both relative to NBS and relative to other participating laboratories, one or more could function as an interim calibration source in the event of disaster at NBS. The maintenance of such service is important, not from the standpoint of providing calibrated weights which are in turn used to calibrate other weights, but because well-calibrated artifacts are needed to characterize modern weighing devices and measurement processes.

With the completion of current activities directed toward the development of equipment and procedures and the evaluation of the air density algorithms, it is planned to re-calibrate these pairs of kilograms relative to the prototype kilograms.

Perhaps the most widely available calibration procedure is that associated with establishing compliance with adjustment tolerances. Here the user's choice of source may be either practical or economical or both. The state laboratories and

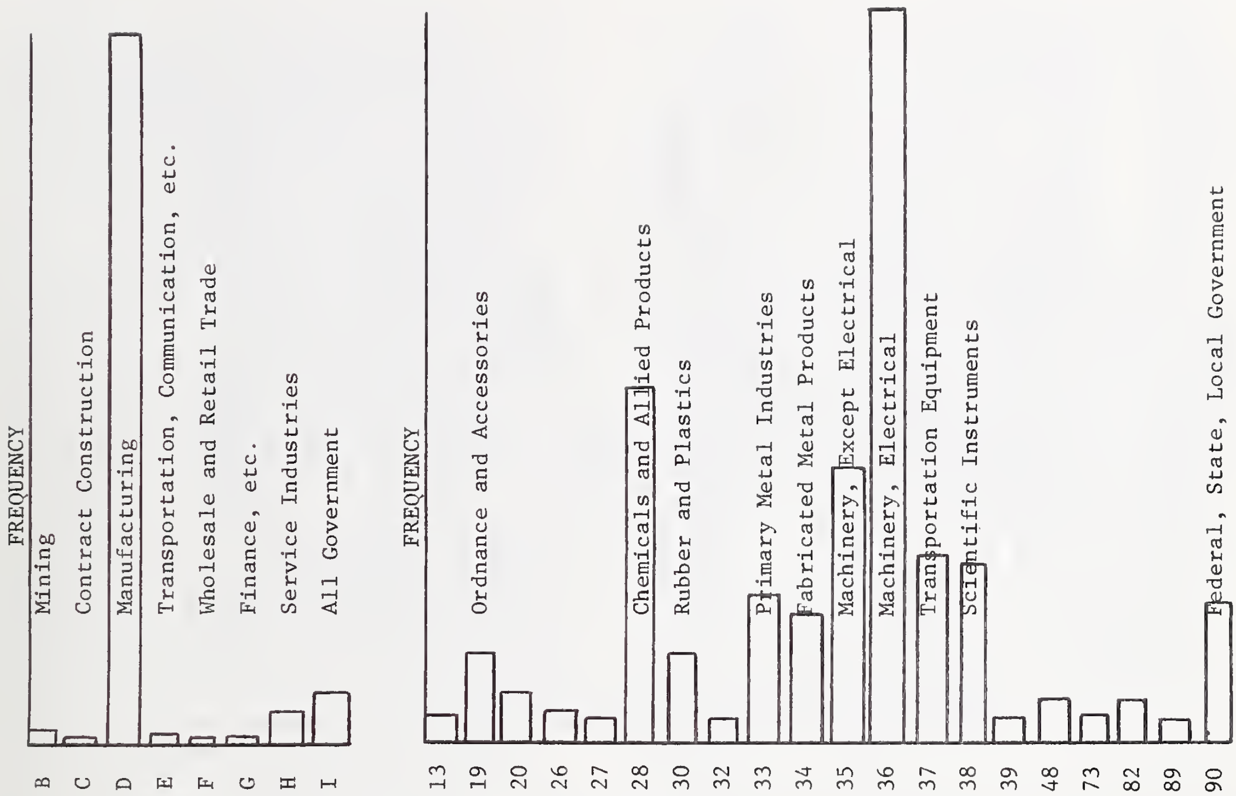


Figure 5
Mass Customer Profile (Major SIC Groups)

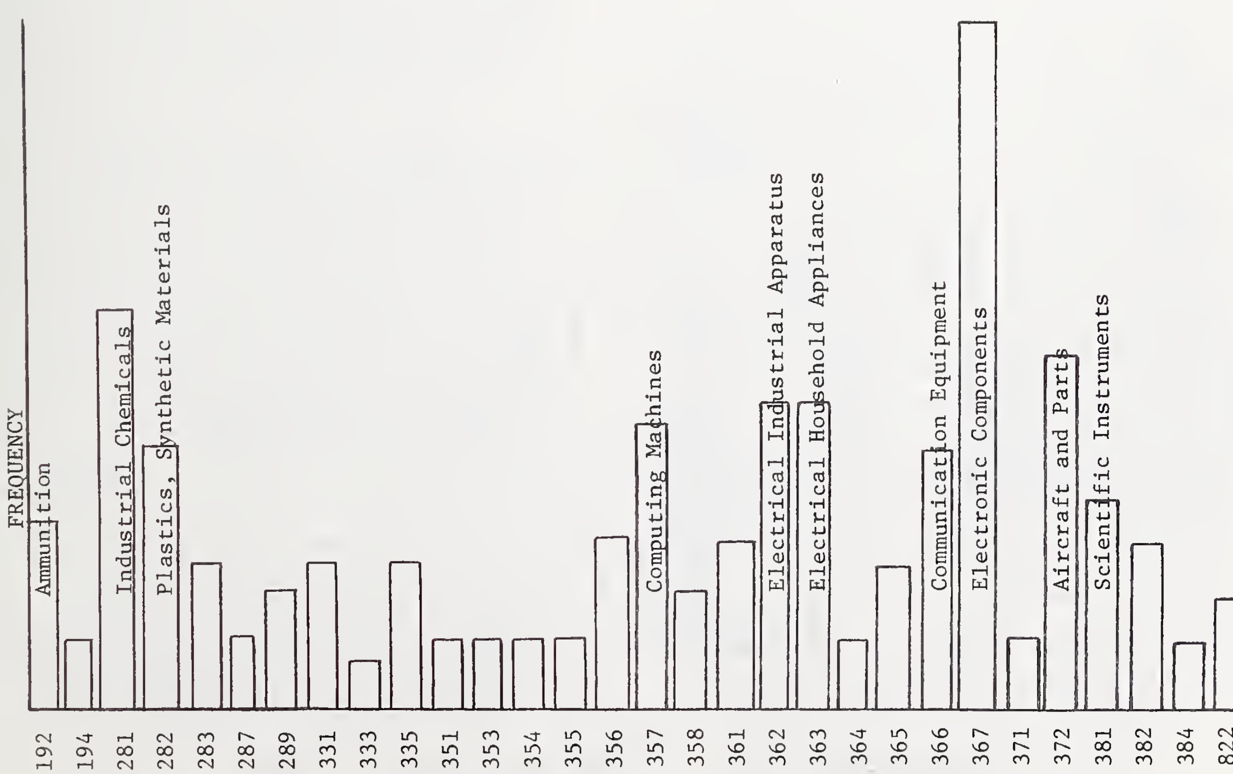


Figure 6
Mass Customer Profile (Three Digit SIC Groups)

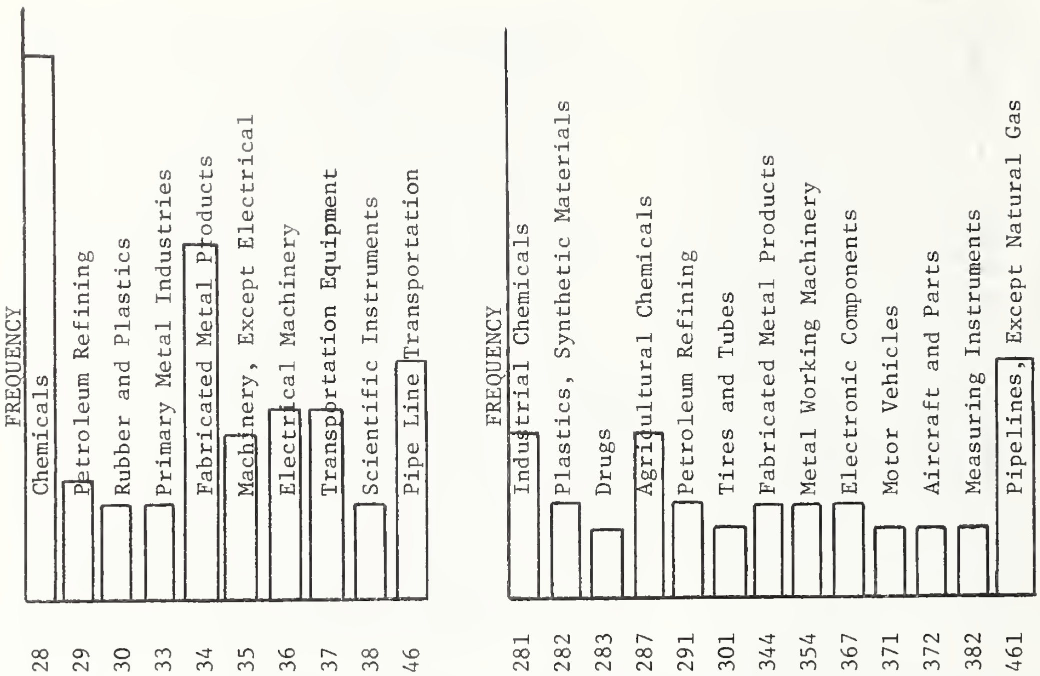


Figure 7
Volume Customer Profile (Two and Three Digit SIC Groups)

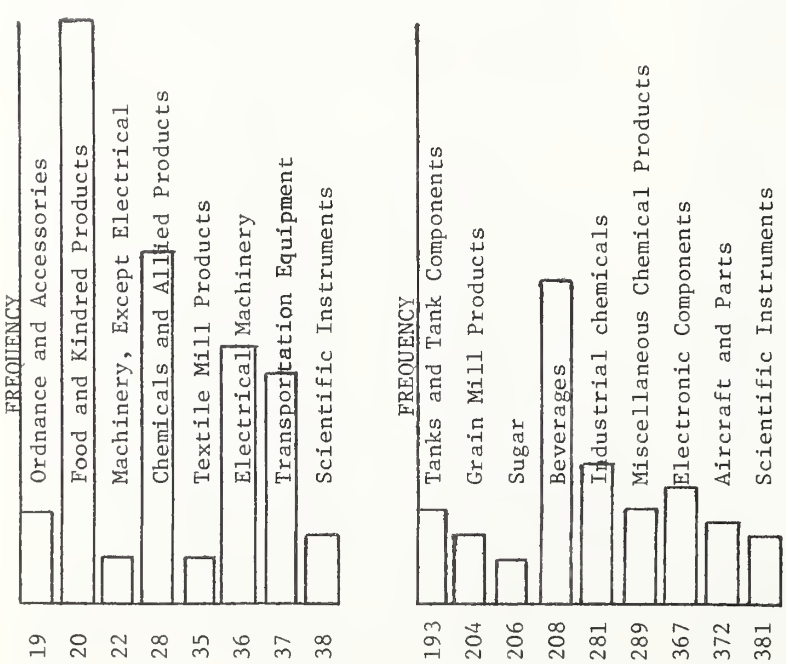


Figure 8
Density Customer Profile (Two and Three Digit SIC Groups)

the weight and balance manufacturers provide calibration services complete with proper evidence for compliance with "traceability" requirements. Many former users of the NBS services now utilize these sources with substantial economic savings. (Some states provide such services at no cost.) In some cases NBS calibration services are used for this purpose, i.e. the NBS assigned values are compared with the adjustment tolerance limits to verify compliance, and the limitation on the use is then set by the tolerance class rather than the uncertainty of the value. In these cases the decision is political rather than economic, i.e. use the NBS calibration services in lieu of justifying an alternate source.

There are no technical reasons to support the NBS calibrations in the areas of volume and density measurements. The methods used at NBS are well documented and widely disseminated. Adequate equipment is generally available in the user's facility. However, with the exception of IRS (hydrometers) and FDA (glassware) previously mentioned, attempts to develop alternate sources have not been successful. The reasons for this are somewhat complex. In the case of the small user, i.e. a hospital laboratory, the practice of self-calibration diverts resources from the primary mission of the laboratory. Further, such practice raises the question of defense in the case of challenge by those who make judgments based on the measurement output of the laboratory.

For large uses, i.e. the petroleum industry (volumetric process), the alcohol and sugar industry (hydrometers) there appear to be two reasons, both associated with the interface between the producers and users of measurement data. One is the need for a consistent defensible reference. The second is the widespread belief that where large amounts of money are involved, measurement data will always be biased in the favor of the organization which has produced the data[1]. In such an environment the need for unbiased "third party" calibrations is essential.

4.2.4 Funding Sources for NBS Services

The two NBS organizations which are administratively separate have different funding patterns.

The Mass and Volume Section profile, both for funding and staff, is shown below.

	Staff		Funding ($1000)		
				Reimbursable	
Yr	Total	Prof	NBS	Work	Total
1970	21	6	300	160	460
1971	17	6	325	165	490
1972	17	7	380	110	490
1973	9	2	210	60	270
1974	10	3	205	35	240

The large change between 1972 and 1973 was the result of the establishment of the Dimensional Technology Section. The work of maintaining and characterizing the measurement processes of NBS, and general support to the appropriate segments of the national measurement system, accounts for most of the work and is funded directly by NBS. Measurements which are done for others are, in most cases, charged on the basis of "at cost."

The staff profile of the section does not reflect the utilization of the services provided by both the Office of Measurement Services and by the Statistical Engineering Laboratory. In both cases, many of the respective staff members are considered as "ex officio" members of the Mass and Volume Section.

The Office of Weights and Measures operates under a total budget of just under $450,000 with a staff of 18.

4.2.5 Mechanisms for Supplying Services

Access to the unit is provided through the calibration services. The transfer mechanism is the Report of Calibration which is returned to the submitter along with the calibrated items. In the case of mass calibrations the report is essentially a computer prepared "laboratory notebook" which not only gives the results of the calibrations in several different forms, but also completely delineates the details of the measurements which were made and the status of the performance of the measurement processes used. All calibration reports show the conditions under which the results apply, as well as realistic certainty statements which permit the user to evaluate the results relative to his requirements. In some instances, where there is a history of NBS calibration of certain items, the previous history is taken into account in the assignment of value, and associated uncertainty.

(1) There is a published strategy for biasing measurement data where disagreements are resolved by NBS measurement with the party having the greatest discrepancy with the NBS paying the cost for the referee measurement.

The documentation associated with the Mass Measurement Assurance Program includes the calibration of the participant's standards, the characterization of the participant's process based on measurement data from his facility, a verification of the consistency of the results through independent calibrations of an arbitrarily selected set of weights by both the participant and NBS. In addition, the participant is provided with control chart data which will permit a continuous monitoring of his process performance. Follow-up documentation may include recalibration of his standards at NBS, recalibration of his standards in his facility relative to furnished NBS standards, a re-evaluation of the consistency of measurement between his facility and NBS, and finally, an occasional "update" of pertinent parameters for his process.

Detailed access to measurement methods and procedures is provided through the generation of a literature base, and through consultation. The literature base consists of a series of publications ranging from "OVERLAP," an irregular news letter to MAP participants, to NBS reports, Technical Notes, Monographs and formal publications in journals such as "Metrologia." For the most part method and procedures are covered in detail in NBS reports. The intent, in general, is to provide a depth of detail sufficient to not only permit the interested user to make the measurement, but also to permit him to assess the uncertainty of his result. The methods presented can be simplified as appropriate to his requirements, or to the requirements addressed by voluntary standards groups.

Tutorial assistance has been provided through participation in seminars conducted by the Mass and Volume Section, and by the Office of Measurement Services. On occasion invited talks have been presented at various society conferences, including the National Conference of Standards Laboratories, the IEEE, the American Defense Preparedness Association (formerly the American Ordnance Association), the Aerospace Industries Association, and others. The most effective access to methods and procedure, however, is direct consultation relative to a particular measurement requirement. These consultations range from inquiries concerning the availability of appropriate standards to system problems concerning the health and welfare of the nation (e.g. determining the amount of coal dust in mines, and the costing of measurement in laboratories of the Food and Drug Administration) and large segments of the national economy (e.g. bulk measurements of petroleum and nuclear materials).

The Office of Weights and Measures, acting as the secretariat of the National Conference of Weights and Measures, provides both administrative and technological services to that organization and its various study committees. OWM provides a calibration service to the state laboratories for items which are not designated "primary" standards. The items include trailer mounted provers used to test a variety of tanks and metering devices, large weights used for testing large capacity scales, miscellaneous glassware items used for testing liquid packaging containers, and the like. OWM conducts extensive training operations for all levels of personnel within the state weights and measures organizations. OWM also operates a program designed to verify the consistency of mass measurement in the various state laboratories. OWM operates, on an intermittent basis, the railway track scale test cars which provide a means for calibrating railway master scales, and such other privately owned scales as arranged for in the course of planning the itinerary for the two test cars.

4.3 Impact of NBS Services

4.3.1 Economic Impact of Major User Classes

The user classes, discussed in Section 4.2.2, show a degree of commonality between the three areas of measurement. This in turn suggests that there may also be a commonality between all of the users of the NBS calibration services in all measurement areas. In considering impact, it seems important to identify this commonality in order to differentiate between the users who are in essence "told" to use NBS (e.g., by contractual requirements) and those who use NBS calibration services as a matter of need or convenience. This is not to imply that those who are "told" to use NBS would not normally come to NBS anyway, but rather to differentiate between realistic calibration needs and the artificial needs generated within the infrastructure.

Table 8 is a summary of all of the users of all NBS calibration services, by dollar volume, and by number of facilities served for fiscal year 1975. The military contractor category of the private sector includes 70 corporations which account for in excess of 87% of military research, development, test and evaluation contracts ($5,474 billion); 46 of these 70 corporations, which account for 50.9% of the RDT&E contracts, are large industrials

(Fortune's "Top 500"). The total industrial sales of these 46 (1974) is $129,463 billion, thus the military business is only about 2.5% of their total effort. Further, the total sales of these 46 represent only about 15.5% of the total sales of the "Top 500" ($833,956 billion or 59.3% of the 1974 GNP, $1,406.9 billion).

Table 9 Survey of Users of All NBS Calibration Services (1975)

	Cost of Calib	No. of Facilities Served
Total Government	$ 542,812	63
Dept of Defense	$ 486,085 (89.5%)	(35)
OTHER	56,727 (10.5%)	(28)
Total Private	$1,234,844	871
Military Contractors	$ 615,050 (49.8%)	(224)
OTHER	$ 619,794 (50.8%)	(647)
Overall	$1,777,656	934
NCSL Membership	$1,157,862 (65%)	(238)
Non-NCSL (accounts over $5,000)	$ 225,910 (12.7%)	(18)
OTHER	$ 393,884 (22.3%)	(678)
(Average cost/user $580)		

The National Conference of Standards Laboratories is a non-profit, laboratory-oriented organization which promotes cooperative efforts toward solving common problems faced by standards laboratories in their organization and operation. With few exceptions the membership is comprised of government laboratories supporting hierarchy chains of calibration laboratories, and organizations which must interface with contractual requirements imposed by governmental agencies, primarily the Department of Defense. The membership, which is not generally end-use oriented, accounts for 65% of the total NBS calibration effort.

Non-NCSL members with accounts over $5000, of which approximately 50% of the $225,910 is associated with the calibration of products from less than 10 instrument manufacturers, accounts for 12.7% of the NBS effort. For the remainder, 22.3%, the average cost per facility, for 678 facilities, is slightly less than $600. An unidentified number of the facilities in this group are subcontractors which are required to "maintain" certain measurement capabilities, and, on occasion, items submitted for periodic recalibration have been received in the same unopened package which was used to ship the items after the previous calibration.

The above summary of the users of NBS calibrations is descriptive of the users of mass, volume and density calibrations. The impact of the NBS services is the degree to which these services benefit the user in attaining measurements adequate for his needs, either realistic or imagined (e.g., established by a bureaucratic infrastructure). The degree to which direct services are required is the ratio of an acceptable uncertainty of the results from the user's process, under actual conditions of use, to the uncertainty of the NBS calibration measurements. For example, the ratio of the uncertainty of the internal balance weights of one balance manufacturer who is a participant in Mass MAP, to the uncertainty of the NBS calibration is on the order of 1.5 to 2, obviously requiring direct contact. As a result, the dissemination of the mass unit as embodied in stainless steel is widely available with little degradation. On the other hand, the same ratio for acceptable commercial weights ranges from 100 to 1000, thus adequate services are available from many sources and those who insist on NBS calibration are merely buying a name. Generally speaking, there are very few uses of mass, volume, and density calibrations with requirements commensurate with the uncertainty of the calibration results.

In contrast, the consultative activities, from short telephone discussions to long term continuing studies are directly related to specific measurement requirements or measurement assurance requirements. Two such long-term activities are related to the nuclear power industry and the petroleum industry.

In the nuclear power industry, the first quantitative measure of the amount of material in a "spent" reactor core occurs after the core material has been dissolved from its cladding. The amount of material is determined from assaying samples drawn from a tank of "known" volume. The result not only establishes the monetary value of the material, but also establishes the base for material accountability under the nuclear safeguards program. The Mass and Volume Section has developed and documented measurement techniques for determining the contained volume of large tanks. Working with voluntary standards groups, the techniques are being incorporated in standards which will become industry standards. This type of measurement support activities at 3 U.S. government reprocessing facilities which handle material used by the military. Should commercial reprocessing activities be authorized for the U.S. the section's activities in this area would support that effort. The projected value of the resultant electric generating capacity for 1985 from reprocessed fuel is in excess of $5 billion. Should the plutonium fuel cycle be used then tank volume measurements become critical for accountability and safeguards purposes.

The Mass and Volume Section supports the petroleum industry in three ways: the calibration of large volumetric provers which are used worldwide to test metering devices; the calibration of hydrometers, density being an important parameter in processing and application; and currently the American Petroleum Institute/NBS Physical Properties Project. An estimate of the worldwide commitment to petroleum measurement is shown in table 9.

The average "barrel" is measured twelve times with numerous custody changes between the well head and the ultimate user of the finished product. Shipper/receiver differences in terms of dollars are based on bulk measurements of quantity, which in turn is dependent on the properties of the material being transferred. Measurement detail is a consensus decision establishing the basis (e.g., NBS calibrated provers) and the extent to which systematic errors are minimized with respect to the cost of the material and the cost and practicality of measurement procedure. Attention to detail is directly proportional to the cost of the material.

The worldwide pricing structure is based upon the bulk volume and density at 60°F. Since custody transfer takes place at temperatures differing from the standard temperature, computation of the volume at 60°F is done using the measured temperature and the density at the time of transfer (e.g., as measured with a hydrometer), the measured value as determined by a calibrated metering device, and a volume reduction table accepted as an industry standard. Discrepancies in the table are amplified when large temperature and density changes occur in transit, e.g. on-loading in the middle East; and off-loading at a North Atlantic port.

The current volume reduction table is based on thermal expansion coefficients and densities of North American crude oils and products prepared by NBS around 1915. In 1973 production from North American fields had dropped to 25% of the total production. It has been known for some time that the table does not reflect the characteristics of presently marketed crudes, however, the error relative to the cost of the material was considered acceptable. At the current price for imported crude oil, a .16% error over a temperature differential of approximately 40°F represents an inventory loss in transit of $5 million per month at the current import rate of 8 million barrels/day. The joint NBS/API activity is to characterize both crude and products on a worldwide basis (67% of 1975's proven reserves). This data will be the basis for a consumer's decision relative to both the method for reducing values to a common basis and the measurement detail associated with determining the appropriate parameters.

4.3.2 Technological Impact of Services

Historically, NBS impacted the weight manufacturing industry through its technical publications such as Circular #3 and 547. The tolerance classes set up in these documents are widely accepted.
The impact on the precision balance industry has been less profound due perhaps in large part to the fact that this industry is largely European based. However, at the 2500 lb level the "Russell" balance, named after a Bureau employee, is the standard of the nation. More recently, the NBS-2 type of kilogram comparator, manufactured by a U.S. concern, has found a market among other national laboratories. Commercial weighing devices manufactured to conform to Handbook 44 also reflect NBS thinking.

With respect to volume standards, the NBS role has been less innovative, but the methods of calibration throughout the industry owe a great debt to NBS. The continuing calibration effort, although small, provides the unifying tie point for a sizable, but diffuse, industry.

The impact on the makers of density measuring equipment has been of yet another kind. In this case, the detailed technological base of density measurement was developed at NBS. The proper configuration,

Table 9

PETROLEUM MEASUREMENT COMMITMENT

Commitment	Crude Petroleum	Finished Products	Total
Measurement Facility Investment	$800,000,000	$2,000,000,000	$2,800,000,000
Equivalent Full-Time Personnel	22,500	27,500	50,000
Measurement Points*	255,000	395,000	650,000

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Frequency "Average" Barrel Measured	12
Cost of 0.5% Measurement Error Per 1000 Barrels Petroleum at $13.00 Per Barrel	$65.00
Monitoring discrepancy per day at current import rate	$500,000.00

*Tanks, pipelines (meters), tankers, barges, tank cars and tank trucks

ESTIMATED WORLD-WIDE OIL INDUSTRY
INVESTMENT IN BULK PETROLEUM
LIQUID MEASUREMENT

methods of use and necessary precautions are all spelled out in NBS technical papers. The industry is based on these principles.

At a higher level of accuracy, the NBS techniques of hydrostatic weighing represent the "state-of-the-art" and are universally recognized as such. This work continues with the silicon density work previously mentioned.

NBS has a technological input to other specification-preparing groups, both government and private. For example, the appropriate section of the NASA Mass Properties Manual were prepared by the section. Procedures and statistical methods prepared by the section have been incorporated in various published API procedures. Where possible the section has taken the initiative to see that the procedures are appropriate for the task, that the user understands what he is supposed to do, and that the equipment furnished will indeed do the job.

The section staff members are consultants to the Institute of Nuclear Materials Management (INMM) Writing Group 8 and subgroups thereof which have the task of preparing specifications or guides for the measurement of nuclear materials in cooperation with ANSI. The specifications in preparation are:

(1) ANSI N15.18 "Mass Calibration Techniques for Nuclear Materials Control"

(2) ANSI N15.19 "Volume Calibration for Nuclear Materials Control"

The above standards, when accepted and formally approved in accordance with ANSI procedures, will no doubt be made mandatory by NRC (Nuclear Regulatory Commission) in the nuclear industry.

The staff has participated in the work of ASTM subcommittee E18, Hydrometer Subcommittee. In early 1974, the parent committee, E1, on Methods of Testing, elected to disband itself. The subcommittee E18 has been redesignated E1.05, under a different parent committee. The section will continue to be a part of this committee because of the strong reliance of the industry on artifact standards.

The National Conference on Weights and Measures had its beginning in 1905, when the Director of the National Bureau of Standards called a meeting of representatives from the several States

"to bring about uniformity in the State laws referring to weights and measures, and also to effect a close cooperation between the State inspection services and the National Bureau of Standards."

From an initial attendance of 11 persons, the Conference has grown until now it brings together at its meetings a total of approximately 500 persons comprising weights and measures officers, other officials of the Federal, State, and local governments, and representatives of equipment manufacturers, industry, business, and consumers. The Conference develops many technical and general recommendations in the field of weights and measures administration, and its programs explore the entire area of this economically important segment of governmental regulatory service.

The participation is in national and international activities in the fields of weights and measures standards and practical metrology. Such participation includes:

(a) the development of and negotiation toward the adoption of both national and international specifications in the assigned area;

(b) correspondence and other communication with experts of the United States and of other nations;

(c) technical committee activities;

(d) attendance at and participation in appropriate meetings and conferences of the Federal and State Governments and of regional groups, business, industry, and educational institutions.

4.3.3 Pay-off from Changes in NBS Services

Substantive changes resulted from two factors; one, a concentrated effort in the early 1960's to completely characterize the mass measurement processes at NBS, and two, the recognition of measurement as a production process whose product (measurement results) should be evaluated relative to the end use rather than relative to state-of-the-art measurement capabilities, e.g. the "best" measurement process is one which produces adequate results in the most economical manner. As a result of the first effort, the basis for judgment concerning the adequacy of a measurement was changed from operator opinion to quantitative tests relative to pertinent process performance parameters. For the first time realistic uncertainty statements, based on demonstrative evidence, permitted unbiased comparison of measurement results from different measurement processes. Realistic uncertainty statements, in turn, permitted an assessment of measurement process detail relative to end use requirements.

The techniques were extended to the field by changes in reporting format, tutorial training at NBS, and technical publications. This effort permitted the development and acceptance of alternate sources for routine calibrations for both weight sets from 100 g down, and for volumetric glassware. Weight manufacturers, utilizing adaptations of the techniques used at NBS, were able to market calibration services acceptable to a large portion of the user community at a cost to the user substantively less than the cost for NBS calibration. In the area of volumetric glassware, the Food and Drug Administration was the primary user of the NBS calibration services, primarily to verify compliance with specification tolerances. NBS efforts devoted to the development and acceptance of suitable specifications, to the verification that manufacturers' products did indeed meet these specifications resulted in a change in the method of processing glassware. The agency now procures glassware through the established procedures of the General Services Administration with a direct saving in excess of $150,000 per year, the amount previously spent annually for NBS calibrations.

The reduction in the number of calibrations for manufacturers and suppliers opened a direct channel of communication with people involved in operating measurement processes. As the characterization of the NBS processes progressed responses to inquiries became objective rather than subjective. Ultimately, the routine "fee schedule" calibrations were replaced by "at cost" calibrations in which the calibration effort was tailored to the particular customer's needs. The measurement assurance program concept was developed and augmented. This concept has now been accepted in many other areas of measurement. The concept is used in the nuclear weapons industry to monitor the performance of the facilities involved. As a direct result of this program, the section was asked to make an objective survey of the nuclear reprocessing industry relative to mass and volume measurements.

Continued efforts devoted to the characterization of measurement processes and the development of measurement methods provided direct support to accomplishments ranging from the redetermination of Avagadro's

Number, to the resolution of litigation concerning the performance of a group of 30 kg balances procurred by OWM for the new state laboratories. Studies on the density of single crystal silicon resulted in a "solid object" density standard overcoming the limitations associated with water. Procedures were developed and documented which would provide a base for determining the volume of large tanks in the nuclear industry.

Detailed analysis of the calibration user clientele and the way in which the users utilized the calibrated items were made. In many instances it was questionable as to whether the NBS calibration efforts had any real impact on the quality of the work done by the user. It was concluded that the "catalog-fee schedule" invited commitments of NBS facilities without prior discussions concerning the adequacy of the effort relative to the particular task. Many requests for calibrations were, and still are, required for compliance with various standards. It was decided that participation in the preparation of voluntary standards should be limited to consulting rather than direct participation. It was felt that as a consultant, NBS could aggressively increase the span of input to the voluntary standards procedures (see figure 3). In the case of old, established standards, this has not always been successful. However in the development of voluntary standards for the nuclear industry, NBS, acting as a consultant, has an effective input over the whole span of the process, from the identification and quantification of the requirements by the regulation, to the development of methods and techniques, the preparation of the appropriate voluntary standard, the demonstration of the adequacy of the standard, the acceptance of the standard by the regulator, and the manner in which compliance with the standard will be judged.

The increased span mentioned above has resulted in a fundamental change in the scope of certain new voluntary standards in the nuclear industry. Traditional older standards are essentially detail standards specifying itemized equipment lists and procedural steps; such standards, essentially without exception, ignore discussing in detail the uncertainty of the result. (It is presumed that adequacy relative to a particular requirement has been considered by the committee which prepared the standard.) The new standards are performance standards, concentrating on the methods for assessing the performance of existing processes relative to specified requirements. In a producer-consumer relationship, this action gives the producer a freedom for choice and at the same time, the consumer is assured that the requirement is satisfied.

Perhaps the largest benefit from change is the progress which has been made in relating the ideas of Mach, Carnap, Eisenhart, and others to modern measurement processes. It is now possible to describe most measurement processes in generalized terms independent of process detail. This permits a logical delineation of requirements relative to a particular task, which in turn provides a list of the elements which must be tested to establish that the performance of that process is adequate for the intended usage. As this work is refined and disseminated, it will impact the design and development of future measurement systems. One of the encouraging factors relating to this work is the ever increasing number of people who are now aware that there is something more to measurement than possession of adequately blessed standards and the blind following of a specified procedure--people who can discuss in some detail measurement processes, process characteristics, and measurement requirements relative to an identified need of importance in accomplishing a specific task.

4.4 Evaluation of NBS Program

The two groups within NBS which support the mass, volume and density system are organizationally separated with essentially unrelated missions. One group is concerned with the legality of measurement and equity in the marketplace, particularly in regard to consumer products. This group is, in a sense, semi-regulatory. That is, having created a system for control largely based on visibility which has become a consensus system for the various states, this group is mostly concerned with implementation of the system. The system controls a large segment of the instrumentation industry as well as the control measurements at the consumer level. Typical of all large consensus systems, it cannot respond rapidly to changes in technology. The ritualistic aspects of the effort tend to take precedence over the efficiency of the effort and, in like manner, administrative activities predominate. While the technological requirements of the system are not stringent, the lack of technological resources seriously limits the scope of the programs.

The second group is concerned with the adequacy of measurement throughout the system. The constituency of this group is voluntary with one exception. As "keepers of the kilogram" the group is a "servant to all who desire, or are directed to establish, a direct traceability to the unit." This group, in the early 1960's, aggressively undertook a long-range plan to change from merely being "keepers of the kilogram" to becoming a center for measurement excellence in the areas of assigned responsibilities. One of several goals was that no current or future task should be limited by the inability to make adequate measurements. Through the mechanism of characterizing the calibration processes, the basis for measurement assurance was established, e.g. operationally verifiable evidence that process performance is as expected. The efficiency of the measurement effort was addressed by emphasizing that the "best" process was that which produced adequate results with minimum effort. Cooperative programs were established with other facilities to study factors affecting the consistency of measurement over time and over the environmental conditions in which measurements must be made.

By and large, the transition has been successful. Measurement assurance relative to the transfer of the unit has been adopted in several measurement areas. Even this, however, has not been without difficulty, as illustrated by the various National Academy of Sciences Evaluation Panels.

In 1969, the evaluation panel recommended: . . . extension of the Pilot Program (now called the Measurement Assurance Program) into the volume calibration activity, specifically, and into other NBS calibration activities, generally . . .

As the Measurement Assurance Program was developing in the area of length measurement, in 1970 the evaluation panel was divided in opinion to the point that a minority evaluation was submitted. It was quite clear that NBS had failed miserably in presenting the intent of the program.

In 1972, the panel "endorses" NBS policies pointing to expansion of the MAP program, and in 1975, the panel report states:

"The panel is extremely pleased to see the progress which has been made in the Measurement Assurance Program in the Mass and Volume and the Dimensional Technology Sections. We believe the measurement assurance approach will provide a more viable method of transferring standards from the National Bureau of Standards to commerce and industry by placing a greater emphasis on measurement assurance and the error bands associated with measurements and less emphasis on attempting to transfer precise absolute measurements. Greater confidence can be placed on the use of the measurements and standards at lower costs, both to The National Bureau of Standards and to commerce and industry. The panel believes there would be benefits in extending the assurance program in the future to all dimensional measurements."

Thus, over a six year time span, the intent of the program was finally understood, at least with regard to the transfer of the unit. It would seem that more attention to the educational aspects of the program would have considerably reduced the friction and would have shortened the time span between introduction and acceptance.

With one exception, the measurement assurance approach is not reflected in voluntary standards. The exception is with members of the Institute for Nuclear Material Management who are incorporating the approach in some of the voluntary standards being prepared for the nuclear industry. There may be several reasons for this, one of which is the lack of aggressive or appropriate selling on the part of NBS. Traditionally, voluntary standards are consensus standards in which the preparing committee assumes the responsibility for the adequacy of the specified procedure and interpretation relative to a specific task. Few if any such standards include error analysis or any discussion of methods to assess the uncertainty of the result. Individuals who constitute these committees, however, recognize that while such standards may be necessary to order in the marketplace, or in the simplification of the exchange of data, the use of these standards is not always sufficient relative to the task at hand. The resulting standards tend to represent a minimal consensus relative to an interfacing problem rather than realistic efforts at the point of decision.

The above implies that if the benefits of measurement assurance are to be realized in industry, there must be a one-on-one interaction at the point where the benefits are real. With regard to NBS as a whole, this is a null effort for two reasons; one obviously the futility of a one-on-one contact with everybody, and the second, the absence of an identifiable measure of success. If a company should adopt measurement assurance procedures with any measure of success, and there have been several which have seen fit to do so, the fact is immediately privileged information.

It would seem inevitable that as the constituency grows, the philosophy would become identifiable in future voluntary standards. Such an effort is a long, slow process, as is any worthwhile reform, with periods far longer than the normal budgetary cycle.

With regard to other aspects of the program of the latter group, the range of activities has increased greatly over the past 15 years. "Customized" at-cost calibration services are furnished in all measurement areas. There are active efforts with tangible results ranging from the development of precise research weighing devices and the study of air density as it relates to mass measurement to development and tutorial efforts concerning bulk mass and volume.

The program details reflect a consideration of the question, "What is required?", "When is it needed?", "Will large segments of the user community benefit in any way?", "Will the technical competence of the section improve by undertaking the task?", and "Are the necessary supporting services available?" With regard to the latter question, this group has been particularly successful in utilizing NBS resources outside of the group, and other facilities in efforts supporting the various tasks.

4.5 The Future

The most striking characteristic of the Mass, Volume and Density Measurement System is its apparent stability. For hundreds of years, it has evolved by a slow linear extrapolation, each change firmly based on past experience. This apparent stability comes in part from inertia of all parties involved; the scientists and educators, the suppliers of equipment and the users, and in part from the fact that the needs which were the genesis of a formalized system have not changed in centuries. The impact of near revolutionary changes over the past 25 years has influenced not only the entire system, but the current role of NBS and other national laboratories and will indeed influence the future as well.

Considering the system as two elements, one including activities associated with the definition of the unit, and the other including activities associated with the dissemination of the unit, the future of the former element is by far the easiest to discuss.

With regard to the defining artifact, the national laboratories collectively will resolve the problems associated with the variability of the platinum-iridium alloy kilograms and the transfer of the mass unit as embodied in these artifacts to artifacts made of other materials such as stainless steel, or single crystal silicon. The technology is available and it is only a matter of concentration of effort. While NBS will have a role in this work, relative to practical mass measurement, these problems are largely academic, the resolution of which will be beneficial to a relatively small segment of the scientific community. Undoubtedly, isolated efforts will be made to construct a mass unit based on a constant of nature. Should these efforts be successful, the results will be limited by the complexity of the measurement technique to definition of the unit and is not likely to be competitive with the artifact-based system for some time.

With regard to dissemination, the current practices originated at the turn of the century. Today, there is no technical reason why BIPM cannot be given the responsibility for the transfer of the mass unit from the defining artifact, whatever it may be, to practical artifacts for all who have need for direct access to the unit. In fact, such is being recommended informally to emerging nations by both BIPM and others who are knowledgeable concerning mass measurement. A decision to centralize first level dissemination of the unit would be advantageous from both an economic and a scientific point of view. It would, however, effect the current roles of some of the various national laboratories.

One factor which will set the level of the routine access to the unit as currently provided by NBS is dependent upon the degree to which those who provide goods and services are required by law or regulation, to defend their measurement practices or results. Most of the current requests for calibration in mass, volume and density could be technically satisfied by referral to others, e.g. state laboratories, manufacturers, commercial laboratories, or by the users themselves. Such facilities, however, do not generally have sufficient stature to alleviate questions which could arise in a defense situation, e.g. questions concerning adequacy of method and results, questions concerning "unbiased" results, questions concerning the adequacy of alternate methods and procedures relative to those which are specified in contracts or regulations. The prudent entrepreneur is now reluctant to utilize services other than those of NBS and if increased pressure is placed on measurement defense, will be more so. Increased pressure on the defense of measurement results will bring an increased calibration load, or will require a mechanism to extend the present NBS "disinterested third party blanket" to cover other facilities.

In terms of the immediate future, NBS must continue to maintain and provide access to a practical mass scale of sufficient quality to serve all of the needs of the country. The mechanisms for such access, however, are influenced by both the quality of the instrumentation generally available to the user and the level of adequacy required for his particular task. Transfer of the unit to certain equipment manufacturers with minimum degradation will be a continuing need. With regard to the general user, however, the quality of the instruments has reached the point where sophisticated time-consuming efforts are necessary to characterize their performance. Simple procedures to verify adequate performance relative to end use requirements will not require traditional access to the mass scale. This in turn will further erode the calibration work load.

There are requirements for mass, volume and density measurement instrumentation (or systems) which are beyond the capabilities of commercially available equipment. For economic reasons, commercial equipment features rapid, convenient measurement at a precision level adequate for the largest majority of users. It is not practical for most manufacturers to consider modifications to production units to improve performance beyond an order of magnitude or to undertake the development of precise instruments for a limited market. An increasing role of NBS in areas where the requirements are beyond the capabilities of commercial equipment is consultation relative to increasing the precision of measurement and, in situations where the need is relative to the health and welfare of the nation, the development of adequate prototype measurement systems. For such services to be effective, however, requires that "hands on" measurement activities, e.g. the providing of routine calibration, must remain above some "critical level," even if artificially generated.

5. SUMMARY AND CONCLUSION

The national measurement system for mass, volume and density is stable and adequate relative to the needs as currently perceived. There are some questions concerning the efficiency of the current measurement efforts within the system which cannot be resolved by NBS, e.g. social implications of change and a large scale education program relative to the fundamentals of measurement. While NBS is a partner in the literally millions of measurements which are made each day, by providing access directly or indirectly to the unit as requested and by acting as an unbiased reference in the case of dispute, it is presumptuous to assume NBS to have much, if any, real leverage relative to the activities of the system. Over the course of history the development of commerce and industry has been first the recognition of need and then the application of ingenuity to satisfy that need. This has not changed in principle, only in complexity. Scientific data and measurement fundamentals are partners in such a system, while standards serve only to smooth the interactions between various elements of the system. Very few tasks require the ultimate measurement capabilities, e.g., studies of fundamental constants and certain classified requirements. For the remainder, there are numerous solutions which will produce adequate results, the final form of which depends on many factors.

In one sense, NBS has utilized its basic assets (motivation, resources and time) to develop a competence in determining realistic requirements and in provided guidance in the development of processes which will meet such requirements in the most economical manner. There are, however, economic-political-social forces, both with NBS and within the system, which strive for a more tightly governmentally controlled system resulting in new responsibilities for NBS which may or may not be within the present capabilities of the organization. In the absence of major change, as might be imposed on the structure by these forces, the current level of effort at NBS is considered sufficient to maintain a minimal level of competence, to maintain an adequate access to the unit, to maintain reasonable progress in the advancement of measurement application and capability. Decreases in staff size or level of support would result in essentially zero progress in one or more of these areas.

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APPENDIX A. METHODOLOGY OF THE STUDY

The material in this study was based on a number of published and unpublished documents. Extensive use was made of the files of the NBS Mass and Volume Section. Material on the program of the NBS Office of Weights and Measures and its relations with the National Conference on Weights and Measures was obtained from the annual reports of the latter body. Additional information was obtained from the staff of the NBS Office of Weights and Measures. With respect to the International Organizations, use was made of material prepared for the U.S. Advisory Committee on the International Organization for Legal Metrology by the NBS Engineering and Products Standards Division. Data on NBS customers was developed from the files of the Office of Measurement Services.

A survey was run of selected customers, using economic data from Standard and Poor's Index of Corporations, Dunn & Bradstreet, and Moody's Handbook of Common Stocks. For the purposes of our study, we have sought to obtain trends in the interpretation of our customers' Standard Industrial Classification codes instead of attaching significant weight to the individual numbers since many of our customers are conglomerates.

A canvass of industry was made to establish a preliminary data base to confirm a few of our basic ideas concerning the structure of the mass measurement systems. The canvass consisted of two parts: an informal question letter and/or telephone interview with responsible individuals within an organization. In all cases no formal questionnaire was sent "blindly" into an organization. A high-ranking contact within a company was first established within our area of interest; a preliminary telephone interview was conducted; and if the need existed, a letter outlining other detailed questions was subsequently sent to the interviewee for his comments. An effort was made to look objectively at our NBS Customer Profile and select the SIC categories which could be interpreted to imply "first-order measurement-intensive" industries. By selecting companies from our customer list which possessed the majority of these codes within their products or services rendered, we were able to develop a systematic "sample" of the users. The canvass questionnaire is reproduced below:

PLEASE COMMENT ON AS MANY QUESTIONS AS POSSIBLE. USE ADDITIONAL SHEETS OF PAPER TO PRESENT YOUR VIEWS. ALL ANSWERS WILL BE STRICTLY CONFIDENTIAL. COMPLETION ON OR BEFORE NOVEMBER 5 WOULD BE APPRECIATED.

1. EXPLAIN THE NATURE OF YOUR BUSINESS IN TERMS OF SERVICES AND PRODUCTS RENDERED. PLEASE LIST AS MANY USES AS YOU ARE AWARE OF FOR MASS DETERMINATIONS. BE SPECIFIC.

2. HOW MANY DOLLARS AND/OR MAN YEARS DOES YOUR COMPANY EXPEND ANNUALLY IN SOME FACET OF MASS MEASUREMENT? IS THERE SOME COST-EFFECTIVE FIGURE THAT HAS BEEN COMPUTED IN TERMS OF THE INVESTMENT IN MASS DETERMINATIONS VERSUS PRODUCTIVITY?

3. IF YOU ARE A BALANCE AND/OR WEIGHT MANUFACTURER, PLEASE GIVE THE NUMBER AND SALES OF BALANCES ANNUALLY AND ALSO THE NUMBER AND SALES OF WEIGHTS.

4. WHO ARE YOUR MAJOR CUSTOMERS AND THEIR USERS (INTERNAL AND EXTERNAL) WITH RESPECT TO MASS DETERMINATIONS? PLEASE SPECIFY IN DETAIL THE ACCURACY AND PRECISION YOUR USERS NOW REQUIRE AT EACH STEP IN THE TRANSFER. IS THERE A FORESEEABLE NEED FOR GREATER ACCURACY AND PRECISION? IN OTHER WORDS, ARE YOUR CUSTOMERS REALLY USING ALL THE ACCURACY YOU NOW SUPPLY THEM? IF NOT, WHY NOT? (WE NEED AN EXHAUSTIVE ANSWER TO ALL OF NO. 4).

5. WHAT TYPES OF INSTRUMENTATION FOR MASS DETERMINATIONS ARE USED IN YOUR FACILITY? HOW DO YOU PROCEED IN THE CALIBRATION OF THESE DEVICES?

6. TO WHAT EXTENT DO REGULATORY AGENCIES (LOCAL, STATE, FEDERAL) GOVERN THE PRODUCTION AND/OR SALES OF BALANCES AND WEIGHTS?

7. DO YOU KNOW OF ANY PROBLEMS IN MANUFACTURING PROCESSES WHERE AN IMPROVEMENT IN THE ACCURACY OR PRECISION OR METHOD OF MASS MEASUREMENT MIGHT HELP RAISE PRODUCTIVITY?

8. WHAT TYPE OF PERSONNEL DO YOU HAVE INVOLVED IN MASS MEASUREMENTS? IS THERE ANY TYPE OF ADDITIONAL TRAINING YOU WOULD LIKE THESE PERSONNEL TO RECEIVE? IN WHAT AREAS?

9. DO YOU FEEL THAT IF YOU HAD TO "PROVE" THE ACCURACY OF YOUR MEASUREMENTS IN A COURT OF LAW, YOU WOULD HAVE SUFFICIENT EVIDENCE TO CONVINCE THE JURY? WHAT TYPE OF EVIDENCE WOULD YOU PRESENT FOR YOUR DEFENSE?

10. IF YOU USED THE SERVICES OF NBS, PLEASE STATE IN WHAT WAY. IF YOU ARE INVOLVED IN THE MASS MEASUREMENT ASSURANCE PROGRAM (MMAP) PLEASE SPECIFY IN DETAIL

YOUR LIKES AND DISLIKES. HOW CAN ANY, OR ALL, OF THESE SERVICES BE IMPROVED?

11. WHAT TYPE OF TRAINING SEMINARS AND/OR PUBLICATIONS WOULD YOU LIKE TO SEE EMANATE FROM NBS? IN WHAT AREAS OF INTEREST? TOWARD WHAT LEVEL OF PERSONNEL SHOULD THESE BE GEARED?

A typical response to the above questionnaire is this:

" 1. Our laboratory is under contract with the Atomic Energy Commission. Nature of work is classified and relative to the National Weapons Defense Complex. Mass determinations are used in:
   1. Research and development of explosive and nuclear items.
   2. Mass Standards Laboratory - Calibration of weights and balances.
   3. Production of miniature detonators and associated devices.

" 2. Seven man years are expended annually for calibration and maintenance of balances and weights. In addition, an undetermined number of scientists, technicians and workers use balances in their daily work assignments.

" 3. Does not apply.

" 4. Users of mass measurement equipment cover a wide spectrum as stated in Question No. 1. Accuracy and precision required vary according to use and range from being able to use a substitution balance without where $\pm$ .010 milligrams is required at the first transfer level (weight calibration).

" For example: Products being developed in the R & D areas may require a $\pm$ .010mg uncertainty. Calibration of the measuring equipment requires a minimum uncertainty in the mass standards, as the balance used in the areas consume most of the allowable error. Miniature detonators require weighings less than 50mg to an uncertainty of $\pm$ .2mg. Check standards used with this production equipment must be held to less than $\pm$ .015mg if product is to be within the accepted tolerance.

" Accuracy and precision requirements in the Mass Standards Laboratory are adequate, but can be reduced further if applying corrections to micro work necessary. Production requirements are constantly changing and are generally more difficult to meet each year. Improvements are needed in weighing equipment available from the manufacturer and not from the laboratory or NBS calibrating organization. In most cases, the customer is using the accuracy supplied.

" 5. Our laboratory has over 600 mass measuring instruments, representing most manufacturers, ranging from platform scales to quartz fibre microbalances. Most instruments are commercially acquired, although some balances are customized or adapted to our particular needs. Majority of equipment is substitution type analytical balances. Others include:
   Torsion Type Prescription
   Top Loaders
   Two Pan Free Swinging
   Two Pan Electronic
   Torsion Roller Smith Type
   Quartz Fibre

" Procedures for calibrating vary according to balance design and intended use. Internal weights are calibrated for bias. Precision is determined by repeated weighings at designated loads.

" Standard balances are calibrated via the National Bureau of Standards Mass Measurement Assurance Program.

" 6. Local, State or Federal agencies do not govern the production and/or sales of balances and weights. There is no noticeable effect on weighing equipment from these agencies.

" 7. None

" 8. Personnel involved in mass measurements are hired as unskilled and untrained. Our Mass Standards Laboratory provides a training class to provide the necessary training to operate the equipment proficiently. No additional training is required.

" 9. Sufficient evidence is maintained to prove the stated uncertainties in our Standards Laboratory mass measurement process. Statistical data and control charts furnished by the National Bureau of Standards Mass Measurement Assurance Program are maintained for this purpose. Similar information is available for production balances when weighing to tolerance approaches the capability of the equipment used.

"10. Our laboratory is an active participant in the National Bureau of Standard's Mass Measurement Assurance Program. There is very little criticism of the program; the calibration data received has been extremely beneficial to our organization and the assistance and cooperation from NBS personnel is above our expectations. The turn-around time on some jobs is less than desirable at times, and more frequent issue of up-to-date control charts would be advantageous.

"11. I would personally like to see more detailed procedures written in "users'" language on calibration procedures relative to mass measurements, other than weight calibrations. For example, procedures for calibrating small glass volumes and density measurements. Bowman and Schoonover's paper "Procedure for High Precision Determinations by Hydrostatic Weighing" is an excellent document, but unsuitable for routine density measurements. A less complicated proven procedure is desirable in many laboratories."

We have not limited our contacts to the industrial community; indeed, we have established contacts within other governmental agencies, hospital and laboratory personnel, and also medical societies. Specific contacts include:

Mr. Charles Stockman
Maryland Office of Weights and Measures
Department of Agriculture
College Park, Maryland

Mrs. Martha Winstead
Quality Control Coordinator
Southbend Medical Foundation
Southbend, Indiana
(219)234-4176

American Society for Medical Technology
Ste. 200
5555 West Loop South
Houston, Texas 77401
(713) 664-8121

Mr. David M. Jeffers
Administrative Technologist
Department of Pathology
York Hospital
York, Pennsylvania 17405

Mr. Robert Schoeneman
Internal Revenue Service
Alcohol, Tobacco and Firearms Division
Washington, D.C. 20226

Mr. Charles Muirhead
National Ocean Survey
Oceanographic Division
6001 Executive Blvd.
Rockville, Maryland 20852

Dr. James D. MacLowry
Clinical Pathology Department
Clinical Center
National Institutes of Health
Bethesda, Maryland 20014

APPENDIX B

The past of the Mass and Volume Section is inseparably intertwined with the history of Weights and Measures and NBS. As one reviews this history to identify strengths and weaknesses, one cannot help but note the progress of people through the organization over the years. As people move through the organization, so move philosophies and the way things are done, and to some extent, the way others view NBS. One can see, through the anecdotes of the past, only a generation removed, and through reviews of the historical records, a pattern which not only reflects the development of the section, but also of the NBS as a whole. Historically, it doesn't really matter why certain things were done; it is certain that the reasons appeared to be valid to those faced with the decisions which had to be made, but what was done is important to an understanding of why things are the way they are today. For the purpose of this discussion, the history of the section, and NBS, has been arbitrarily divided into "eras," which, in addition, have been arbitrarily named "Getting Started," "Confusion," "Transition," and "A New Start."

"Getting Started"

The basic tools of the trade are not new, the balance originating some time in the Bronze Age, and with "traceability" of the unit over at least 4500 years going back to Nebuchadnezzar. The mathematical tools also originated far back in time, with averaging in the days of the Romans[1]. Weighing by substitution, normally called "by the method of Borda," was used by Amiot in 1776. Transposition weighing, "the method of Gauss," and "least squares," are attributed to Gauss in the early 1800's. It is doubtful, however, that Gauss invented transposition weighing since it is the basic method of testing an equal-arm balance. He may, however, have been the first to treat the method in a mathematical analysis. Weighing designs started with Tartaglia in 1556, and Bachet in 1612, with later contributions by Hassler in 1817 and Broch in 1886. The science (or art) of mass measurement started in this country with Hassler.

Hassler was a competent metrologist, comparable with the builders of the kilogram in France, and the reconstructors of the pound in England. Fischer brought to the newly formed NBS the disciplines of Hassler, as he had learned them from those who had been instructed by Hassler himself [3]. He brought with him the weighing designs of Hayford which predate those of Benoit of BIPM [4,5]. Hayford's work has never been given the attention it deserves, perhaps because of the prestigious position of Benoit, and the fact that Benoit's presentation was somewhat more general. Fischer, together with his knowledge and the standards from the Coast Survey, became a part of the Weights and Measures "Section" of Division 1, under the direct supervision of Stratton.

Among the earliest circulars of announcements of the services that the new NBS could provide were those in the area of mass measurement and in the testing of glass volumetric apparatus.[1] By 1910, Fischer was Chief of the Weights and Measures Division, with 3 sections which were the genesis of the present Mass and Volume Section, and 2 sections which would eventually become the Office of Weights and Measures. Pienkowsky was the Chief of the Mass Section through 1940. Circular 3, Design and Test of Standards of Mass, (Rev. 3), prepared by Fischer and Pienkowsky, is a classic in the area of mass measurement.

Circular 3 treated both the problem of design and adjustment of weights, and the scientific use of mass measurements. For commercial use, three sets of adjustment tolerances were established: Class A, for state standards; Class B, an intermediate class which saw little use; and Class C, for commercial weights. This tolerance structure evolved from an end use requirement, that of weighing large quantities of materials with multiple lever scales. The problem was to establish a commercial tolerance for "tip" weights which, when multiplied by the lever ratio of the available scales,

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1 This, and the balance of this paragraph is an extremely brief summary of the history presented by C. Eisenhart in references [1] and [2].

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[1]The first five circulars are:

NBS Circular 1 The National Bureau of Standards
2 Measurements of Length and Area Including Thermal Expansion
3 Design and Test of Mass Standards
4 Verification of Standards of Capacity
5 Test of Clinical Thermometers

would not introduce an unreasonable systematic error in the weight of the goods. Having arrived at these limits, Class B and Class A tolerance limits were established such that compliance with Class C tolerances could be established with a minimum of measurement effort.

A story relating to the accomplishment of the above task has been passed down from those who were present at the time. Fischer was in the habit of keeping notes on his shirt cuff. The task of establishing the tolerance structure had been under discussion for some time, and at such a noontime discussion, Fischer worked out the tolerances on his shirt cuff. He had them typed immediately, but neglected to record the logic behind their origin. The shirt was laundered and the detailed logic upon which the structure was based was gone forever.

Pienkowsky was a tough taskmaster. Two types of calibrations were offered, one resulting in a "test report," and the other in a "certificate." The issuance of a "test report" usually meant that something was inferior, that the item did not warrant the best effort. Years of experience were required before one was qualified to work with items which warranted a "certificate." Weighing designs were used in both cases, and the quality of the measurement was established by the use of "check equations," e.g., if $A-B=X_1$, $B-C=X_2$ and $A-C=X_3$, then, if all is in order $(X_1+X_2)-X_3$, the "check equation" should be within some established limit. While Pienkowsky was the only one who knew the basis for the established limits, everyone in the group knew what they were and strived mightily to have their work be acceptable.

In this era the thermal problems of the equal arm balance were not as yet understood. The best work was done in isolation. Computations were done by hand with the use of slide rules and logarithmic tables. The work was checked and rechecked.[1] Work on large capacity scales, and the testing of railway track scales started in about the middle of the "era." A large effort was devoted to the testing of all kinds of large scales in addition to the railway track scales. With the track scale test cars operating out of a field station on the outskirts of Chicago, a truck equipped with large weights and weight handling equipment operated out of Washington. For remote scales, such as mine tipple scales, a large number of commercial 50 lb weights had to be "manhandled" to the scale location. With practice, one could pick up two in each hand, an amazing feat which no doubt supplemented the paycheck through side bets with the miners.

With the organization of the National Conference of Weights and Measures in 1912, additional sections were added to the Metrology Division to support that organization. This action initiated a rift which, up to now, is only partially repaired. Pienkowsky, in charge of mass measurements, was concerned with the scientific aspects of mass measurement up to 50 pounds, yet had to interface with both the Scale Unit and the legal aspects of weighing. The Scale Unit, because of the handling difficulties with large weights, was primarily engineering, and, to some extent, art oriented. The Scale Unit was concerned with the correctness of the result relative to a particular usage. The Weights and Measures Unit was concerned primarily with the legal aspects of metrology, e.g., right by definition. The Mass Unit insisted that the balance was a mass measurement device. The Scale Unit was more oriented in the practical usage of large weights; the Weights and Measures Unit was only interested in establishing systems which could not be attacked legally. Two anecdotes clearly illustrate the rift.

While the Weights and Measures Unit was stressing the importance of standards, one member of the Scale Unit would on occasion, and much to the dismay of the Weights and Measures Unit, calibrate a standard with a collection of flat irons, frying pans, stove lids and the like, all of which had been carefully calibrated in advance. State weights and measures people were taught to (1) pick up the weight in both hands (so as not to drop it), (2) approach the balance with care (so as not to fall), (3) bow slightly (so as to clearly identify the weight before it was placed on the balance pan), (4) place the weight gently on the balance pan, and do likewise for the second weight. Without the reasons which, of course, were a matter of routine within the Mass and Scale units this was interpreted as (1) approach the balance with awe, (2) genuflect, (3) put the weight on the pan, and do it all over again. Needless to say, there were very strong feelings between the various sections.

The close of the "era" was largely a matter of coasting on reputation, or position. Much time was devoted to detail of compliance with specifications, and to the extension of the tolerance limits to the variety

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1 Each operator was assigned a specific colored pencil, thus from the array of colored check marks on the computation sheet, one could identify the various "checkers."

of weights in common use and some of which were not so common, the onza and adarme.[1]

The program was in essence a semiregulatory action e.g., differentiating what would receive a "test report" and what would receive a "certificate" increased. Aside from Circular 3, little was done to advance the understanding of mass measurement, and to provide a direct service to the user. The Director signed each report, which in turn was embossed with the official Bureau seal. Since weights could not be "marked" without destroying the calibration, the "mark" was engraved on the case, which in turn was wrapped, tied with red ribbon and "sealed" with sealing wax and an appropriate signet.

"Confusion"

Reorganization early in the "era" changed the Weights and Measures Division to the Metrology Division and established the Office of Weights and Measures under the direct supervision of the Director. This action essentially severed the Office of Weights and Measures from the support of the technical divisions, including editorial review. Authority to sign "Test Reports" and "Certificates" was delegated to the section. The ritualistic procedures were, however, maintained.

About midway in the "era," the Mass Section and the Scale Section were combined and transferred to the Mechanics Division. This placed the new section in the area of applied science. Circular 547, the first of a planned series, updated the design and tolerance structure established in Circular 3. The philosophy of Circular 547 was oriented more toward "what they should have" rather than toward "what do they need." Manufacturers of weights were consulted and the tolerance structure was based on their estimates of the ability to adjust weights. These estimates turned out to be optimistic and, as a result, there were many rejections for "out of tolerance." The situation was eventually resolved by revising the specifications.

This presentation e.g. is another example of numerous attempts of NBS personnel to achieve a semiregulatory action, first the preparation of the specification, then the rejection for noncompliance. Much work was done on the drafts of the documents to follow 547, but none were completed and published.

Simplified procedures were published in the area of volume and density measurements. A method for testing the new quick weighing balance was published. Under the urging of the Office of Weights and Measures, a 1000 lb equal arm balance was developed [6]. By and large other publications of the "era" followed a rather fixed pattern: general classes of equipment were described together with brief outlines of test procedures used by NBS; some form of tolerance structure was presented; detailed discussion of what was necessary to receive a "certificate," and what would get only a "test report;" and finally a description of the mechanism whereby one submitted items to NBS for test.

Toward the end of the "era," the Mass and Scale Section was once again returned to the Metrology Division. At approximately the same time, the Office of Basic Instrumentation was established under the supervision of the Director and the position of Assistant Director for Testing was established. With regard to the section, in spite of internal conflicts between the Mass Unit and the Scale Unit, this marked the start of real progress, particularly with respect to the studies of the balance. The influence of the Statistical Engineering Laboratory, established in the late 1940's was beginning to be evident in the calibration programs. Higher management decisions, however, encouraged dissemination through equipment manufactures and networks of calibration laboratories. The success of such an action presumes that the second level laboratories assume the role of interfacing with the user. As it turned out, the second level laboratories elected to become "carbon copies" of NBS. Somewhere along the line, a "hierarchy" became firmly entrenched, with mission oriented facilities located several steps removed from NBS, and with no direct communication.

With respect to manufacturers, with tacit NBS approval, calibration "certificates" and the like were a part of doing business with the "hierarchy," with NBS frequently being a de facto extension of the manufacturer's quality control organization. It was a common practice for manufacturers and distributors to stock NBS calibrated items, with an add on "handling" charge far in excess of the NBS fee for the work. The practice of doing calibration work for manufacturers and distributors was encouraged by the use of "number of items calibrated" as a measure of the effectiveness of the section.

By the end of the "era," several basic papers had been published with regard to de-

1 The onza is the ounce of Spain and Spanish America. The adarme is 1/16 of an ounce.

tailed studies of balance characteristics [7, 8, 9, 10, 11]. The development of a precision kilogram balance had been started. Methods for calibrating weights in the direct reading balances were developed and published. The two-knife constant load 50 lb balance was at the state of evaluation of the development model [12]. The program for new state standards had been prepared. The "era" closed with the introduction of "traceability" through U. S. Air Force Bulletin No. 520. The introduction of the concept without definition created an endless scene of confusion.

"Transition"

The "transition" era included both the change from the monolithic structure of NBS to the present Institute structure, and the move from Washington to Gaithersburg. Hallmarks of the era were the technological explosion of the space age and the start of an extensive re-evaluation of the role of NBS. The "up through the ranks" method of filling vacancies was wanning, with new faces and new ideas appearing at all levels of management. The National Conference of Standards Laboratories was formed, thus uniting those who were faced with carrying out the quality control aspects of government procurement in the area of space exploration and defense. MIL-C-45662A, Calibration System Requirements, provided in part the missing definition of "traceability." Eisenhart's classic paper, "Realistic Evaluation of Precision and Accuracy," was presented in 1962 [13]. In 1963, by decree, uncertainty statements were required on all reports. Later that same year "certificates" were abolished, a positive move away from the semiregulatory action associated with the previous "report" and "certificate." Measurement results were reported on a "Report of Calibration." Where a "certificate" was mandatory, the institute Director would "certify" only that the measurements were made.

Early in the "era" there was a growing divergence of opinion concerning the interfacing of NBS with the users of the calibration services. At the section level, it was recognized that various end use requirements could not afford the degradation of the units through a hierarchy of calibration laboratories, and that there was a real need for the dissemination of measurement procedures. Most echelon laboratories were more concerned with emulating NBS than with being centers of measurement excellence. Lower level laboratories were faced with real measurement problems. The Assistant Director for Testing, however, was slow in recognizing this need, with the result that frequently NBS was presenting two "faces" to the users. With the press of cost-effectiveness measures, by the end of the era it was recognized in part within NCSL that the role of the calibration laboratory was limited.

Through this era, the Mass and Volume Section completely revamped both the program structure of the section, and the services provided. Each action, starting with obtaining a commitment from the Statistical Engineering Laboratory to support the evaluation of the measurement processes, was the result of micro-issue and micro-measurement system studies completed prior to starting the action. The capabilities of the section were augmented with the increasing use of computers, both time sharing and otherwise. The section staff, relieved from the tedious detail of checking and rechecking, could finally begin to think about what they were really doing.

The first computer prepared report substantiating a measurement process operating in a state of statistical control was issued in late 1963.[1] A large educational effort in mass measurement techniques, and in the characterization of measurement processes, was a part of the work with weights for force machines. Studies were made concerning the performance characteristics of mass measurement processes in other facilities. In late 1965, the Director of IBS gave verbal approval to proceed with the Mass Measurement Assurance Program (called at the time the Pilot Program in Mass Measurement). By late 1967, the program was operational, and tests were underway to evaluate, for the first time in a controlled manner, the measurement capabilities of one segment of the national measurement system, that associated with mass measurement.

Throughout this era there was a steady flow of papers, both tutorial and technical. Training conferences were held at NBS, and the section staff was invited to describe the programs at various meetings of professional societies. By virtue of a knowledge of the measurement process parameters, the "lost time" on the move to Gaithersburg was less than one week. One particularly difficult task associated with the move concerned the facilities which had been designed

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1 With the introduction of computer prepared reports, many of the rituals, including tying packages with red ribbon, sealing with wax and an official seal, were discarded.

and constructed on the basis of the anticipated role of the sections in the mid 1950's and which, by now, had considerably changed.

"A New Start"

This is the current era, and from the standpoint of calibration services, it is the era of the Measurement Assurance Programs. In the early days of this era, the Director of IBS established the Office of Measurement Services as an operating Division, and for the first time, NBS was able to present one "face" to the users of the calibration services. Efforts to unify the activities within the Metrology Division by the establishment of branches were not successful. In early 1970, the Metrology Division was disbanded, and the activities were combined with those of the Atomic Physics Division to form a new division, the Optical Physics Division. Immediately following, the Mass and Volume Section absorbed the Length Section and the Engineering Metrology Section, becoming the Mass, Length and Volume Section.

From the formulation of the new section until mid 1971, the activities were largely directed toward cleaning up a large backlog in the engineering metrology area, and in the establishment of the Measurement Assurance Program in the area of gage block measurements. In mid 1971, the Dimensional Technology Section was formed, assuming responsibility for both engineering metrology and length measurements (with the exception of tapes). The responsibility for the completion of the MAP program in gage blocks, however, remained as a responsibility of the Chief of the Mass and Volume Section, acting as a Special Assistant to the Division Chief for Measurement Assurance Programs.

The marriage of one of the most conservative areas of NBS with one of the most highly specialized scientific areas was to be an experiment. It is perhaps too early to evaluate the merits of the action. From the metrologist's viewpoint, it certainly provided a wealth of resources, however, a great effort had to be made in order to formulate the myriad of problems in such a manner that (1) the problem is of interest to the scientist, and (2) that the results from the scientist can be utilized in a practical sort of way. The measurement expertise of the section has assisted in certain areas, e.g., the redetermination of Avogadro's number, but, with few exceptions, there was no real interest in metrology to the depth necessary for assistance in problem formulation and solution.

Early in the era, the section accepted the task of the application of measurement process analysis techniques to the problem of reprocessing spent reactor fuel elements [14, 15]. This initial work was supported by other agency funding. A continuing activity over the era has been in consultation with appropriate committees working on specifications and guidelines for both mass and volume measurements in this field. The first specifications are now in the balloting stage, eventually to become ANSI standards for the industry [16, 17].

In early 1972, a precision kilogram balance, NBS-2, was shipped to BIPM [18]. As a part of the transfer, BIPM personnel spent approximately 1 month at NBS learning about our procedures, methods of data analysis, and the concepts of characterizing the performance of a measurement process. Over the past few years this balance has been used to evaluate the stability of Pt-Ir kilograms in preparation for planned intercomparisons of prototype kilograms [19]. In 1973, a new version of the report of mass calibration was introduced, a laboratory notebook type of report with a complete documentation of the measurements, and the status of the measurement process at the time the measurements were made. Much interest in these procedures has been shown by both Italy and Sweden.

In late 1974 the gage block measurement processes were operating in a state of statistical control, with new reporting procedures, and the development of detailed MAP procedures were under discussion. Bowman et al had completed the determination of pure single crystal silicon, the basis for a solid density standard. With the publication of procedures for the calibration of volumetric glassware, all of the procedures now in use at NBS are in the literature [20].

These brief remarks indicate the history of the section and the manner in which it has been operated over the years. The isolation with respect to the Office of Weights and Measures remains (primarily at the management level since the key working technical staff of OWM are former members of the Mass and Volume Section).

The important contributions, other than the direct support to certain specific areas of science and that obviously associated with providing access to the mass unit, have been in the contributions to the understanding of the mass measurement process, and in the applications of measurement assurance procedures. The problems facing the section at this time are (1) those associated with the activities of the OIML, which are regulatory in nature and obviously in direct conflict with the directions of the section activity over the past 15 years; (2) the problems associated with the anticipated recalibration of the prototype kilograms by BIPM, scheduled tentatively to take place within the next several years; and (3) the extension of the mass unit to practical mass measurement scales.

The present environment of NBS reflects several distinctly different philosophies. Perhaps the largest group is the highly specialized who, after a cursory look at the role of measurement, has decided that the "way to go" is to organize, or legalize, measurement. The concepts of "certified standards," and "traceability" are the "obvious solution to all measurement problems" and with the problem taken care of in this manner, one can go back to the more interesting things. This philosophy was strongly advocated by the top administration up to the middle of the "transition era," at about which time it reached its peak. When carried to the extreme, such a policy becomes self-serving, that is, having created the organization, one exists to support that organization. In the meantime, there is little, if any, direct support to the user.

The opposing philosophy, originating in about the middle of the "transition era" concerns the adequacy of the measurements which have to be made by the user. Measurement assurance is merely doing what has to be done in order to be sure that the measurement is adequate for the intended use. To support this, one must look for the problems, then provide the most economical solutions. Of course there is a need for good standards, Standard Reference Materials and the like, but they are means to an end, not the end itself. Success is measured by the status of the measurement system itself, and not by the number of "certified standards" provided by NBS. To carry out such a program requires a willingness to learn, and a substantial commitment of time on the part of both NBS and the user. Needless to say, such programs are strongly supported from that segment of the user community which has real measurement problem but not in a coordinated way. It is unfortunate that coordinated opposition comes from those who see NBS activities as a simple means to meet contractual requirements.

APPENDIX B
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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.)*

This document, one of several similar documents resulting from the NBS study of the National Measurement System, reflects the results of intensive studies carried out from 1972-1975 relative to Mass, Volume and Density measurements in the United States. The history and the current status of these measurements is discussed as well as the relative role of NBS. A bibliography is included.

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