NBSIR 75-825

THE NATIONAL MEASUREMENT SYSTEM FOR CRYOGENICS

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U.S. DEPARTMENT OF COMMERCE, Rogers C. B. Morton, Secretary
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Acting Director

FOREWORD

CONCEPT OF A NATIONAL MEASUREMENT SYSTEM

"Concurrently with the growth and industrialization of this nation, there has developed within it a vast, complex system of measurement which has made possible the very growth that brought the system into being. This National Measurement System (NMS) stands today as one of the key elements in a worldwide measurement system that links all major nations together in a consistent, compatible network for communication and trade.

"Briefly stated, the essential function of the NMS is to provide a quantitative basis in measurement for (i) interchangeability and (ii) decisions for action in all aspects of our daily life -- public affairs, commerce, industry, science, and engineering.

"Our National Measurement System is one of a number of mutually interacting systems within our technologically based society that form the environment in which the individual citizen must live and function. Familiar examples are the communication, transportation, educational, medical, and legal systems, all of which may be included under the general heading of social systems.

"In view of the demonstrated value of the systems approach for the understanding and improvement of hardware such as computers and weapons, some of these social systems are being subjected to the same type of analysis. The National Measurement System, which evolved in this country with little formal recognition as a system, is now being examined in this way at the National Bureau of Standards (NBS) which undertook the study of NMS partly because of a growing realization of the all-pervasive nature and great economic importance of the nation's measurement activities, and partly because of the challenge to NBS in putting its splendid new facilities to optimum use for the benefit of the nation. Such optimum use can be approached only when NMS, of which NBS is a central element, and the services it requires for effective operation are sufficiently well understood.

"Because the government has wisely refrained from assigning leadership of NMS to NBS by law or executive order, the Bureau of Standards must maintain this leadership through demonstrated competence and general acceptance of its capability. This situation presents both a challenge and a responsibility. The NBS must make a continuous effort to understand the structure and operation of the NMS, to assess the value of its services for national objectives, and to develop means for evaluating its effectiveness.

"Our study of the National Measurement System is still in its early stages. There remains much work to characterize inputs and outputs, interactions with other social systems, involvement with national objectives, the functions of NMS elements, and couplings between the elements."

This description of the National Measurement System was first published by Dr. R. D. Huntoon in Science, 158, 67-71, October 6, 1967. *Dr. Huntoon at that time was director of the Institute for Basic Standards, of the National Bureau of Standards. For the reasons stated in the above quotation, Dr. Huntoon began and fostered systematic studies of the National Measurement System of which the following work is a part.*

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ABSTRACT

The Cryogenics Division of NBS has evolved as the nation's central laboratory for cryogenics, much as NBS itself has evolved as the nation's central laboratory with both broad and specific responsibilities. Cryogenic measurement and data outputs provide the common foundation for all the institutions and agencies throughout the nation employing cryogenics to solve their problems.

This Study of the National Measurement System showed that the Cryogenics Division of NBS provides almost every category of measurement and data service that NBS itself provides: not just an instrumentation system (including, for example, pressure, temperature, density, liquid level, flow rate, etc.), but also properties of fluids (both thermodynamic and transport properties); properties of solids (thermal, mechanical and electrical); an interface with the users through systems integration and advisory and consulting services; and a dissemination network through the Cryogenic Data Center.

This study documents the impact, status and trends of the cryogenic measurement system and specifically illustrates these characteristics wherever possible with a specific case study, a recently completed measurements and data program for the flowmetering of liquid nitrogen.

Key Words: Cryogenics; data; flowmeter; instrumentation; measurements; National Measurement System.

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EXECUTIVE SUMMARY

The National Bureau of Standards is not responsible for only one unit of measurement, or even a set of measurements. Rather, the legislative mandate calls for NBS to provide a base for such a *system*, *coordinate* that *system*, and furnish essential *services*. Thus it is the responsibility of NBS to assure the proper functioning of the Nation's *system* of physical measurement, the National Measurement System. Accordingly, the present microstudy was conducted to examine and document the way in which the NBS Cryogenics Division is meeting its particular responsibility to assure the proper functioning of our system of cryogenic measurement.

The Cryogenics Division of NBS provides the measurement and data services that support a whole technology. Almost every category of measurement and data service is offered that NBS as a whole provides: not just an instrumentation system (including, for example, pressure, temperature, density, liquid level, flow rate, etc.), but also properties of fluids (both thermodynamic and transport properties); properties of solids (thermal, mechanical, and electrical); an interface with the users through systems integration, and advisory and consulting services; and our own dissemination network through the Cryogenic Data Center.

This study shows that there are three specific emerging technologies within this broad area of Cryogenics which need a complete and consistent system of measurements and data.

For instance, a comprehensive measurement system for *liquefied natural gas* needs to be developed, with special emphasis on quantity gaging in storage, flow-metering for both mass and heating value, and basic measurements of thermal and mechanical properties of structural materials.

Basic measurements and data are required to support the development of *hydrogen* as a fuel, to improve hydrogen liquefaction efficiency, to recover liquefaction energy, to document hydrogen-compatible materials of construction, to develop improved insulation materials, plus measurement tools and techniques for the eventual commercial exchange of liquid hydrogen.

Superconductivity connects cryogenic measurements and data to the electrical power industry, for power transmission, generation, and storage. Knowledge needed here includes heat transfer rates, behavior of helium refrigerant flow systems, and the degradation of the superconductors with time and stress. Other practical uses of superconductivity are becoming apparent, such as the application of Superconducting QUantum Interference Devices (SQUIDs) to problems ranging from mineral prospecting to magnetocardiography. Accordingly, the needs to support this technology encompass instruments and techniques for physical measurements plus a technical data base.

The technologies discussed above show the importance of cryogenics in commerce in the U.S. today, and also show its truly diverse applications. If there were a "General Cryogenics Corporation" like a General Motors, it would appear in the top 10% of the Fortune list of the 500 largest U.S. Industrial Corporations. But it is important to note that there is <u>not</u> a "Cryogenics Corporation", *per se*. Cryogenics is an infrastructure industry. Similarly, the national system of cryogenic measurements is an infrastructure of cryogenic technology itself. The crucial question of this report is, how well does the measurement and data structure support the technology as a whole?

This study shows that some parts of the cryogenic measurement system seem to be characterized by adequate services and quality assurance (cryogenic temperature measurements, for instance). It appears one should have less confidence in other parts of the system. Pressure measurements, for instance, which are probably the measurement most widely made in all of cryogenics, appear not nearly so well supported, especially pressure measurements in extreme environments. Attention by NBS to these issues is in order.

Especially apparent at this time is the need for a different kind of measurement, namely one that describes the *quality* or *availability* of the commodity. Specifically, we refer not so much to the flow measurement of liquefied natural gas, for example, as to the need to measure its potential heating value.

It appears that one component of the problem of cryogenic measurement is that the field is somewhat static. There has been no concerted national effort since the peak of the space program.

A second part of the problem arises from the way cryogenic measurements fit into the National Measurement System. As long as only a single agency or one sector of our economy (National Aeronautics and Space Administration, the aerospace industry) was using essentially all of the results of its own measurements, then that part of the National Measurement System was internally consistent and in harmony with itself. Now, however, cryogenics is becoming more commercialized and moving to the market place, and thus external consistency as well as internal consistency is required to make this part of the National Measurement System work.

The third part of the problem is perhaps a derivative of the first. Because the field is relatively static, a crucial question is not being asked: are there predictable technological developments that will either create a need for new cryogenic instruments, or possibly provide an altogether new measurement means?

Certain parts of the cryogenic measurement system at the national level seem to be disconnected, or working independently of one another at this time. For instance, our perception is that the U.S. Coast Guard has the necessary authority to regulate certain aspects of liquefied natural gas transportation by setting certain physical standards, measurement codes, and practices. They may do this without necessarily having recourse to the NBS. Other national authorities, especially in the area of public safety come to mind. Accordingly, it appears that this part of the measurement system is disjointed. There is no objective reason why it should remain so. It would be in accord with the NBS mission and tradition to pursue these issues and resolve them.

A goal of this study was to achieve both conceptual breadth and depth by examining our role in the national measurement system as a whole, and illustrating this role with a specific case study, the liquid nitrogen flowmetering program. This program was instigated by the needs of state weights and measures officials, the industry concerned, and the public for confidence in the custody transfer of liquid nitrogen. This effort used nearly every competence and capability that NBS has developed: measurement services (tests and calibrations of meters), property data (thermodynamic property data for cryogenic fluids), standard codes and practices (Handbook 44), dissemination services (Office of Weights and Measures, the National Conference of Weights and Measures), and both voluntary and regulatory standards activities (through the most relevant industry group concerned - the Compressed Gas Association, and by adoption in state codes).

The general conclusion of this study is that the cryogenic measurement system is doing its job adequately at reasonable cost. There is no widespread feeling of inadequacy, such as that which led to the creation of the National Bureau of Standards seventy-five years ago. On the other hand, there are both systematic and specific deficiencies that can and should be corrected. Further, there are several areas in which the cryogenic measurement system will be subjected to severe strains in the foreseeable future, unless appropriate responsive steps are taken soon.

Specific needs and responses, which are only summarized here, are documented within the body of the report.

1. INTRODUCTION

National commerce in cryogenics, a vital outgrowth of the chemical industry, exceeds $2 billion annually. It is both a domestic and international business, which may be broken down into three areas. They are:

- Industrial Gases and Equipment
- Liquefied Natural Gas
- Superconductivity.

Industrial Gases and Equipment. Industrial gases provided by cryogenic techniques are very important commodities. According to the most recent Department of Commerce survey, the annual production of liquid oxygen is about $300 million, 50% used in the production of steel and 20% in the chemical industry. Aerospace use is less than 2% -- even less than that used for sewage disposal. Minneapolis, Tampa, New Orleans, and Fairfax County, Va. are among the many places that use oxygen to speed up sewage treatment by factors of 3 to 5. More than 50 oxygen plants are planned or under construction in the U.S. for sewage treatment.

Fifty to sixty percent of all the hospitals in the U.S. presently store their breathing oxygen as liquid, and the American Hospital Association states that every new hospital costing $1 million or more uses liquid oxygen.

Annual sales of liquid nitrogen are about $150 million, with over $50 million being used for food freezing.

One major airline uses 1.8 million pounds of liquid nitrogen per year for galley cooling. Company officials claim that "the procedure is wondrously simple and reliable and that the experience has been so favorable that all future aircraft will use the same technique." The Department of Transportation has watched this system closely to get a "feel" for the logistics of supplying cryogenics necessary for ground transportation systems.

Recently, a 400 ton-a-day liquid nitrogen plant was opened at Stafford, Texas to supply nitrogen to a major semiconductor device manufacturer to protect electronic parts from impurities during manufacture. Similar facilities exist in the Bay Area of California to support the electronics industry there.

Liquefied Natural Gas (LNG). It is predicted that by 1985 10% of our natural gas will be imported as LNG from Alaska or foreign sources. There are approximately 19 applications pending before the Federal Power Commission for permission to import LNG or to liquefy and store it for interstate use. These applications are not trivial. To illustrate, one peak shaving facility in Iowa will cost $23 million. Import terminals, including ships and pipelines have been described at costs for $2 to $6 billion.

Superconductivity. Although practical uses of superconductivity are not extensive at present, we expect these applications to grow and mature in the next few years. Present day superconducting magnets for liquid hydrogen bubble chambers rank as the largest solenoid magnets in the world.

Cryogenic processes seldom result in an end product in themselves, but rather play an essential supporting role in other more visible industries. As mentioned, 50% of the liquid oxygen production goes into steel making and another 20% into chemicals. Forty percent of the space industry is cryogenic based. The steel, chemical, and space industries are highly visible, but the cryogenics industry is not. If one were to go shopping for cryogenic merchandise, he would find little, for cryogenics is indeed an infrastructure industry.

It is thus the nature of cryogenics that it be largely hidden and obscure to most observers, while at the same time occupying a central position of great potential leverage on the nation's essential industries - steel, chemicals, space, transportation, agriculture, sewage disposal, and so forth. It would therefore be imprudent to leave the workings of cryogenics to chance, and accordingly this study of the National Measurement System was undertaken to document and evaluate the adequacy of our measurement and data services to this vital technology.

In making an inventory of all of our measurement services, we find that we offer nearly every type of service that NBS as a whole does, e.g., conceptual knowledge, instrumentation, reference materials, standard samples, reference data, and specifications. We have also documented our operations through the dissemination network, e.g., regulatory agencies, state offices, and central standards authorities. We have achieved both conceptual breadth and depth by examining first our role in the National Measurement System as a whole, and then illustrating this role with a specific case study.

2. STRUCTURE OF THE MEASUREMENT SYSTEM

The National Bureau of Standards is not responsible for only one unit of measurement, or even a system of measurements. Rather, our legislative mandate calls for NBS to *provide a base* for such a system, *coordinate* that system, and furnish essential *services*. Examination of these statues shows that the NBS has both unique and special responsibilities in relation to the Nation's science and technology, and very broad responsibilities as well.

So it is with the cryogenics at NBS. We are not responsible for "a" unit of measurement or even a tidy set of measurements. Just as it is a general NBS role to make science useful, so it is our *role* to make cryogenics useful. We do not develop technology. We do help others with applied research services to produce, diffuse, and enhance the value of practical knowledge. Our goal is to strengthen and advance the Nation's cryogenic science and technology--in short, make cryogenics useful.

Accordingly, since we do help support a whole technology, we find that we must provide almost every measurement and data service that NBS as a whole provides: not just an instrumentation system (including, for example, pressure, temperature, density, liquid level, flow rate, etc.), but also properties of fluids (both thermodynamic and transport properties); properties of solids (thermal, mechanical and electrical); an interface with the users through systems integration, and advisory and consulting services; and our own information dissemination network through the Cryogenic Data Center.

Table 1-1. Organization and outputs of NBS Cryogenics Division

Functional Organization	
Metrology	*A Centralized National Effort*
Solids Properties	
Fluids Properties	
Systems Integration	
Data Center	

Outputs

- Measurement Techniques
- Data for Decision Making
- Data for Reliable Design
- Technical Analyses
- Safety Criteria
- Impartial Assessment
- Information Services
- Technology Transfer
- National Standards

We are organized by function to provide these outputs (see table 1-1). We have found that such a functional approach generally serves us better than a programmatic one. Cryogenics is an evolutionary technology and our strength lies in being able to meet changing programmatic needs. We have in fact evolved as the Nation's central laboratory for cryogenics, much as NBS itself evolved during its early years as the Nation's central technical laboratory with both broad and specific responsibilities. Our outputs provide the common foundation for all the institutions and agencies throughout the nation employing cryogenics to solve their problems. The following sections will illustrate how we provide these services in practice.

2.1 Conceptual System

The Cryogenics Division of NBS is the only federal laboratory exclusively in cryogenics dedicated to helping develop and promote the successful application of all aspects of this science. As such, the conceptual system that encompasses our work ranges from the generation of basic, conceptual knowledge (e.g., fundamental constants, superconducting quantum interference phenomena) to specific problem solving for government agencies and other public institutions (e.g., technical advice to the Electric Power Research Institute on refrigerators for cooling superconducting electric power transmission lines). The specific quantities and phenomena that need to be measured relate to the properties of liquids and solids needed by engineers for design and construction purposes and also by scientists to improve the understanding of the physics of fluids. These properties (see also Section 2.2.3) include, but are not limited to, the thermodynamic property of fluids (compressibility, entropy, enthalpy, specific heats, sound velocities); electromagnetic properties (diekectric constant, refractive index); and transport properties (viscosity and thermal conductivity coefficients). The data required on solids (metals, alloys, and composites) used at low temperatures include the mechanical, thermal, and electrical properties.

Effective and reliable measurement systems are required for certain physical parameters at low temperatures, notably: pressure, temperature, density, liquid level, quantity, and flow rate, and, more often than not a very difficult parameter to realize in practice, the total "usable" mass.

The conceptual system also encompasses the <u>use</u> of low temperature phenomena as tools for the measurement of other physical parameters (see section 2.2.5.2) such as the electrical volt, noise, current, power, flux magnitude, etc.

2.2 Basic Technical Infrastructure

As indicated in Section 1., the cryogenic measurement system supports an international technology that ranges from multinational trade in liquefied natural gas to supplying breathing oxygen for hospitals. Accordingly, the technical infrastructure that supports this system in turn runs from the International Organization of Legal Metrology to state weights and measures officials, as a minimum. The following sections will describe some of the more important institutions and systems that help make this part of the National Measurement System function.

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

Several states, an industry association, and national and international organizations recently cooperated in a technical program to assure adequate quality control in one part of the cryogenic measurement system, namely the flowmetering of liquid nitrogen. We shall use this example to highlight the various standardization institutions that must interact to assure effective measurement control in even so small a part of the cryogenic measurement system.

Background. Liquid nitrogen is an important article of commerce--approximately $150 million worth per year changes hands. Its uses include food freezing, airline galley cooling, and providing a protective atmosphere for semiconductor manufacture and float glass production. Regardless of its wide use, it is a difficult commodity to measure for it is nearly always a boiling, two-phase mixture, whose value depends in part upon its density and in part upon its refrigeration capability. Commonly used practices of custody transfer had a vague technical basis, which inhibited both compliance and regulation, regardless of how well intentioned either party may have been.

In 1966, at least three groups took this problem under consideration. The description below is in approximate chronological order, but no great significance should be attached to the dates. The three groups did initiate their work separately, but eventually worked together toward a common solution, and often with overlapping membership. This example is presented to show an institutional structure through which standards are effected.

The Instrument Society of America Ad Hoc Committee on Cryogenic Flowmetering. The decision of the Instrument Society of America to establish this Ad Hoc Committee was based, in part, on a recommendation for "Calibration Standards for Turbine and Mass Flowmeters, Particularly for Cryogenic Fluids" from the first ISA Standards and Practices Panel Session held in conjunction with the 1965 Annual Conference. The committee membership was broadly representative of all concerned--States weights and measures officials, cryogenic fluid buyers and sellers, and meter manufacturers. The membership is shown in table 2-1.

Table 2-1. Instrument Society of America Ad Hoc Committee on Cryogenic Flow Measurement

University of Colorado
National Bureau of Standards
Transcontinental Gas Pipe Line Company
Missiles & Space Division, Douglas Aircraft
Cox Instruments
Wyle Laboratories
Potter Aeronautical
Air Reduction Company
NASA - MSFC
California Bureau of Weights & Measures

The abstract of the final report by the Ad Hoc Committee recommended: (a) a national standard and transfer standards; (b) an accepted methodology; (c) a national authority to develop the standards, transfer standards, and methodology; and (d) educating all personnel in the state-of-the-art of cryogenic fluid flow measurements.

The Compressed Gas Association Model Code. The Compressed Gas Association is a non-profit membership corporation chartered in the State of New York that represents all segments of the compressed gas industry in the United States, Canada, and Mexico. They also have associate members in European and Asian countries. Among its membership are over 250 companies (including North America's largest firms) devoted primarily to producing and distributing compressed, liquefied, and cryogenic gases, as well as leading chemical industry corporations that have compressed and liquefied gas divisions. A few of the members of the Compressed Gas Association who were most interested in liquid nitrogen flowmetering are shown in table 2-2.

It is estimated that the domestic companies listed below produce in excess of 95 percent of the cryogenic fluids marketed in this country.

In June 1967, the Compressed Gas Association proposed to the National Conference on Weights and Measures a model code for flow metering of cryogenic fluids. Although the Conference on Weights and Measures noted that cryogenic flow measurement problems were, at that time, centralized only in a few states, the Compressed Gas Association proposal was a significant step in national recognition of cryogenic flow measurement problems.

Table 2-2. Representative members of the Compressed Gas Association

Domestic:
Air Products and Chemicals, Incorporated
Air Reduction Company
Liquid Carbonic Corporation
Linde Division - Union Carbide Corporation
National Cylinder Gas Div. - Chemetron Corp.
International Oxygen Manufacturers Assoc.
CVI Corporation - Pensalt Chemical
Foreign:
British Oxygen Company
L'Air Liquide
Linde AG (Lotepro)
Messer-Griesheim

The California Code on Cryogenic Measuring Devices. The regulatory agencies saw a real need for traceability to a national standard since they are usually obligated by law to perform "type approval" inspections. In the fall of 1967, the State of California Bureau of Weights and Measures began hearings on its own proposed code for cryogenic fluid measurement devices used in California. After several hearings in the fall and winter of 1967-68, the code was adopted and made law in California on June 1, 1968.

The State of New Jersey was not far behind California with respect to such regulations. New Jersey officials stated that with the introduction of sales of cryogenic fluids to the trucking industry for use as a refrigerant, they would be forced to find some means of developing an acceptable proving method. Further, with the advent of the Sales Tax in the State of New Jersey, and no exceptions being known at that time given to the sale of cryogenics at the retail level to trucks, it was felt that the commodity would be subject to that tax.

Because such state agencies are obligated to promulgate regulations controlling the use of any commercially used weighing or measuring devices, including those used in cryogenic fluid commercial sales or custody transfers, the needs of these agency officials as expressed by them are pertinent and important to the subject at hand. They summarized their needs as follows:

"(1) With respect to standards, there should be a national "facility", a final "authority", a "referee" that would not be in competition with private industry.
(2) This "agent" should provide the necessary methodology to preserve the accuracy and precision of field measuring methods.
(3) This "agent" should continue to investigate new measuring methods in order to advance the state-of-the-art."

The International Organization of Legal Metrology. Just as the States preferred a central authority to coordinate these activities on a national scale, the gas producers themselves desired to coordinate such a standardizing activity on an international scale. Accordingly, the International Organization of Legal Metrology was brought into the program at the beginning to facilitate the adoption of the findings of this program as an international code. The collaborating countries are Austria, France, India, Italy, Japan, Netherlands, Poland, United Kingdom, Switzerland, Czechoslovakia, and the USSR.

2.2.1.2 Survey of Documentary Standards

Measurement accuracy must be assured to avoid failure in complex engineering designs and sophisticated experiments. But accuracy is even more important when quantities of goods or services in commerce are being measured. If a free-enterprise economic system is to thrive in a modern industrial society, buyers and sellers in the marketplace need to have as much confidence in the quantity and performance of goods exchanged as they do in the amount of moneys paid.

We will continue to use the liquid nitrogen flowmetering program as a specific example of the process by which practices and data become codified and have the effect of law.

As mentioned, State regulatory agencies have a real need for traceability to a national standard since they are obligated by law to perform type approval inspections. This is clearly outlined, for example, in the Business and Professions Code of the State of California. One provision of this code reads as follows:

"2500.5. The directory by rules and regulations shall provide for submission for approval of types or designs of weights, measures, or weighing, measuring, or counting instruments or devices, used for commercial purposes, and shall issue certificates of approval of such types or design as he shall find to meet the requirements of this code and the tolerances and specifications thereunder.

"It shall be unlawful to sell or use for commercial purposes any weight or measure, or any weighing, measuring, or counting instrument or device, of a type or design which has not first been so approved by the department; provided, however, that any such weight, measure, instrument, or device in use for commercial purposes prior to the effective date of this act may be continued in use unless and until condemned under the provisions of this code. (Added by Ch. 893, Stas. 1949.)"

After the hearings described in Section 2.2.1.1 had been held, the code was adopted and made into law in California on June 1, 1968. Of the code specifications, one of the most significant was tolerance.

"The maintenance tolerance shall be four percent (4%) of the indicated delivery on underregistration and two percent (2%) of the indicated delivery on overregistration. The acceptance tolerance shall be one-half the maintenance tolerances."

The State of California also suggested that "best values" of data be included in the California Code. The gases under consideration were limited to oxygen, nitrogen, argon, and hydrogen. The scope of the data required was increased to include saturation densities over a broad range of pressure and temperature for each gas. At the request of both the Compressed Gas Association and the State of California, a document was produced specifically to allow traceability of selected values.

These properties data are specifically called out in the California Code and accordingly has the same weight of law as the flowmeter calibrations and tolerances themselves, viz.:

"3081.2.6 Saturated Liquid Densities. Saturated liquid densities of Oxygen, Nitrogen, Argon, and Parahydrogen as prepared by the National Bureau of Standards, Boulder, Colorado, shall apply (Refer to National Bureau of Standards, Technical Note No. TN-361)."

This program on cryogenic fluid transfer is only one of the most recent instances where common data have proven beneficial to industry and Government. Many other times government agencies with to evaluate efficiency claims and production capacities projected by "paper studies". A complete and consistent set of design data is essential to this purpose. The National Aeronautics and Space Administration, National Accelerator Laboratory, Navy and other government agencies, for instance, specify that a common data base be used in its proposals to provide a sound basis for evaluation. Data so codified are in a very real sense "documentary standards", although not strictly speaking *de jure* standards.

2.2.2 Instrumentation System

Cryogenic instrumentation as a discipline is primarily concerned with the condition or state of cryogenic fluids, such as pressure and temperature. Such information is typically required for process optimization and control. In addition, as cryogenic fluids become increasingly commercially important, there is the question of "how much" is there? Accordingly, the instrumentation system must be able to provide answers in terms of liquid level, density, and flow rate.

A derivative question is arising more and more frequently, namely, of what utility or quality (in the same sense as thermodynamic availability) are the goods? As it is not "good enough" to count BTU's alone in energy conservation questions (the level of thermodynamic availability must be considered), so it is that the "availability" of the cryogenic fluids must be taken into account.

This was a nagging question during the space program when a so-called "empty" tank of liquid hydrogen could still contain 2% or so of its original mass, as a dense but unusable fluid. It is of importance today in the metering of liquefied natural gas, for instance, where the integrated heating value--which depends upon composition--is the preferred unit of commerce, rather than just the volume that has changed hands. This section addresses the measurement tools and techniques that are currently used to probe this part of the cryogenic measurement system.

2.2.2.1 Measurement Tools and Techniques

(1) Pressure. Of all the measurements made on cryogenic systems, surely one of the most common must be that of pressure measurement. Pressure measurements are made not only to determine the force per unit area in a system, but also to determine flow rate (head type meters), quantity (differential pressure liquid level gages), and temperature (vapor pressure or gas thermometers). Pressure measurements are thus fundamental to the smooth running of much of this part of the National Measurement System.

Pressure measurements in cryogenic systems have, for years, been made by simply running gage lines from the point where the pressure measurement is desired to some convenient location at ambient temperatures and attaching a suitable pressure-measuring device, such as the familiar Bourdon gage.

This system works quite well for most applications; however, there are disadvantages to this straightforward approach that may introduce problems in many systems. The two most important are: (1) reduced frequency response and (2) thermal oscillations. In addition, heat leak, uncertainties in hydrostatic head within gage lines, and fatigue failure of gage lines could become significant in some applications. Such problems associated with pressure measurement at cryogenic temperatures could be eliminated by installing pressure transducers at the point of measurement, thereby doing away with gage lines.

Like all instruments, the output of a pressure transducer depends not only on the primary input, in this case pressure, but also upon extraneous effects, such as the effect of temperature on its various components. Erroneous pressure readings can be caused by both steady state temperature effects and temperature gradient, or thermal shock effects.

While it is agreed that some available pressure transducers are capable of performing satisfactorily at low temperature, other types, e.g., piezoelectric, diode, inductance, reluctance, and electrokinetic devices, may perform equally well or better. It is therefore necessary, for the purpose of comparison, that all types of pressure transducers be tested at low temperature and at various frequencies to determine their potential for cryogenic use. Because pressure sensing devices often behave quite differently in a cryogenic medium, a systematic, well documented testing program is presently needed before all types can be evaluated and compared.

A cryogenic calibration system with varied capabilities is essential for the successful completion of such a program described above. The details of such a system have been described by Arvidson and Brennan [2].

(2) Temperature. Most engineering measurements are made with metallic resistance thermometers, non-metallic resistance thermometers, or thermocouples. Gas thermometers and vapor pressure thermometers find little practical engineering application, and hence are mentioned only briefly in the following paragraphs. A recent compilation of the commercial availability of thermometers is given in "Measurements and Data" [3].

Gas Thermometry. Constant-volume gas thermometry is familiar as a technique for accurate realization of the thermodynamic temperature scale. In such work, the pressure-temperature behavior is made as linear as possible by minimizing the extraneous volumes in the manometer and the connecting tubing. Troublesome corrections for these extraneous volumes decrease with decreasing bulb temperature, inasmuch as the proportion of gas in the bulb increases. On the other hand, gas imperfection increases with decreasing temperature.

If, however, the sensing bulb is made small, as compared to the external volume of the system at ambient temperature, the characteristic is far from linear, the sensitivity increasing greatly as the bulb temperature decreases. By using a Bourdon gage to show the pressure in this device, a simple gas thermometer is achieved that is useful for such purposes as monitoring the cool-down of cryogenic apparatus.

In order to obtain accurate results in gas thermometry, it is necessary to make many corrections. One must account for at least: the imperfection of the gas; the effect of the volume of the gas that is not at the temperature being measured; and the change of volume of the bulb with changing temperature. Accordingly, for engineering applications, gas thermometry is recommended only for indicating the approximate temperature or temperature trend.

Precision gas thermometry falls in the category of fundamental thermometers rather than empirical thermometers. It is much too demanding for common use.

Vapor-Pressure Thermometry. As is well known, vapor pressure is a sensitive but nonlinear function of temperature, providing convenient means for thermometry in limited ranges of temperature that unfortunately, do not join to provide continuous coverage of cryogenic temperatures. For example, the range from 40 K to 50 K is above the range of neon and below that of oxygen and nitrogen. Within its limits, however, this type of thermometer is very accurate.

These thermometers are most accurate in the area of the normal boiling point of the liquid used, and hence could be very useful, albeit over a very limited temperature range.

Advantages of this type of thermometry are that it is sensitive, can have good time response, is not affected by magnetic fields, and needs no calibration. The primary disadvantage is that it can be used only between the triple point and critical point of the fill liquid.

Metallic Resistance Thermometry. Since the resistivity of an element or compound varies with change in temperature, it has in many instances been used as a simple and reliable temperature-measuring device.

While there exist a number of metals that are more or less suitable for resistance thermometry, platinum has come to occupy a predominant position, partly because of excellent characteristics, such as chemical inertness and ease of fabrication, and partly because of custom: that is, certain desirable features such as ready availability in high purity and the existence of a large body of knowledge about its behavior have come into being as its use grew and have tended to perpetuate that use. Its sensitivity down to 20 K and its stability are excellent.

A variety of platinum resistance thermometers designed for engineering applications is now available. As with other transducers, these devices are subject to extraneous effects (noise). In this case, we wish to measure only the temperature dependence of the resistivity. However, we may also unwittingly measure the strain dependency as well. To avoid this, the engineering thermometers are built to imitate the strain free construction of the precision laboratory type thermometers.

There are two basic designs for engineering use: immersion probes and surface temperature sensors. The immersion probes feature a high purity platinum wire encapsulated in ceramic or securely attached to a support frame. Features such as repeatability after thermal shocks, time response in different environments, interchangeability, and mechanical shock tolerance differ between companies and specific designs.

The second type of industrial sensor is broadly known as a surface temperature sensor, whose geometry is such that they make good thermal contact with surfaces of various shapes. Sensors are available for clamping around small tubing, fitting into milled slots, and clamping under bolt heads. The principle advantages of these thermometers are that they are small, typically 0.25 cm x 1.25 cm x 1.25 cm, with perhaps a factor of two variation in any dimension.

Non-Metallic Resistance Thermometry. A number of semiconductors also have useful thermometric properties at low temperatures. A semiconductor has been defined as a material whose electric conductivity is much less than that of a metallic conductor, but much greater than that of a typical insulator. The most promising semiconductors seem to be germanium, silicon, and carbon. The latter, though not strictly a semiconductor, is included in this group because of its similarity in behavior to semiconductors.

Of the three, germanium has received by far the most attention, and germanium resistance thermometers are now available from several commercial sources. The resistance element is usually a small single crystal. Inasmuch as the resistivity is high, the element can be short and thick. It is mounted strain-free in a protective capsule. Because of this combination of features, the germanium thermometer is both rugged and reproducible.

The major disadvantage associated with the use of germanium thermometers is the lack of a simple analytical representation. Each thermometer must be calibrated by comparison at many points in the range of interest if the inherent reproducibility of the thermometers is to be utilized.

Thermistors. Thermistors (thermally sensitive resistors) are essentially resistors made up of sintered metal oxides. Frequently used materials are nickel, manganese, and cobalt oxides. The fact that these resistors are becoming increasingly popular in measurement and control circuits is attested to by the number of companies selling them [3]. The reasons for the increasing use are in part: 1) they are small, which tends to make the time response significantly less than one second; 2) they are typically high resistance units, which reduces the overall effect of lead resistances, and 3) their temperature-resistance characteristics are dependent on materials and procedures which allows thermometers to be developed that are particularly sensitive in limited ranges of temperature.

Thermocouples. Thermocouples have the familiar advantage that the temperature-sensing junction can be reduced in size to almost any desired extent, so that the disturbance to the object being sensed can be made very slight, and the response time can be very fast. They also have a familiar disadvantage; rather small voltages must be measured. In addition, they have a less familiar but very serious disadvantage; the net emf depends not merely on the materials nominally used for the two wires, but also on material inhomogeneities which, if located in a temperature gradient, will introduce parasitic voltages. These inhomogeneities may arise from variations in chemical composition or may consist of crystal lattice imperfections introduced, for example, by kinking the wires. Their presence can be detected by various tests but cannot readily be corrected for, so that testing merely serves to indicate whether a given wire should be discarded or not.

(3) Quantity or Liquid Level. Liquid level is but one link in a chain of measurements necessary to establish the contents of a container. Other links may include volume as a function of depth and density as a function of physical storage conditions. Fortunately, the actual discernment of the liquid-vapor interface (liquid level) is often the strongest link in this measurement process due to the significant progress made here in the course of the Nation's space program. As a result of this intense interest, liquid

level measurements can be made with an accuracy and precision comparable to that of thermometry, for instance, and often with greater simplicity.

This period of development led to many different physical embodiments of liquid level sensors, and there are as many ways of classifying these devices as there are authors who write about them. We shall classify them according to whether the output is discrete (point level sensors) or continuous.

Point Liquid Level Sensors. All liquid level sensors depend for their operation on the fact that there can be a large property change at the liquid vapor interface, a significant change in density, for example. This may not always be the case if the fluid is stored near its critical point, for instance, or if stratification has built up after prolonged storage. Be that as it may, point level sensors are tuned to detect a sharp property difference and given an on-off signal. Several of the more commonly used types are described below.

The thermal or hot wire type senses the large difference in the heat transfer coefficient between liquid and vapor. Since the heat transfer coefficient is much larger in the liquid than it is in the vapor, one can expect, for a given power input, that the transducer will have a different temperature and hence resistance, in the liquid than in the vapor. It is this change in electrical resistance that is actually sensed in a bridge circuit, and hence these devices can be made both simple and fast. Small platinum wires, solid carbon resistors, and thin-film carbon resistors are examples of sensing elements that are used.

The capacitive type depends upon the difference in dielectric constant between the liquid and vapor, which is essentially a function of the fact that the liquid is more dense than the vapor. This sensor is usually made in the form of a bulls-eye, with alternate rings forming the plates of the capacitor, and are installed so that the plane of the rings is parallel to the liquid vapor interface.

The optical type senses the change in refractive index between the liquid and vapor, which of course is closely related to the dielectric constant and density.

This type of transducer contains a light source and a light sensitive cell that are isolated from one another, but which do communicate down a prism. The prism is cut in such a way as to have total internal reflection when in gas, and yet let the light escape when in liquid. This is possible since there is a difference in the index of refraction of the liquid and the vapor, and since the critical angle for total internal reflection depends upon the index of refraction. This type of transducer has a very high in-out signal ratio, for the light detector is almost totally illuminated or totally dark.

There are also several acoustic or ultrasonic devices that depend upon the fact that the damping of the vibrating member is greater in the liquid than in the vapor. Often, a magnetostrictive element is driven at a constant power and is more or less dampened, depending whether it is in liquid or in vapor. The end of these sensors is about the size of a quarter dollar, but this does not in any way indicate the limit of its resolution. These devices can be tuned to detect only a fraction of the total damping that would occur upon total immersion, so that their sensitivity can be much smaller than the total end of the device. Piezoelectric versions of this acoustic type liquid level sensor are also available.

Continuous Liquid Level sensors take many forms. Some methods determine mass, while others are merely interface following, and usually are just continuous analogs of some point sensor. Among the mass sensors are the direct weighing schemes, nuclear radiation attenuation, and RF techniques. The interface-following types include differential pressure sensors, capacitance and acoustic techniques. These are described below.

Direct weighing schemes have been used for oxygen, nitrogen and other dense fluids, but have been handicapped in hydrogen use by the fact that the weight of the container is often large compared to the weight of the contents. In modern weigh-facilities however, the weight of the tank rarely exceeds the weight of the contents (when the tank is full). Calibrated balance weights and strain-gage load cells are most commonly used in this application.

Nuclear Radiation Attenuation has found some success in oxygen and nitrogen systems, but comparatively little use for hydrogen. This is so because hydrogen is nearly transparent to the commonly available sources of nuclear radiation, while the tank walls are relatively "thick" to the same radiation. Hence the fundamental signal to noise ratio is inherently low. Hydrogen does absorb beta radiation rather well, but then "windows" of beryllium or equivalent light metals must be placed in the tank walls. On the whole, this technique appears too sophisticated for simple engineering measurements.

RF Cavity Detection. In this system, microwave energy is introduced into a tank to energize it by setting up electromagnetic fields throughout the entire volume of the tank. The tank interior is a dielectric region completely surrounded by conducting walls. Such a system is called a cavity, and the resonant frequencies established are the normal theoretical modes of the cavity. Considerable development work has been done recently on both uniform density fluids and non-uniform density fluids, and this technique continues to show considerable promise for both mass-gaging and level-gaging in a variety of cryogenic fluids, including hydrogen. RF transmission characteristics through coaxial cables can also be used to detect liquid levels by measuring the time of flight of a RF pulse through the cable [4,5]. This latter technique is called time domain reflectometry.

Differential pressure measurements are simple to visualize, but difficult to realize in practice. "Noise" is always high due to boiling and potential thermal oscillations at the lower pressure tap. Also, the unknown level of the liquid in the gage lines can introduce hydrostatic head errors. In the case of hydrogen, the "signal" is low due to the unusually low density of hydrogen. Better success is obtained with other cryogens of higher density.

Capacitance sensors are widely used for the continuous measurement of the level of cryogens. They do not truly follow the interface, but sense the total contents of the container. That is, the dielectric constant of the gas phase contributes to the output signal, as well as that of the liquid phase. This can be a serious source of error in hydrogen because the density of the cold gas (and hence its dielectric constant) is significant compared to that of the liquid. This problem is especially troublesome in nearly empty tanks, but is often compensated for by either: a) segmenting the capacitor and ignoring the output from those sensor sections located in the vapor phase as the liquid level drops, of b) installing a few point sensors at critical levels and routinely calibrating the continuous sensor against tem. Rod-to-blade and concentric tube configurations are most common in this type of sensor.

In the acoustic devices, the liquid itself is used as the transmitting medium. A transmitter feeds an electric pulse to a transducer where it is converted to an acoustic pulse traveling at sonic velocity to the liquid-vapor interface, reflected back at the same speed to the transducer, where it is reconverted to an electric pulse, and finally sent to a receiver. Knowing the velocity of sound in a given liquid, the pulse transit time from transmitter-to-interface-to-receiver becomes an indication of liquid level. Sometimes an acoustic racetrack of known path length and variable time of flight is included to provide a measure of the density of the fluid. The product of the two measurements tends to give an indication of the mass of the fluid contained in the tank.

(4) Density measurements are closely akin to quantity and liquid level measurements because: 1) both are often required simultaneously to establish the mass contents of a tank, and 2) the same physical principle may often be used for either measurement, since, as noted, liquid level detectors sense the steep density gradient at the liquid-vapor interface. Thus, the methods of density determination include the following techniques: direct weighing, differential pressure, capacitance, optical, acoustic, and nuclear radiation attenuation. In general, the comments made above about the various liquid level principles apply to density measurement techniques as well.

Two exceptions are noteworthy. In the case of homogeneous pure fluids, density can usually be determined more accurately by an indirect measurement; namely, the measurement of pressure and temperature which is then coupled with the analytical relationship between these intensive properties and density through accurate thermophysical properties data.

The case of non-homogeneous fluids is quite different. Liquefied natural gas is often a mixture of five or more components whose composition and hence density varies with time and place. Accordingly, temperature and pressure measurements alone will not suffice. A dynamic, direct measurement is required, embodying one or more of the liquid-level principles described above. Such "densitometers" are presently under development, and it is premature to discuss their capability at this time.

(5) Flow. There are three basic types of flowmeters which are useful for cryogenic liquids. These are the: 1) pressure drop or "head" type, 2) turbine type, and 3) momentum type. We shall discuss each in turn.

Head Meters. This type of meter embodies the oldest method of measuring flowing fluids. The distinctive feature of head meters is that a restriction is employed to cause a reduction in the static pressure of the flowing fluid. This pressure change is measured as the difference between the static heads on the upstream and downstream sides of the restriction.

Theoretical development of the flow equations for head type meters may be found in publications of the American Society of Mechanical Engineers [6].

The appeal of these meters in cryogenics is more than simplicity, and stems from the possibility of eliminating the necessity for calibration, if proper design, application theory, and practices are followed. Design methods for orifices, flow nozzles, and venturi tubes are available in publications of the American Society of Mechanical Engineers [6]. Recommended practice for flange-mounted sharp-edge orifice plates can be found in publications of the Instrument Society of America [7] and the International Standards Organization [8].

The characteristics of the head meter are as follows. The device is strictly a volumetric meter; that is, it can of itself give no information regarding mass flow rate. With appropriate pressure sensing, the range can be extended up to 10 to 1. It is the very nature of these devices that they generate a decrease in pressure by accelerating the fluid. If we are dealing with a saturated cryogen, then this sudden decrease in pressure could lead to vapor formation (cavitation) in the flowing stream and an erroneous flow measurement. Many experiments [9], however, have failed to show any ill-effects attributable to cavitation. Nonetheless, it is good design practice to maintain static liquid pressures within the meter well above the fluid saturation pressure. In spite of all shortcomings, head meters are widely used and quite reliable.

The turbine-type volumetric flowmeter is probably the most popular of the various flowmeasuring instruments, principally due to their simple mechanical design and demonstrated repeatability. The turbine-type volumetric flowmeter is a simple mechanism that consists of a freely spinning rotor having a number of blades, each inclined at an angle to the axis of flow. The rotor is supported in guides or bearings mounted in a housing that forms a section of the pipeline. The angular velocity (rpm) of the rotor may be detected by one of a number of methods; e.g., a permanent magnet encased in a rotor body will induce an alternating voltage in an inductive pickup coil mounted on the housing, or the core of the pickup coil may consist of a permanent magnet and the rotor constructed of a magnetic material so that the change in magnetic circuit reluctance, as each rotor blade passes the coil core, causes an alternating current to be induced in the coil. Capacitive and photoelectric methods of observing rotor rpm have also been used. The primary requirement, however, is that the angular velocity of the rotor be directly proportional to volumetric flowrate, or more accurately, to some average velocity of the fluid in the pipe.

A variation of the turbine type meter is the "twin turbine" type. In this case, two turbines of different blade pitch are coupled together by means of an elastic restraint. Because of the difference in pitch, they would tend to revolve at different speeds. However, this is prevented by the elastic coupling so that they do revolve at the same speed, but with a "phase angle" between them. The magnitude of the phase angle is a measure of the flow rate and is said to be, in fact, a measure of the mass flow rate.

The vortex shedding meter is also a single-phase fluid rate-velocity meter, like the turbine meters, but in a distinct class by itself. The phenomena upon which it is based is the Karman vortex trail and its application to the measurement of flow of liquids and gases is fairly recent [10], probably because only recently have sensors become available to detect the vortices.

The Karman vortex trail is used to explain certain phenomena associated with the flow around cylinders, ellipsoids, and flat plates. For flow around an object, eddys break off alternately on either side in a periodic fashion. Behand the object is a staggered, stable arrangement or trail of vortices. The alternate shedding produces a periodic force acting on the object normal to the undisturbed flow. The force acts first in one direction and then in the opposite direction, setting up a natural frequency of vibration.

If the frequency of the vortex peeling approaches or equals the natural frequency of the elastic system, consisting of the bluff object and its supports, the object may have a small alternating displacement normal to the stream flow. (The vibration of some smoke stacks, the vibration and the fatigue failure or progressive fracture of some transmission lines have been attributed to this resonance phenomenon).

The vortex sensors consist of electronically self-heated resistance elements whose temperatures and therefore resistances vary as a result of the velocity variations adjacent to the body. These velocity variations reflect directly the action of the vortices as they peel off from the downstream edge of the bluff body. The meter factor (pulses/gallon) depends only on the inside diameter of the pipe and the width across the bluff body face. Cryogenic evaluation is limited, to date, but performance on liquid nitrogen and oxygen shows promise.

Momentum Mass Flowmeters. Mass reaction or momentum flowmeters are of three types. There are those in which an impeller imparts a constant angular momentum to the fluid stream, and then the variable torque on a turbine which removes this momentum, is measured. There are those in which an impeller is driven at a constant torque, and then the variable angular velocity of the impeller is measured. And there are those in which a loop of fluid is driven at either a constant angular speed or a constant oscillatory motion, and then the mass reaction measured.

The performance of such flowmeters was determined in a National Aeronautics and Space Administration sponsored flowmeter evaluation program [11]. From the results of this program, it appears that several cryogenic mass flowmeters have been developed that are capable of liquid hydrogen mass flow measurement accuracies on the order of ±0.5 percent. There appears to be degradation of mass flow measurement accuracy, however, when subjected to a two-phase flow.

There are several other concepts of cryogenic fluid flowmeters that are available or are in development. Since they were not evaluated in the previously mentioned National Aeronautics and Space Administration sponsored program, definitive performance results, on the scale of the previously discussed mass flowmeters, are not yet available. These flowmeters are inferential mass flow measurement devices, having in common measurements of fluid density and fluid volume flow or fluid volume flow-induced momentum.

(6) Summary, Measurement Tools and Techniques. Since measurements are the basis of technology and dictate the fineness of our physical observations and control, it appears that this part of cryogenic technology may be lagging. One may conclude: 1) little is being done to bring the cryogenic instrumentation technology of the space program to the market place, 2) if it were, adequate primary instruments and facilities do not exist to bring this part of the National Measurement System under control, and 3) no concerted effort exists to explore the consequences or exploit the opportunities of new technological opportunities.

These conclusions appear to apply generally to each area of cryogenic instrumentation, although, of course with varying degrees of severity. Specific analyses and conclusions appear in each major instrumentation area in Section 2.3, "Realized Measurement Capabilities."

2.2.2.2 The Cryogenic Instrumentation Industry

Commerce in cryogenics is largely an extension of the chemical process industry (SIC Major Group 28). Even such special government programs as the space effort were built upon the existing foundation of the industrial gases and equipment industries to supply liquid hydrogen in unprecedented quantities of many tons per day. Similarly, there is no such entity as a cryogenic instrumentation industry. Rather, those same firms that supply instrumentation to the chemical processes industries modified and extended their existing capabilities into the cryogenic regime. In a few instances, largely due to unique requirements or limited applications, the airframe companies developed a special measurement capability themselves (e.g., measurement and control systems for liquid oxygen in life support systems). The result has been the measurement tools and techniques described earlier in Section 2.2.2.1.

Economic Magnitude. The economic magnitude and rate of growth of cryogenic instrument sales would be interesting to note. However, as indicated above, there is no such entity as a cryogenic instrument industry. Hence the data we might desire are obscured by the data on the measurement industry itself, SIC Major Group 38: Measuring, Analyzing, and Controlling Instruments; Photographic, Medical, and Optical Goods; Watches and Clocks.

Close inspection of SIC Group 38 reveals that cryogenic instruments for laboratory use are found in Code 3811: Engineering, Laboratory, Scientific, and Research Instruments and Associated Equipment. Some of the instruments found in this category are:

- Chemical
- Laboratory apparatus
- Gas analyzing equipment
- Laboratory testing and scientific instruments
- Physics laboratory apparatus and instruments, and
- Standards and calibrating equipment.

By far the greater number of cryogenic instruments will be found in Group 382: Measuring, Analyzing and Controlling Instruments. For instance, Group 3822--Automatic Controls for Regulating Residential and Commercial Environments and Appliances--includes:

- Float controls
- In-built thermostats, filled system, and bimetal types
- Liquid level controls
- Refrigeration controls (pressure)
- Refrigeration thermostats
- Temperature controls, automatic
- Thermocouples, vacuum: glass.

Group 3823--Industrial Instruments for Measurement, Display, and Control of Process Variables; and Related Products--includes establishments primarily engaged in manufacturing industrial instruments and related products for measuring, displaying (indicating and/or recording), transmitting, and controlling process variables in manufacturing, energy conversion, and public service utilities. These instruments operate mechanically, pneumatically, electronically, or electrically to measure process variables such as temperature, humidity, pressure, vacuum, combustion, flow, level, viscosity, density, acidity, alkalinity, specific gravity, gas and liquid concentration, sequence, time interval, mechanical motion, and rotation. Some specific examples pertinent to this study are:

- Flow instruments, industrial process type
- Level and bulk measuring instruments, industrial process type.
- Liquid level instruments, industrial process type
- Magnetic flow meters, industrial process type
- Pressure gages, dial and digital
- Pressure instruments, industrial process type
- Primary elements for process flow measurement: orifice plates, etc.
- Resistance thermometers and bulbs, industrial process type
- Temperature instruments: industrial process type, except glass and bimetal
- Thermistors, industrial process type
- Thermocouples, industrial process type
- Thermometers, filled system: Industrial process type
- Turbine flow meters, industrial process type.

The final classification of interest to us is Group 3824: Totalizing Fluid Meters and Counting Devices, which includes establishments primarily engaged in manufacturing totalizing (registering) meters monitoring fluid flows, such as watermeters and gasmeters; and producers of mechanical and electromechanical counters and associated metering devices. Instruments of interest found here are:

- Counter type registers
- Gages for computing pressure-temperature corrections
- Impeller and counter driven flow meters
- Meters: gas, liquid, tallying, and mechanical measuring - except electrical
- Positive displacement meters
- Propeller type meters with registers
- Totalizing meters, consumption registering, except aircraft
- Turbine meters, consumption registering
- Vehicle tank meters.

Close inspection of the 1967 census of manufacturers reveals the not surprising fact that all temperature sensors or all pressure gages are lumped under one code, regardless of their use. Accordingly, one cannot directly get at the magnitude of the cryogenic instrument business through such conventional means, and other means must be found.

For instance, an industry association occasionally has found it useful to look at a specific segment of their industry. The Instrument Society of America special committee mentioned in Section 2.2.1.1 made such a survey of flow meters, and their findings are shown in table 2-3.

Table 2-3 makes no allowance for the flowmeters that may be employed for liquid hydrogen and LNG custody transfers from trucks or trailers. The total investment of flowmeters is based on a price range of $700 to $2500 per flowmeter.

These figures refer only to the custody transfer (sale) of cryogenic fluids. Much more is at stake if one considers the total production of industrial gases, which are in fact made by cryogenic processes and include in-plant process transfers.

Table 2-3. Flowmeters in custody transfer of oxygen, nitrogen, and argon

Year	Total No. of Flowmeters	Total Investment Flowmeters in Millions	Custody Transfer/Year
1966	1000	$ 1.6	200,000
1967	1140	1.8	228,000
1968	1300	2.1	260,000
1969	1482	2.4	296,400
1970	1689	2.7	337,800
1971	1925	3.1	385,000

These figures were developed by the Instrument Society of America to help demonstrate that flowmetering had an economic magnitude such to merit attention, and that, in fact, this part of the measurement system could not be certified to be in control.

Substructure and Composition; Firms Involved. Several very recent and comprehensive reviews of specific cryogenic instruments and measurement systems have been prepared by the Cryogenics Division of the National Bureau of Standards for the National Aeronautics and Space Administration Aerospace Safety Research and Data Institute. This series includes flow measurement technology [12], low temperature measurements [13], density and liquid level measurements [14], and pressure measurements [2]. These are truly benchmark publications that discuss not only the technology of the measurement, but also give specific performance data. The data below are typical of the level of detail that may be found in all of the reports. They are taken from the treatise on flow measurement [12] for an oscillating piston volumetric flowmeter, as an example:

"The name plate specifications on the 1-1/2 inch meter are:

size - 0.0381 meters (1-1/2 inch)

maximum flow rate - 0.0044m^3s (70 gal/min)

minimum flow rate - 0.0088m^3s (14 gal/min)

maximum pressure - 2.413 MN/m^2 (300 psia)

material - aluminum piston, brass case.

. . . . . .

Table 2-4. Typical flowmeter performance

Flow Rate Gal/h	LO_2 Deviation	Water Deviation	Deviation LO_2 from water
300	-0.4	-0.53	+0.13
450	-0.55	-0.47	-0.08
800	+0.8	-0.5	+1.3
1700	+0.35	-0.7	+1.05
2100	+0.22	-1.05	+1.27

"From this table, the mean deviation of LO_2 from water calibration is equal to 0.73 percent (deviation from standard 14.67 counts per gallon). It may be expected that water can be used for the routine testing of meters of this type and a factor applied to obtain the correct liquid oxygen calibration.

. . . . . .

Table 2-5. Typical flowmeter performance

	1-1/2 Inch Oscillating Piston
Precision (3σ) at Start, %	±0.63
Precision (3σ) at End, %	±0.54
Bias at Start, %	+1.33
Bias at End, %	+0.61
Vol. Metered, m^3 (gal)	1225 (323,800)
Max. Flow Rate, m^3/s (gpm)	0.0044 (70)
Min. Subcooling, K	5

"Data on only one of the 1-1/2 inch nominal size meters are presented as a second meter underwent a reduction in registration by about 1 percent during these tests and was replaced. The change in bias is significant and indicates wear."

This level of detail is typical of all of the studies mentioned above, and accordingly they are highly recommended as source documents.

Certain trade journals also review the instrumentation field. Measurements and Data Journal is published bi-monthly by the Measurements and Data Corporation, 1687 Washington Road, Pittsburgh, PA 15228. In 1974, for instance, this journal published annual staff surveys on:

- Piezoelectric pressure transducers
- Force measurement
- Reluctive, inductive, and eddy-current pressure transducers
- Mass flow
- Capacitive pressure transducers
- Thermocouples and accessories
- Resistance and thermistor thermometry
- Strain-gage pressure transducers
- Turbine flowmeters
- Potentiometric pressure transducers.

These commercial surveys usually include a glossary of terms, physical theory, range, sensitivity, stability, cost, and accuracy. A small part of a typical table on resistance and thermistor thermometers from Measurements and Data, Vol. 8, No. 2, (March/April 1974), is given in table 2.6 to illustrate the very practical and comprehensive data that may be found.

Table 2-6. Resistance and thermistor thermometers

Model	Range	Accuracy and Comments	Price
Thermal Systems			
1001 Ni, Pt	-100/600F	Industrial probe; 100 ohms	$32
Model 1020 Pt	-430/1000F	General purpose RTD	$125
Model 5004	-100/500F	Etched Balco, thin surface sensor	$25
Model 5001-19	-260/400C	General purpose surface sensor; 500 Ohm	$50
Model 1064	-452/500F	Cryogenic platinum RTD	$400
Model 1010	-320/2000F	Hot gas platinum RTD	$800
Model 5002	-150/600F	Surface sensor	$25
Model 5148	-320/2000F	Miniature probe	$300
Thermo Electric Co., Inc.			
16301 Pt Sensor	-200/500C	0.26C at OC for 50-ohm element; 3 C at 500C	
Thermometrics, Inc.			
Series P20, P30, P60, P100	-100/300C	To ±.5% thermistor probe	$1 (Quantity)
Series HTP60, HTP100	-100/450C	Same; hi temp thermistor probes	$5 (Quantity)
Series B10,B14,B43	-100/300C	To ±.5% thermistor beads	$1-$4
Series HTB43	-100/450C	Same; hi temp thermistor beads	$5
Series 1F,2F, FM	-50/150C	To ±.5% thermistor flakes	$3-$20
Series FM	Same	Same	$.60

Every manufacturer that wishes to cooperate is included. Coverage is very close to 100% indeed. The above data were chosen simply as an illustrative but not nearly exhaustive example.

Trends. Trends in instruments for measurement, analysis, and control as a whole can be a helpful indicator even though the actual value of the cryogenic instruments specifically may evade use. The following discussion of trends is taken almost entirely from the "U. S. Industrial Outlook, 1974, with Projections to 1980", a U. S. Department of Commerce annual publication.

"Total industry shipments by manufacturers of measuring and controlling instruments are expected to reach $1.92 billion in 1974, a 7 percent rise over the $1.8 billion estimated for 1973. Industrial process instruments compose approximately 50 percent of this composite group. Business prospects for process instruments are closely related to the trend in capital expenditures for plant and equipment. Major sectors of the process group are the petroleum and chemical industries, prime markets for industrial process instruments.

"Additional industrial instruments are needed for the construction of plants to manufacture synthetic natural gas (SNG) from light oil, and for the facilities required to process and transport (*at cryogenic temperatures in liquid form*) natural gas from overseas sources to depots in the U.S.

. . . . . .

"Maintaining the pace required of a dynamic high-technology industry, manufacturers of measuring and control instruments continue to make substantial investments in newly designed products. These developments reflect customer demands for monitoring and control systems that improve process management, maintain tighter product specifications, achieve economy in production, enhance operating safety, and add to the protection of the environment. New high-temperature and *cryogenic technology* imposes requirements for innovative measuring instrument sensors capable of performing dependable and accurate measurements of ultra-hot and *super-cold processes*."

International Trade . With respect to international trade patterns, the same source continues:

"Technology continues to foster automated monitoring and control of industrial processes, and residential and commercial facilities in the U.S. and world-wide. The automatic temperature control industry, and manufacturers of measuring and control instruments, produce and distribute instruments whose common technology crosses national boundaries.

"Industrial processes and building methods are universal, and can be served throughout the world by instrumentation of similar design. Global leadership demands alert attention to changing requirements in various market sectors, and continuous advances in new product design. Manufacturers in these industries take part in numerous trade shows and exhibits in the U.S., and actively participate in scheduled trade shows and trade missions organized by the Office of International Marketing to reach foreign markets. Exports by both sectors of the instrument industry have steadily increased since 1968, with exports of the measuring and control instrument group progressing at an annual growth rate of 9 percent from 1967 to 1973.

"The Office of International Marketing has prepared a Global Market Survey on Industrial and Scientific Instruments, depicting business prospects in selected foreign markets: Global Market Survey, Industrial and Scientific Instruments, Office of International Marketing, 1972, U.S. Department of Commerce."

Examples of specific international interactions may be found in Section 2.2, where the NBS cryogenic flowmetering program is used to illustrate the process. In this program alone, the NBS Cryogenics Division: cooperated with the International Organization of Legal Metrology (OILM) to facilitate final adoption of our technical recommendations; performed "type testing" of meters of foreign manufacture -- affiliates of U.S. concerns; and encouraged and facilitated the visits and participation of international observers from the PTB; Linde, AG; Messer-Griesheim GMBH; Compteurs Schlumberger, France; and the British Oxygen Co., London.

The Industry as a Whole. A profile of this industry as a whole is given in the Box:

Table 2-7. 1973 Profile: instruments for measurement, analysis and control

SIC code --------------------	3821	3822
Value of industry shipments (millions).	\$1800	\$740
Number of establishments ----	661	105
Total employment (thousands)	67	40
Exports as a percent of product shipments	27.8	4.3
Imports as a percent of apparent consumption	5.5	n.a.
Compound annual average rate of growth 1967-73 (percent):		
Value of shipments (current dollars)	3.6	3.0
Value of exports (current dollars)	9.4	4.2
Value of Imports (current dollars)	25.7	n.a.
Employment -----------	9.2	0.8

n.a.= Not available.

2.2.3 Reference Data

Reference data are needed by the cryogenic community on both fluids and solids. The following sections describe some data producing activities, their users, and the principal means of dissemination.

Properties of Fluids. Pure fluids of interest in the Cryogenic Measurement System include helium, neon, argon, hydrogen, deuterium, nitrogen, oxygen, fluorine, methane, ethane, ethylene, propane, carbon monoxide and carbon dioxide.

The mixtures include air (N_2, O_2, Ar), natural gas (CH_4, other hydrocarbons, nitrogen), synthetic natural gas (CH_4, H_2, CO, CO_2), FLOX (F_2, O_2), and GDL laser fluids (He, N_2, CO_2).

Properties of interest are the thermodynamic properties (compressibility, entropy, enthalpy, specific heats, sound velocities); electromagnetic properties (dielectric constant, refractive index); and transport properties (viscosity and thermal conductivity coefficients).

Properties of Solids. The solids (metals, alloys and composites) used at low temperatures include aluminum and aluminum alloys, copper and copper alloys, nickel and nickel alloys, the austenitic stainless steels, titanium alloys, selected ferritic steels, a variety of superconducting materials, glass epoxy composites, and many more. The data on these materials at the required low operating temperatures include the mechanical, thermal, and electrical properties.

Needs for Data and Their Users. These data are required for many, and often diffuse, purposes including: a) data for material selection in the decision-making phase programs; b) data for equipment or process design and optimization (for example, refrigerator and liquefaction equipment, separation of gases, and storage and transport of liquids); c) data for analysis of the system or experiment, including safety criteria; and d) data for instrumentation and gaging, including sale or custody transfer.

It is important to note that these data are used by the entire cryogenic community, the $2 billion per year industry that supports a wide variety of technologies. To illustrate, the use of less expensive but structurally adequate metal could save $0.3 million on the cost of a single liquefied natural gas storage tank or $1.0 million on the cost of a single ship carrying liquefied natural gas--a total cost saving of as much as $15 million per year. In addition, economic analyses show that the value of the thermodynamic data to the design of a plant or facility is worth 1 percent or more of the capital cost of the entire unit--of considerable value when used for the design of large cryogenic units, many of which run into tens of millions of dollars [15].

A less quantifiable but equally important use of the reference data base is in establishing codes, standards, and recommended practices. These data often form the technical foundation for regulatory decisions by such agencies as the Federal Power Commission, the Department of Transportation, and the Office of Pipeline Safety, as well as the National Fire Protection Agency.

Methods of Acquisition. Data on fluid and solid properties at cryogenic temperatures are obtained by a wide variety of groups in industrial, government, university, and nonprofit laboratories. These data are referenced, compiled, correlated, and critically evaluated by our staff and form the basis for deciding what new measurements are required and which ones are not needed. Our staff performs comprehensive accurate measurements to fill important data gaps and reconcile inconsistencies where necessary.

Methods of Dissemination. The NBS Cryogenic Data Center [16] was established in 1958 and publishes a bi-weekly current awareness list of articles in the fields of cryogenic engineering and cryogenic physics which have appeared in the open literature. In collaboration with the Standard Reference Data Program, an accumulated total of nearly 100,000 technical articles have been received, cataloged and indexed for ready access. In addition, specialized quarterly bibliographies are prepared for: Superconducting Devices and Materials; Liquefied Natural Gas; and Hydrogen as a Future Fuel. The cryogenic community, including libraries, purchase these documents on a subscription basis, which covers the NBS cost of preparation. Subscriptions to these periodicals total nearly 1300 [17].

In addition, the staff of the Data Center responds to over 500 technical inquiries each year. Some of these requests require the use of an automated information system, in which case the user pays a fee for just the costs involved in the automated search.

The Cryogenics Division is the focal point for the measurement and data requirements of the cryogenic community. We established the National Cryogenic Engineering Conferences (CEC), now in their 20th year and NBS continues to be the secretariat. The 20 volumes of the conference proceedings "Advances in Cryogenic Engineering" are major resource documents for the workers in this field. In addition, we sponsor specialized conferences, like the International Cryogenics Materials Conference, and workshops to aid in dissemination of data.

The most prestigious of our outputs are the individual research publications, approximately 60 per year, or roughly one open-literature publication per professional man-year. Special purpose publications are much more numerous, and often more specific and timely. For instance, progress reports and NBS Technical Notes are frequently distributed directly to other agency sponsors and known users on a quarterly basis.

Pattern of Use of the Data in the Measurement System. As mentioned, the users of reference data by the cryogenic community are many and varied. Selected examples have been chosen to illustrate these uses.

a) Nat. Bur. Stand. (U.S.) Tech. Note No. 361 "Standard Liquid Densities of Oxygen, Nitrogen, Argon and Parahydrogen" by Roder, McCarty and Johnson, was prepared in 1968 at the request of the Compressed Gas Association and the State of California, Office of Weights and Measures. Subsequent revisions (1972 and 1974) have extended the range of data and provided a metric supplement. The latter was requested and paid for by the German Government for use in the European trade in cryogenic fluids. These data have now been adopted as a tentative code (law) by the "57th National Conference on Weights and Measures" and are now used as the data base for custody transfer (sale) in all commerce in the Western World for these fluids.

b) A comprehensive program on the thermophysical properties of pure methane has recently been completed. Nat. Bur. Stand. (U.S.) Tech. Note No. 653 "The Thermophysical Properties of Methane, from 90 to 500 K at pressures to 700 Bar", by R. D. Goodwin, contains the most comprehensive and accurate tables and interpolation functions available for methane, and NBS has already convinced the American Gas Association to accept these reference data as "agreed upon" data for the Nation's gas industry. NBS has made similar recommendations to the American National Standards Institute (ANSI) and the International Liquefied Natural Gas Conference, LNG-4, held in Algiers in the Summer of 1974.

c) A compilation and critical evaluation of data: "Thermal Conductivity of Solids at Room Temperature and Below" by Childs, Ericks and Powell, NBS Circular 131, is the basic reference document for all thermal conductivity data in this field. In addition to presenting the available data, it points to the data gaps and guides future research.

d) Many times NBS is called upon by other government agencies to evaluate efficiency claims and production capacities projected by "paper studies". A complete and consistent set of design data is essential for this purpose. The National Aeronautics and Space Administration, Department of Defense and the Energy Research and Development Agency, for instance, specify that NBS data be used in its proposals to provide a common, sound basis for evaluation. Similarly, our recommendations to the regulatory agencies would be open to question if it were not for a sound foundation of valid and consistent data.

e) Accurate density measurements and calculation methods for liquefied natural gas mixtures are being obtained to provide a basis for custody transfer agreements and for mass, density, and heating value gaging throughout the fuel gas industry.

The basis for the custody transfer of liquefied natural gas is its heating value. It is difficult to determine and agree on the heating value of extremely large volumes of natural gas in the liquid state. For example, methods for calculating the heating value of a liquefied natural gas mixture require knowing its density, which in turn depends on its composition, temperature, and pressure. As the composition of LNB mixtures vary considerably, depending on the sources of the gas and the processing conditions, accurate methods are needed for calculating liquid densities at arbitrary compositions, temperatures, and pressures. The accuracy is important because of the extremely large volumes of liquid involved (e.g., 125,000 cubic meters per ship). This project is being funded and guided by a consortium of 18 energy companies, and the results will be the industry "agreed upon" reference data.

2.2.4 Reference Materials

Reference materials are well characterized (and sometimes certified) materials produced in sufficient quantity to assure long term integrity of the measurement process. Reference materials for low temperature applications are continually being developed and characterized to help fulfill our goal of furnishing complete and comprehensive service to the cryogenic community. The materials studied are primarily metals, alloys, and composites. The electrical, thermal, and mechanical properties are the prime characterization parameters. These activities are described below.

Nature of the Data. Reference materials for cryogenic measurement standardization are principally solids, especially pure metals and alloys. Because of the economic significance of heat loss minimization and energy conservation, insulating reference materials are also of considerably importance at this time.

Properties of interest include the thermal conductivity, thermal diffusivity, thermal expansion, specific heat, and electrical resistivity. These properties are among those that depend significantly on variable material production factors.

A broad range of reference materials for each useful property is required to include the range of measurements encountered in practice. For example, thermal conductivity reference materials are required to span conductivities from the low conductivity insulating materials to the very high conductivity pure metals, a range of one million or more. The reference data for these reference materials must be accurate to near state-of-the-art levels. At this stage in the evolution of cryogenic technology, however, the prime requirement is for characterizing more new materials, rather than higher accuracy measurements on "older" materials.

It should be noted that reference data may be of little use without corresponding reference materials. Reference data of material properties can be grouped into two broad categories: those which are not significantly affected by variations in production techniques and those which are. The latter class of reference data require reference materials for their continued usefulness and are of principal importance at low temperatures.

Need for Data and Their Users. Reference materials and concomitant reference data are required primarily for three purposes, all of which form a basis for our national cryogenic measurement system's compatibility and accuracy: 1) to perform comparative measurements in which the measured property value is given directly in terms of the standard; 2) to perform apparatus check-out, thus basing the performance of the apparatus on the standard; and 3) to train new personnel, thus propagating a high level of reliability and expertise. We must be prepared to fulfill all three of these requirements to ensure compatibility within the Nation's measurement system and to promote meaningful measurements.

Methods of Acquisition. Reference materials are produced by industry and government under carefully controlled production conditions to assure maximum homogeneity of the material lot. The NBS Office of Standard Reference Materials (OSRM) produces, certifies, and issues reference materials and, as such, is the world's largest. Reference data for these materials must be determined by standards laboratories of the highest recognized expertise in order to realize their full utility.

The Properties of Solids Section of the Cryogenics Division of NBS has been active in establishing thermal conductivity, electrical resistivity, and thermoelectric reference materials. Recent efforts have resulted in establishing three metal reference materials covering a wide range of conductivity and temperature. These reference materials have been described by Hust, Sparks, and Giarratano [18, 19, 20, 21]. Another pertinent cryogenic reference device, and associated reference materials for measuring very low temperatures, has been described by Schooley [22]. Current plans are to extend this effort to insulating materials and other solid materials. One program to establish several insulating reference specimens, in conjunction with the National Aeronautics and Space Administration space effort, was undertaken by this laboratory, but remains incomplete at this time.

The NBS Office of Standard Reference Materials, as the world's largest source of reference materials, offers approximately 850 different items for sale. About 33,000 units worth approximately $1.6 million are sold annually. Information regarding these reference materials is available directly from the Technical Representative of the Office of Standard Reference Materials, Mr. R. W. Seward, phone (301) 921-2045, and also by catalog [23].

Certificates are issued with these materials listing the property and their accuracies.

"Uncertified" reference materials, usually known as research materials, are also provided by this office and other components of NBS. They serve a very valuable purpose as common source materials in round-robin intercomparison, as do the Standard Reference Materials. They also play a unique role in the calibration of research apparatus and methods, as opposed to engineering, or process quality control uses. These research materials are especially valuable as a foundation for comparing data obtained from different sources or by different means during the course of an experimental program.

Patterns of Use of Materials in the Measurement System. A few specific examples may be helpful to illustrate how reference materials are used. For instance, Hust [18] describes the preparation and characterization of an electrolytic iron. This thermal conductivity sample was characterized over the range 4 to 300 K to meet industry and government needs in 1971. The temperature range of this material was just recently extended by Hust and Giarratano [21] to 1000 K. Only a few of these materials are sold annually, especially when compared to the large volume of chemical composition samples that are distributed. However, the impact of this small number of samples may nonetheless be comparable, if one considers the improved reliability and confidence in the data that are subsequently published, following the common use of these materials in many laboratories employing many different procedures.

Many research groups routinely "prove" their apparatus with these research materials before publishing any data. In the past, discrepancies of 50% in thermal conductivity data were not uncommon. In one documented instance, a team at a major Mid-Western University has spent two years improving their data accuracy and credibility through the use of precisely the research material just described. In another instance, during the late 1960's, NBS was requested to provide consultation services for a thermal and electrical properties project in conjunction with a nuclear powered rocket program for the

National Aeronautics and Space Administration. Several measurement laboratories were involved, and the question of data accuracy between laboratories became a significant problem. To answer this question, we arranged a round-robin study on four reference materials. The results of this study were essential to the laboratories involved. In general, it showed that good agreement could be expected, but it also showed that large discrepancies could occur, even with simple measurements such as electrical resistivity. For instance, one of the four laboratories reported vastly different results that were later proven to be erroneous.

NBS has initiated a conscious and deliberate program of establishing selected research materials. These are referred to as "uncertified reference materials" since they are not accompanied by reference data. They are, however, highly characterized from the standpoint of homogeneity. These materials provide an excellent basis for intercomparisons of data. Subsequent studies performed on them allow a more logical intercomparison of data, thus improving our theoretical knowledge of the behavior of materials. This program is still in its infancy, and while much remains to be done, it also shows much promise.

2.2.5 Science and People

2.2.5.1 Cryogenic Measurements in Science

Cryogenics and measurements at cryogenic temperatures are widely used in research and investigation in basic science. Many Nobel Laureates received their honors either because of work directly in cryogenic sciences or because of work in which cryogenic measurements were indispensable. An imposing list of such Nobel Prize winners follows:

1902 Pieter Zeeman
Influence of magnetism upon radiation

1904 Lord Rayleigh
Density of gases and his discovery in this connection of Argon

*1910 Johannes Van der Waals
For his work concerning the equation of state of gases and liquids

*1913 H. Kammerlingh Onnes
For his investigations into the properties of bodies at low temperature that led, among other things, to the preparation of liquid helium

1920 Charles Guillaume
Finding cheaper materials for national prototype standards (Ni-Steel) INVAR

*1934 H. C. Urey
Discovery of D_2--was produced by distillation

1936 P. J. W. Debye
Debye theory of specific heats

*1949 W. F. Giauque
For his contribution in the field of chemical thermometry, particularly concerning the behavior of substances at extremely low temperatures

*1957 T. D. Lee and C. N. Yang
Upsetting the principle of conservation of parity as a fundamental law of physics

1960 D. A. Glaser
Invention of bubble chamber

1961 R. L. Mossbauer
Recoilless nuclear resonance absorption of gamma radiation

*1962 L. D. Landau
Pioneering theories of condensed matter, especially liquid helium (He^3)

*1968 Luis W. Alvarez
Decisive contributions to elementary particle physics, in particular "for his discovery of resonant states" through his development of hydrogen bubble chamber techniques and data analysis

*1972 John Bardeen, Leon N. Cooper, and J. Robert Schrieffer
Exposition of the "B-C-S" theory to explain superconductivity on a microscopic basis

*1973 B. D. Josephson, Ivar Giaever, and Leo Esaki
The discovery of tunnelling supercurrents (the Josephson-Junction)

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*Cryogenics crucial to the investigation

The kinds of people working in this part of the National Measurement System, and the fields of science that support it, are in part illuminated by the above list, especially during the last decade or so. There may be a trend away from the very basic work of Mossbauer and Landau, for example, to work of almost immediate practicality (BCS, Josephson, etc.). This is probably only an apparent trend, for who is to say that any work meriting the Nobel prize in physics is not basic?

Of more immediate concern to us is not only the ubiquitous nature of cryogenics in basic science, but also how often NBS has directly played a key role. For instance, the Lee-Yang parity hypothesis was experimentally proven by an NBS team--Dr. E. Ambler, and others. The BCS Theory was supported in part by the "isotope effect" experiments by Emmanuel Maxwell at NBS in the 1950's. Luis W. Alvarez, in his Nobel acceptance speech, said in part:

> ". . . problems involved in building and housing the 72-inch bubble chamber. We were also extremely fortunate in being able to interest the National Bureau of Standards in the Project. Dudley Chelton, Bascom Birmingham, and Doug Mann spent a great deal of time with us, first educating us in large-scale liquid hydrogen techniques, and later cooperating with us in the design and initial operation of the big chamber."

(The first publication on the 72-inch bubble chamber was authored by NBS Cryogenics Division Staff.)

2.2.5.2 Cryogenic Science in Measurements

This list of Nobel Laureats may also serve to illustrate the use of cryogenic science in measurements--employing cryogenics *per se* to develop new or improved measurement technology in fields outside of cryogenics.

For instance, Donald Glaser invented the bubble chamber that won him his Nobel Prize. Glaser recognized the principal limitation of the Wilson cloud chamber namely, that the low density particles in the cloud could not intercept enough high-energy particles that were speeding through it from the beams of powerful accelerators. Glaser's first bubble chamber operated near room temperature and used liquid diethylether. To avoid the technical difficulties presented by such a complex target as diethylether, Professor Luis Alvarez of the University of California devised a bubble chamber charged with liquid hydrogen. Since hydrogen is the simplest atom, consisting only of a proton and an electron, it interferes little with the high-energy processes being studied with the giant accelerators, although it is readily ionized and serves well as the detector in the bubble chamber.

The first large liquid hydrogen bubble chamber was installed at the Lawrence Radiation Laboratory of the University of California and first operated in March 1959. A remark was made that this 72-inch liquid hydrogen bubble chamber would be the equivalent of a Wilson cloud chamber one-half mile long. They could not really be equal, however, because the cloud chamber does not have the great advantage of utilizing the simplest molecules as the detector.

The most recent application of cryogenic phenomena to measurement science involves the so-called Josephson junction. Some of the most exciting phenomena worth exploiting in instruments and devices occur at weak electrical contacts between superconductors, known as Josephson junctions. They can be simple structures, consisting only of two pieces of superconducting metal lightly touching together. Often one of them is a fine wire reminiscent of the "cat whisker" of the early days of radio. Sometimes the structures are thin evaporated films, with barriers consisting of very thin layers of insulating material (or normal metal) or very narrow constrictions. The importance of Josephson junctions arises from the extraordinary way they respond to voltage and magnetic flux.

Under the influence of a small applied voltage, the current through a Josephson junction oscillates at a frequency strictly proportional to the voltage. The factor of proportionality (about 484 MHz per μV) is a fundamental constant of nature; twice the electric charge of the electron divided by Planck's constant. It has been measured with high accuracy (about one part in 10^7) by Langenberg and his group at the University of Pennsylvania. The accuracy of this measurement was limited at the time by the definition of the volt. Frequency was (and still is) the quantity which could be measured best, and the standard volt was maintained by a group of chemical cells. However, the Josephson junction has proven itself, and the legal volt has been maintained by this means since July 1, 1972.

If a Josephson junction serves to close a small superconducting loop, it becomes sensitive to magnetic flux as a result of quantum mechanical interference between electrons travelling around the loop. This results in a periodic response to magnetic flux, the period being the magnetic flux quantum (h/2e, or about 2×10^{-15}W), another fundamental constant of nature. This device has come to be known as a SQUID, an acronym for Superconducting QUantum Interference Device. It is the world's most sensitive magnetic sensor.

A most promising application of the SQUID is in magnetocardiography. The action of a beating heart generates small electric currents that can be magnetically recorded with the aid of a SQUID. The resulting record bears a strong resemblance to an electrocardiogram, but no electrodes are used to obtain it. Mere proximity of the instrument is sufficient. It has been discovered that, in addition to the short pulses of current generated by normal action of the heart, steady currents associated with various kinds of injury may also be detected. This may give useful diagnostic information that is not readily obtainable in any other way without surgery.

Another application that has been established in the field is electromagnetic sounding to depths of a few kilometers in the earth. A SQUID magnetometer has proven to be the best instrument for these measurements and has been used to map a geothermal energy basin in California.

Other applications of these very sensitive magnetometers include magnetoencephalography, geomagnetism, and communication through ground or water at frequencies of a few hertz, which would rapidly attenuate signals at higher frequencies.

The periodic response of the SQUID to magnetic flux suggests a new style of electrical metrology. One could measure current by counting off magnetic flux quanta in the same way that we measure length by counting off wavelengths of light. The Cryoelectronics Section at NBS is working on this now. Preliminary results indicate that it will be a powerful technique both for direct current and for radio frequencies up to the microwave range. Another advantage of electrical measurements employing cryogenic devices in general is the high sensitivity attainable because of the freezing out of thermal background noise.

The last area of activity to mention in applying cryogenics to other measurements is the extension of radio technology into the submillimeter-wave to far-infrared range of frequency. Possibilities include communication, radar, and astronomy. The recent development of powerful, coherent sources (such as the hydrogen-cyanide, water-vapor, and carbon-dioxide lasers) has stimulated exploration in this field. Receivers have lagged behind the development of transmitters, but with Josephson junctions we can hope for receivers of the same quality as we have at normal radio frequencies. The pioneering work was done by Grimes, Richards, and Shapiro when they were all at the Bell Telephone Laboratories. An NBS team, notably McDonald and Evenson, are synthesizing signals of stable and accurately known frequency throughout this range by using Josephson junctions to generate harmonics and mixtures of signals from the primary sources. One of their objectives is to extend this activity up to the range of visible light (using devices other than Josephson junctions for the final stages) and to measure the frequency of visible light of a well defined wavelength, such as is used for the standard of length. This raises the possibility of using a single standard for both length and time. Such a standard will have practical advantages as well as satisfying admirers of the theory of relativity. The technology they are generating will be directly usable for the other purposes mentioned.

These are just a few examples of the many existing and future applications of cryogenics, especially superconductivity, applied to electronics. The first few commercial instruments are appearing on the market; we can expect their number to grow.

One of the barriers to the widespread application of superconducting devices is of course the need to provide a liquid-helium environment. For small instruments, dissipating minute quantities of power, this is not such a severe problem as it might be for big machines. Liquid helium is widely available. Compact, portable containers can be engineered to run for several days between refills. In fact, the development of the SQUID, which has an established reputation as the world's most sensitive magnetic sensor, has now reached the stage that it is becoming the most convenient and portable instrument for many geophysical measurements. In collaboration with the United States Geological Service, a SQUID magnetometer was tested for electromagnetic prospecting for geothermal sources in the geyser basin near Clear Lake, California. It proved to be a handy instrument for this purpose. The same instrument was also taken as airline hand luggage to the Republic of Chad in Africa to make magnetic observations during the solar eclipse. Weighing only 10 kg, the instrument gave no trouble and showed that it is ready for use in even the most remote parts of the world.

2.3 Realized Measurement Capabilities

This section summarizes state-of-the-art technology for cryogenic instruments.

Pressure transducers are normally placed in a temperature controlled environment near room temperature. Some available pressure transducers are capable of performing satisfactorily at low temperatures, but new types such as piezoelectric, diode, electrokinetic, etc., may perform equally well or better. Information on their performance is needed.

For a detailed review of the ranges, accuracies, and precisions attained in pressure measurements, see the comprehensive review by Arvidson [2]. Table 2-8 below is reproduced from that work.

Temperature measurements are unquestionably in better shape than any other cryogenic measurements. Adequate calibration facilities exist, as well as a large body of knowledge that together help keep this part of the National Measurement System in control. Industrial type platinum resistance thermometers are routinely used, for instance. Improvements in their interchangeability would be desirable, as well as some simple thermometry for crude temperature indications and the monitoring of process trends.

Table 2-9 summarizes some representative characteristics of the best known types of cryogenic thermometers.

The terms "reproducibility" and "accuracy" require some explanation. Reproducibility means the variability observed in repeating a given measurement using the best present-day laboratory techniques. Changes produced on thermal cycling of the thermometer to and from ambient are included in this parameter. Accuracy means the significance with which the thermometer can indicate the absolute thermodynamic temperature. This includes errors of calibration and as errors due to nonreproducibility, the

Table 2-8. Cryogenic pressure transducers.

Characteristic	Strain Gage	Capacitance	Crystal	Reluctance
Frequency response, Hz	to 40 k Hz	to 500 K Hz	0.5 to 1 M Hz	1 K Hz (approx.)
Nominal sensitivity, % full scale	0.5	1.0	0.5	1.0
Thermal stability	Excellent for compensated bridge winding	Approx. temperature drift; 0.025 % per deg F	Good	Approx. 0.02% per deg F
Linearity, %	< 0.1	~ 1.0	0.5	~ 1.0
Response to vibration, noise, acceleration	Negligible for light-diaphragm and fully-rigid types	Low, but noticeable	Can be appreciable; also highly sensitive to electrical "noise"	Low, but noticeable; about 1.0% per 100 G
Drift, %	negligible	1.0 (excluding temperature drift)		2.0
Hysteresis, %	Approx. 0.2	1.0	negligible	0.5
Open-circuit full-scale output	Order of 50 mv	Order of 5 v	Order of 1 mv	Order of 5 v
Overload, %	Generally about 100; to 500 for special types	Order of 100	Satisfactory for elastic limit of crystal; poor for higher loads	Order of 100
Ease of calibration	straightforward	straightforward	No static calibration possible; dynamic calibration tricky	straightforward
Typical pressure sensing device	tube or diaphragm	diaphragm	crystal	diaphragm or twisted torsion tube
Cooling	Some designs air or water cooled (special types have heat-transfer rates to about 7.0 BTU/in^2/s	Some designs air or water cooled (special types have heat-transfer rates to about 7.0 BTU/in^2/s	Generally none possible	Generally none possible
Remarks and limitations	Good all-around. Expensive repair and replacement of parts on high-performance designs	Excellent instrument except for drift. Larger and more complex than strain gage	Unique in ultra-high frequency range. Not useable below about 5 Hz.	Maximum temperature 200 F. Low frequency response

former usually being much more significant.

The approximate numbers given for these quantities represent good current practice. It may be possible to do better by extreme care. On the other hand, in most engineering measurements a lower order of accuracy is permissible, and this may allow relaxation of certain requirements such as strain-free mounting of resistors, homogeneity of thermocouple materials, purity of vapor-pressure fluid, sensitivity, and accuracy of associated instruments, etc.

For temperatures above about 20 K, the metallic resistance thermometers are more sinsitive than the nonmetallic resistance thermometers. Temperatures above 20 K can be measured routinely with an industrial type platinum resistance thermometer with an accuracy of better than 100 mK and time responses somewhat better than 1 second. Accuracy at the millidegree level requires a precision capsule type platinum resistance thermometer and careful calibration.

Carbon thermometers are generally used for low temperature measurements (T < 80 K) when accuracies of ± 0.1 K or ± 1% of the absolute temperature are needed. Millidegree accuracy is attainable using germanium resistance thermometers at temperatures below 20 K. The primary drawback to germanium thermometers is that no simple analytical representation is available that represents the resistance versus temperature characteristics, even for a given class of doped germanium crystals. A many point comparison calibration is required if all the inherent stability of the resistor is to be utilized.

Vapor pressure and gas thermometry offer sensitive methods of temperature measurement with the advantage that no calibration is necessary. Further advantages are that these transducers are not sensitive to magnetic fields or electric fields. In the case of vapor pressure thermometers, the time response may be made comparable to the resistance thermometers.

A sensible recommendation about which type to use cannot be made without knowing the specific measurement requirements. The generalization most likely to hold true, however, is the following: for crude temperature indications and monitoring trends, a gas thermometer will probably be suitable; for more accurate work, vapor pressure or resistance thermometry is recommended; for engineering application in this latter area, the need is for inexpensive devices that do not call for unique calibration.

An outstanding review of cryogenic temperature measurements has recently been published by Sparks [13]. The above material borrows freely from this excellent benchmark study.

Level detectors for cryogenic fluids were extensively developed during the space program, but it is remarkable how little

Table 2-9. Some approximate characteristics of the most widely used classes of cryogenic thermometers.

TYPE	RANGE K	BEST REPRODUCIBILITY K	BEST ACCURACY[a] K	RESPONSE TIME S
RESISTANCE THERMOMETERS				
Platinum	10-900	10^{-3}-10^{-4}	10^{-2}-10^{-4}	0.1-10
Carbon	1-30	10^{-2}-10^{-3}	10^{-2}-10^{-3}	0.1-10
Germanium	1-100	10^{-3}-10^{-4}	10^{-2}-10^{-3}	0.1-10
THERMOCOUPLES				
Gold-Cobalt vs Copper	4-300	10^{-1}-10^{-2}	10^{-1}	0.1-1
Constantan vs Copper	20-600	10^{-1}-10^{-2}	10^{-1}	0.1-1
VAPOR PRESSURE				
Helium	1-5	10^{-3}-10^{-4}	10^{-3}	0.1-100
Hydrogen	14-33	10^{-3}	10^{-2}	0.1-100
Nitrogen	63-126	10^{-2}-10^{-3}	10^{-2}	0.1-100
Oxygen	54-155	10^{-2}-10^{-3}	10^{-2}	0.1-100

a-Including nonreproducibility, calibration errors and temperature scale uncertainty space hardware is actually used in the commercial sector. A deliberate effort to adapt space instrumentation to commercial and industrial applications may be worthwhile.

Primary instruments and facilities to calibrate liquid level devices do not exist, and accordingly it is questionable whether this part of the National Measurement System is in control. Furthermore, a large body of knowledge and experience needs to be developed to move with assurance from this relatively clean measurement to the practical measurement question of "how much does the tank really contain?"

Performance characteristics vary widely, depending upon the fluid being measured, its temperature, pressure, and even orientation. Accordingly, no brief summary is possible. The best complete review of this measurement may be found in the work of Roder [14].

Density is an inferential measurement and, as such, it should be traceable to a national standard, such as a national density reference system. Primary instruments to calibrate densitometers do not exist.

Several physical principles of cryogenic density measurement have been brought well forward by the space program. Notable are the capacitance, vibration, and nuclear radiation attenuation schemes. Microwave methods are recently moving to the forefront. Roder [14] has recently summarized this field as well.

Flow. There is no shortage of physical principles upon which to base a cryogenic flowmeter. Depending on the need, they range from simple pressure drop meters to sophisticated mass reaction types. Flow, however, is a derived quantity, and as such flowmeters require traceability to a reference system to establish credibility.

Summary. One component of the problem of cryogenic instrumentation is that it is largely static. Not much has been accomplished technically since the peak of the space program. There is little evidence of the commercialization of these instruments.

A second part of the problem arises from the way cryogenic measurements fit into the National Measurement System. As long as only a single agency or one sector of our economy (National Aeronautics and Space Administration, the aerospace industry) were using essentially all of the results of their own measurements, then that part of the National Measurement System was internally consistent and in harmony with itself. Now, however, the prospects are that cryogenics is becoming more commercialized and moving to the market place and thus external consistency as well as internal consistency is now required to make this part of the National Measurement System work. Primary instruments and facilities to calibrate the derived quantities--liquid level, density, and flow--do not exist. Accordingly, there is less confidence that this part of the cryogenic measurement system is as well under control as temperature is.

The third part of the problem is perhaps a derivative of the first. Because the field is static, a crucial question is not being asked: are there predictable technological developments that will either create a need for new cryogenic instruments or possibly provide an altogether new measurement means?

2.4 Dissemination and Enforcement Network

Standards are the means used to judge something as authentic, good, or adequate. They are the measures to determine what a thing should be, or whether it is correct. Thus, there are standards for measurements--prototypes, artifacts, the physical realization of a conceptual measurement--standard constants, including property data; standards of quality, of performance, and of practice (codes). The public outputs are usually pieces of paper--documentary standards. Behind all of these paper standards are the physical measurement standards that national authorities keep in their custody as artifacts, or that they define in terms of some physical phenomena.

Every form of standard, from the documentary standards to the physical embodiments, are essential to the proper functioning of the measurement system. In the discussion below, the word standard will be used deliberately ambiguously to indicate that all types of standards are involved in the dissemination and enforcement network.

Much of the Dissemination and Enforcement Network has been discussed in Section 2.2.1.1, "Standardization Institutions" and 2.2.1.2, "Survey of Documentary Standards." Here, we shall highlight this network with a specific case study, the Cryogenics Division's liquid nitrogen flowmetering program.

2.4.1 Central Standards Authorities

National Conventions. In the case chosen as the illustrative example, NBS itself was the relevant national authority.

This came in part because NBS has the ability to provide both national standards and international standards through such well established NBS mechanisms as NBS Handbook 44. It also came in part because our most useful and important type of standard setting activities may be the de facto standards --

which exist and are accepted just because NBS exists and is accepted -- such as the thermodynamic properties work mentioned in Section 2.2.1.2.

The State of California, during the hearings in the fall and winter of 1967-68, clearly developed and documented their need for a central, national authority. The record shows in part:

"With respect to standards, there should be a national facility, a final authority, a referee, that would not be in competition with private industry."

This expresses rather clearly the need for a centralized national effort in such matters that at first do not appear to transcend state boundaries.

International Conventions. The Compressed Gas Association was strongly motivated to deal with one national laboratory rather than 50 state laboratories. Recognizing this problem on an international scale, we at NBS have:

- Cooperated with the International Organization of Legal Metrology (OILM) to facilitate the adoption of the findings of this program as an international code;

- Performed type testing of meters of foreign manufacture as an integral part of the program. (See for instance, NBS Tech. Note 624, "An Evaluation of Several Cryogenic Turbine Flowmeters");

- Promoted and facilitated a six week visit by Dr. Josef A. Eberle of the Physikalisch-Technische Bundesanstalt (PTB). One result of Dr. Eberle's visit was his translating into German of our NBS Report 9778, "Cryogenic Flow Research Facility Provisional Accuracy Statement" to be used as a model by the PTB. Other international observers included Dr. Walter Linde and Dr. Klaus Schmidt of Lotepro, Inc., (a subsidiary of Linde, Germany); Dr. Helmut Peter and Dr. S. K. Windgassen of Messer-Griesheim, Germany; Dr. Heribert Wenzel of Linde (Munich, Germany); Dr. Jacques Hermel of Compteurs Schlumberger, France; and Dr. J. B. Gardner of the British Oxygen Co., England.

- One of the most important transactions occurred in an un-official way. Specifically, the Compressed Gas Association, which supported the eventual flowmetering program, formed a steering committee to help provide a degree of quality control to the program, but especially to help substantially by providing guidance and advice at critical stages of planning and implementation of the program. This committee met three to four times a year during the nearly eight year life of the program. In addition, state weights and measures officials routinely attended these meetings, which provided an invaluable forum for the cooperative solution of vexing problems. The real impact of this type of program may indeed lie in this kind of cooperation and communication.

NBS-Infrastructure. Within the NBS itself, there is a very strong and viable infrastructure that undergirds the whole standards setting activity. In this case, for instance, it included:

- The Institute for Basic Standards itself, whose statutory responsibility to provide basic measurements and standards made the cryogenic flowmetering program possible.

- The Office of Measurement Services, which provided guidance on accuracy statements, and experience in conducting round robins.

- The Patent Advisor, who provided guidelines for handling proprietary information on the performance of specific flow meters.

- The Office of Weights and Measures, (OWM), which publishes Handbook 44 and provides the secretariat to the National Conference on Weights and Measures (NCWM). The OWM gave our program the direction and mechanism to make its results have the effect of law.

- The Applied Mathematics Division, which helped plan experiments for statistical soundness and assisted in analyzing the results. This provided a scientific basis for interpreting claims in the trade literature of "accuracy" and "repeatability".

- The Cryogenics Division itself provided the essential technical base and resources. It is true time and again that the sound fixing of standards cannot occur in an ivory tower. It requires good judgment, and this can be applied only when there is sound comprehension not only of the science involved, but also of the ways in which it is being applied, and more subtly, of the ways in which it is likely to be applied in the future.

2.4.2 State and Local Offices of Weights and Measures

The state regulatory agencies saw a real need for traceability to a national standard since they are obligated by law to perform "type-approval" inspections. In the fall of 1967, the State of California Bureau of Weights and Measures began hearings which have already been described in Section 2.2.1.1. With the assistance of NBS, a code was adopted that was felt to represent equitably the capability of the meters then used in commerce. It must be admitted, however, that the tolerances chosen were arbitrary, with little or no cryogenic testing to back them up. The State of California, frustrated by their legal requirement to regulate the sale of liquid nitrogen, but with no technical capability to do so, essentially had no other choice. They set the same standard for liquid nitrogen as was then in force for gasoline. The suppliers, in effect, said "prove it". This impasse was resolved by the liquid nitrogen flow program.

Fortunately, perhaps, the original tolerances proposed by the State of California were later demonstrated by NBS to be realistic and feasible, a finding which facilitated the early adoption of the code. The producers were especially pleased to be able to deal with one central laboratory rather than 50 separate state labs. We regard this as a good example of "New Federalism" at work--as NBS competence is directly transferred to the states.

2.4.3 Standards and Testing Laboratories and Services.

Round-robin intercomparisons are at the heart of transferring the NBS measurement capability to the states, producers, and meter manufacturers. For instance, especially in the earlier stages of the physical evaluation of our own flow system, round-robins were conducted with industrial testing laboratories. These included the facilities of the Linde Co. at Tonawanda, N.Y., Air Liquide near Paris, The British Oxygen Co. in London, and Messer-Griesheim at Dusseldorf, Germany. This cooperation not only gave us a feeling of confidence in our own facility, but also opened the door for international agreement (via the OILM, for instance).

In addition, it is known that the State of California has already calibrated over 95% of all the meters used there in liquid nitrogen commerce. To further facilitate such intercomparisons, NBS has built and is currently proving a transfer standard of its own.

2.4.4 Regulatory Agencies

For this case study, consumer organizations *per se*, federal agencies (regulatory and otherwise), and the National Conference of Standards Laboratories (NCSL), a quasi-governmental regulatory unit, did not play a major role, although they surely would in other types of studies. This is so because the specific program highlighted here, concerning the metering of liquid nitrogen, was prompted by an unresolved technical controversy between certain state weights and measures bodies and the producers of a specific commodity. Accordingly, federal agencies, other than our own, had little or no interest or part to play; direct contact with the consumer was not necessary. The consumer's viewpoint was adequately represented by the State bodies, and in fact, the California hearings deliberately solicited the consumer's opinion. The National Conference of Standards Laboratories (NCSL) as a whole was of little interest to this particular study, for a much more narrow and intense resource existed as a sub-set of the NCSL, namely the ISA Ad-Hoc committee already mentioned.

2.4.5 Industrial Trade Associations

An unusually significant and interesting interaction occurred in the following way. The Compressed Gas Association, which supported the eventual flowmetering program, formed a steering committee to help provide a degree of quality control to the program, but especially to help substantially by providing guidance and advice at critical stages of planning and implementation of the program. As mentioned, this committee met three to four times a year during the nearly eight-year life of the program. In addition, state weights and measures officials routinely attended these meetings at our request, and often with our financial support. This provided an invaluable forum for the cooperative solution of vexing problems. The real impact of this program may indeed lie in this kind of cooperation and communication--structured yet unofficial.

2.5 Direct Measurements Transactions Matrix

Understanding the National Cryogenic Measurement System is closely related to understanding the cryogenic community, which is largely related to the production and use of cryogenic fluids. The following section profiles the supply and use of cryogenic fluids.

2.5.1 Analysis of Suppliers and Users

The cryogenic fluids with the largest dollar value of sales are: oxygen, nitrogen, helium, hydrogen, argon, and liquefied natural gas. Krypton, neon, and fluorine are also considered to be cryogenic fluids, but the quantities produced are very small and are not discussed here.

The value of the six fluids considered here was about $166 million in 1960. By 1968 the value had tripled to about $532 million. (These are values of liquids and gases produced by cryogenic processes and do not include low-purity gases or gases produced by electrolysis.) From 1960 to 1968 the annual growth rate averaged about 15%. However, the market began leveling off at $795 million in 1973. By examining each fluid and its market in turn, we see that it is not reasonable to expect both a constant and uniform growth rate for all fluids. The arguments for this less optimistic projection follow for each fluid.

Oxygen. High purity (greater than 99.5% pure) liquid oxygen is mainly produced by cryogenic air separation processes (electrolytic oxygen amounts to much less than 1% of high purity production). Low purity production (less than 99.5% pure) is about 1/6 of the high purity oxygen production.

A major use of oxygen is in the basic oxygen process for steel, which consumes about 80×10^9 std ft^3 per year, and open-hearth steelmaking where oxygen lances use over 50×10^9 std ft^3 annually. These uses are the main factors in the growth of oxygen production in recent years. The chemical industries come next, using some 15% of production, followed by welding, nonferrous metal refining, aerospace and breathing uses. It might be pointed out that the chemical industry is growing much faster than most segments of the United States economy and thus might be expected to contribute even more to the growth of oxygen production than does steel.

Shipments[1] of liquid oxygen are decreasing as a fraction of total production. This can be attributed to the fact that more liquid oxygen facilities are being built right at the users' doorsteps, and also that National Aeronautics and Space Administration consumption of liquid oxygen is decreasing.

Looking ahead, the industry itself predicts annual growth rates of 5-15% for the coming decade [24]. Using an average of 10%, we should reach 10^{12} std ft^3 by 1983.

New uses of oxygen could change this outlook materially. For example, the treatment of sewage and wastes by bubbling large amounts of oxygen through the tanks offers cleaner discharge, better phosphate and nitrate removal, and reduces the need for agitation, which speeds the sludge separation process. Approximately four times the oxygen concentration can be achieved in this way as compared to air bubbling, thus improving the bacterial degradation rate and helping the environment support aquatic life. The amounts of oxygen needed for this purpose in two or three decades could equal the amounts now used in steel.

Nitrogen. The economic importance of nitrogen is about half that of oxygen. It is the fastest growing of the major industrial gases. Nearly all high purity nitrogen is produced by the air separation process. More liquid nitrogen is shipped (as opposed to in-plant transfers) than is the case with oxygen. This is apparently so because the producers (often located near oxygen consumers) are not always located close to the nitrogen consumers, such as the food freezing industry. Nitrogen is used as an inert atmosphere in many metal, electronic, chemical, and aerospace industries. (See Section 1.0).

Looking beyond 1975, industry spokesmen feel that the past rate of growth will not be maintained, but will be greater than that of oxygen [24]. From 1960 to 1968, the rate was about 26%, but this is predicted to level out at 15-20% in the next decade.

Nitrogen is already widely used for food preservation, refrigerated transportation, and cryo-biology. Practically all the frozen shrimp in the U.S. are processed in this way, and nearly all the west coast lettuce shipped to the East comes under a cold nitrogen blanket. There are now approximately 500 truck stops in the U.S. where a truck can take on diesel fuel at one end, and liquid nitrogen at the other. The essential feature is that each truck now carries a simple tank of liquid nitrogen instead of a mechanical refrigerator.

Helium. The great majority of the proven, economically recoverable helium sources in the Western Hemisphere are found in the Texas-Oklahoma-Kansas area of the United States. These known reserves are estimated at over 150×10^9 std ft^3.

Most of the helium used in the United States has gone to government agencies such as the National Aeronautics and Space Administration, the Department of Defense, and the Atomic Energy Commission, which are required to buy their helium from the Bureau of Mines in order to finance the conservation program. Private producers entered the market with deliveries almost equal to that of the Bureau of Mines in 1967. The decreasing aerospace budget has resulted in smaller deliveries by the Bureau of Mines, which means less helium can be bought for conservation. (Each cubic foot of lost sales reduces the reserve purchases by 2.4 cubic feet.) These factors indicate that a readjustment of helium price structures may occur in the near future.

[1] Shipments is used in the special sense that it occurs in the Census of Manufacturers. It means the value of shipments, which is the net selling value, f.o.b. plant, after discounts and allowances and excluding freight charges and excise taxes.

One of the first tasks assigned by the Congress to the newly created Energy Research and Development Administration is to conduct a thorough study of the need for helium in energy applications (e.g., superconducting electrical power systems). The recommendations of this study will doubtlessly have a profound effect upon future helium conservation efforts in the United States.

Hydrogen. Liquid hydrogen production depends more on defense and aerospace activity than does oxygen or helium. Since the National Aeronautics and Space Administration used between 1/3 and 1/5 of the hydrogen produced, its variations had a large effect on the total picture. While the average rate of annual growth was greater than 30% during the 60's, it would appear that 10% is more likely during the 70's. Fields of hydrogen use, which seem likely to grow, are hydrogenation of edible oils, atmospheric control in the electronic and electrical machinery industries, and deoxidation in heat treating of metals. If hydrogen realizes its potential as a fuel, there may be explosive growth here (See Section 5.0).

Argon. Some 70% of the argon produced is used for welding reactive metals, but the continuous casting process of steel production could potentially use many times the current production (worth around $32 million in 1968) as a blanketing agent. Argon has shown an historical growth of about 17% annually from 1960 to 1968, matching the growth rate of oxygen for the same period. This is logical, since argon is produced cryogenically as a by-product in the air separation process for oxygen. If the continuous casting technology develops sufficiently to create a huge demand for argon, it would also give impetus to the oxygen producers located near the steel mills. If this new market does not develop, the growth of argon will probably be held to about the same rate as oxygen, or 10%.

Liquefied Natural Gas (LNG). In 1968, the least economically important of the cryogenic fluids was LNG, worth about $24 million. However, in 1972 it had already grown to third place and may be first shortly after 1976. LNG is used mainly for peak shaving purposes in areas where large volume gas reservoirs are unavailable, and also for base load supplies where pipeline gas is not feasible. It is predicted that LNG produced in the United States will have a value of about a billion dollars a year by 1976 [25], or over 10% of the total natural gas production of the country.

LNG is used as a replacement for gasoline in some vehicles to reduce pollution and gain in operating economy. All the fleet vehicles of San Diego Gas and Electric run on LNG, as well as about half the buses of the Chicago Transit Authority. All the off-the-road equipment of U.S. Steel in the Mesabi range likewise use LNG.

Other uses investigated include temporary consumer supply during pipeline disruption or maintenance, as a petrochemical feedstock, desalinization of sea water through freezing, and refrigeration and power supply for food freezing plants. The concept of clustering several industries that need refrigeration around a re-gasification facility should be considered more thoroughly. Many re-gasification plants waste the huge cold-potential by absorbing their heat from the air or ocean.

Profile Summary. In conclusion, then, it would appear that the growth of the cryogenic fluids industry will continue, but at a rate somewhat smaller than during the past decade, LNG excepted. A growth rate of around 10% seems a reasonable expectation, arrived at by weighting the growth rates of the individual gases according to the 1968 production figures. However, if LNG fulfills its promise, the rate could be much higher.

2.5.2 Input-Output Direct Measurements Transactions Matrix

General. A matrix has been constructed to show the transactions between suppliers and users. The elements indicated on table 2-10 include, for instance: The knowledge community, standards organizations, the instrument industry, NBS, regulatory agencies at all levels, industrial associations, and the general public. The entries in the intersection boxes describe the interaction as a whole within the Cryogenics Measurement System, not just those involving the Cryogenics Division of NBS alone, and certainly not just the flowmetering program used elsewhere in this report as a specific example.

Format. In the center of each box is a numeral indicating the magnitude of the transaction on a semi-quantitative "volume" basis:

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

In the lower left hand corner, there is a digit describing the rate of change of transactions at this intersection:

Table 2-10. Direct measurements transactions matrix

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR CRYOGENICS — SUPPLIERS / USERS	Knowledge Community 1	International Metrological Organizations 2	Documentary Standards Organizations 3	Instrumentation Industry 4	NBS 5	Other U.S. Nat'l. Stds. Authorities 6	State & Local OWM's 7	Private Stds. Laboratories 8	Regulatory Agencies 9	Department of Defense 10	Other Federal Agencies 11	State & Local Govt. Agencies 12	Industrial Trade Assoc. 13	Misc. Industrial & Commercial 14	General Public 15
1 Knowledge Community	4 1 2 2	4 1 2	4 1 2	2 1 3	4 1 4	3 1 1 2	3 2 2	2 1 3	3 1 2 2	2 1 3 2	3 1 2 2	2 1 2	2 4	2 3	
2 International Metrological Organizations	4 1 2	4 4	4 1 2	2 1 2 N	4 3 4 2	3 1 1 2	2 1 N	2 2 N	3 2	3 1	2 1		1 2	1 2	
3 Documentary Standards Organizations	4 1 2	4 2	4 1 4	3 1 3 2	4 1 3 2	3 1 1 2	3 1 3 2	2 1 2	3 1 4 2	3 1 2	2 2 2	2 2 2	2 1 3 2	2 3 2	2 1 1
4 Instrumentation Industry	2 1 3	2 1 3	3 1 3 2	2 3	3 1 3 2	3 1 1 2	3 1 2 2	2 4	3 1 2 2	2 3	2 2	2 1	2 3	1 3	1
5 NBS	4 1 4	4 3 4 2	4 1 3 2	3 1 3 2	4 1 3 2	3 2 1 2	3 1 2 2	2 2 2	2 1 1 2	3 4 2	2 1 4 2	2 1 2 2	2 1 4 2	2 1 3 2	1 2 1 2
6 Other U.S. Nat'l. Stds. Authorities	3 1 1 2	3 1 1 2	3 1 1 2	3 1 1 2	3 2 1 2	3 2 3 2	2 1	1 1	2 2 2	3 3 2	2 1 2 2	1 1 2	2 1 2 2	2 1 2	
7 State & Local OWM's	3 2 2	3 1	3 1 3 2	3 1 2 2	3 1 2 2	3 1	4 1 4 2	2 1 3	3 1 1 2			1 1 2	2 1 3 2	2 1 1 2	2 1 1
8 Private Stds. Laboratories	2 1 3	2 1	2 1 2	2 4	2 2 2	1 1	2 1 3	1 2	2 1	2 1	2 2	2 2	2 2	2 2	1 1
9 Regulatory Agencies	3 1 2 2	3 1	3 1 4 2	3 1 2 2	2 1 1 2	2 2 2	3 1 1 2	2 1	2 1 2 2	1 1 1 2	1 1 2 2	1 1 2 2	2 1 3 2	2 1 2 2	2 2 1 2
10 Department of Defense	2 1 3 2	3 1	3 1 2	2 3	3 4 2	3 3 2		2 1	1 1 1	2 1 4 2	2 1 3 2	1 1 1 2	2 1	1 1 2	1 1
11 Other Federal Agencies	3 1 4 2	2 1	2 2 2	2 2	2 1 4 2	2 1 2 2		2 2	1 1 2 2	2 1 3 2	2 1 3 2	2 1 2 2	2 1 3 2	1 1 1	2 2 1 2
12 State & Local Govt. Agencies	2 1 2		2 2 2	2 1	2 1 2 2	1 1 2	1 1 2	2 2	1 1 2 2	1 1 1	2 1 2 2	2 2 2 2	2 1 3 2	1 1 1 2	2 2 2 2
13 Industrial Trade Assoc.	2 4	1 3	2 1 3 2	2 3	2 1 4 2	2 1 2 2	2 1 3 2	2 2	2 1 3 2	2 1 2	2 1 3 2	2 1 3 2	2 1 2 2	2 1 3 2	2 2 1 2
14 Misc. Industrial & Commercial	2 3	1 1	2 3 2	1 3	2 1 3 2	2 1 2	2 1 1 2	2 2	2 1 2 2	1 1	1 1 1	1 1 1 2	2 1 3 2	2 2 3 2	1 1
15 General Public			2 1 1	1	1 2 1 2		2 1 1		2 2 1 2	1 1	2 2 1 2	2 2 2 2	2 2 1 2	1 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		

SUPPLIERS

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

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

N = Declining volume or needs
0 = Stable
2 = Growing
4 = Explosive growth or discontinuity on hand

In the upper left hand corner, a digit indicates the importance or criticality of the transaction:

1 = Purely a matter of convenience; transaction not essential; reasonable alternatives readily available
2 = Economically important; strongly desirable
3 = No satisfactory alternate source; legally required
4 = Essential; sole source; matters of life and death

In the upper right hand corner, another digit indicates the (in)adequacy of the transaction goods or services:

0 = No foreseeable improvements needed or desirable
1 = Under control, but could be improved
2 = Only marginally O.K.; significantly inadequate
3 = Seriously deficient
4 = Out of control; thoroughly unsatisfactory

The general code for a stable field is a zero. For ease in reading, all zeros have been suppressed in the table. There are no intentional omissions, as an "X" would have been used to indicate a factor deliberately excluded.

Double-lines are used to help subdivide the large matrix into smaller ones. For instance, double lines are found on either side of "NBS", and they are also used between the Department of Defense Sector and the Regulatory agencies.

Highlights. *International Metrological Organizations and NBS*, in the field of this microstudy, have only a moderate volume of transactions between them, hence the "2" in the center of the box. These transactions are growing -- "2" in the lower left hand corner -- as the importation of LNG increases. The interaction is essential -- "4" in the upper left corner. They are under control, but could be improved as the volume and variety of the transaction increases -- "1" in the upper right corner.

NBS and Other U.S. National Standards Authorities. A useful example here is our interaction with the U.S. Coast Guard, which is indeed a national authority that sets minimum specification and performance standards for ships that may use U.S. ports. We help by supplying technical information on the properties of LNG, potential hazards, handling procedures, and structural materials. The volume of this transaction is minor at present (1, center); is growing (2, lower left); is strongly desirable (3, upper left); and could be significantly improved (2, upper right).

It appears that the U.S. Coast Guard has final legal authority to set the standards required and to define the measurement codes and practices to test whether or not the standards are being met. The U.S. Coast Guard may do this without necessarily having recourse to the NBS. Accordingly, it appears that this part of the measurement system is disjointed at the present time. There is no objective reason why it should remain so.

Item 12, *State and Local Government Agencies*, for this microstudy includes: The New York City Fire Department and similar jurisdictions concerned with the safety of LNG.

The *General Public* has little direct contact with cryogenics, since it is essentially an infrastructure industry. However, transactions do occur in such diverse areas as liquid oxygen for breathing therapy, artificial insemination, cryo-embalming, and questions of safety regarding the storage and transportation of cryogenic fluids.

2.5.3 Highlights re Major Users

It has been claimed that cryogenics is nearly a $2 billion industry, and that there is widespread interest in it. The discussion below gives a few indicators leading to these claims and highlights the major users.

2.5.3.1 Industrial Gases and Equipment

Industrial gases are at present the backbone of this industry, and will continue to be while the liquefied natural gas component builds up. At some time in the future, LNG may surpass industrial gases (Carbon Dioxide, Acetylene, Nitrogen, Oxygen, Argon and Hydrogen --SIC Code 2813), but the value of shipments of industrial gases was $795 million in 1974, produced in 507 establishments employing 9,000 people [26]. A "rule-of-thumb" for this industry is that it has roughly three equal components: liquids, gases, and equipment. Therefore, if the liquids and gases sold were worth about $800 million, then the cryogenic equipment is worth about half of this again, $400 million, making the total about $1.2 billion.

The annual investment in capital equipment is at least 15% of sales [27] or about

$280 million. Thus the total expenditure in cryogenics is about $1.5 billion per year. These figures exclude LNG, but it is not hard to imagine the value of LNG bringing the total close to $2 billion.

In order to be more specific, we have analyzed the public Annual Reports of a few of the major corporations engaged in cryogenics. The findings are given below, and we may safely assume that the figures given are realistic, as such reports are carefully controlled by the Securities and Exchange Commission (SEC). Not all of the reports are from the same year. One is from 1971, for instance, but this discrepancy will only serve to make the figures conservative, as newer figures would be greater due to real growth, inflation, etc.

Table 2-11. Net sales of major cryogenic companies in the U.S.

Corporation	Net Sales
Chemtron Gases Group, formerly National Cylinder Gas (1972)	$ 156.4 M
Union Carbide, Linde Div. Gases and related products (1973)	581.0
Air Products and Chemicals, Gases and Equipment Group (1971)	209.6
Airco, Industrial Gases and Cryogenics Group, formerly the AiReduction Co. (1972)	240.0
Cryogenic Technology Inc. (1974)	33.0
Total	$1,220.0 M

These are not all the companies doing business in cryogenics, but they are representative of the principal ones. (Note that this demonstrable figure of $1.22 billion compares favorably with our previous "rule-of-thumb" estimate of $1.20 billion.)

We can still add approximately 15% [27] for the annual capitalization rate, or $183 million, and thereby get $1.403 billion as the annual size of the cryogenic gases, liquids, and equipment industry.

2.5.3.2 Liquefied Natural Gas (LNG)

The following is a brief summary from the published literature that tends to establish the dollar value of the LNG industry on an annual basis.

Import-Export. The Minerals Yearbook [28] states that 2.2615 billion cu. ft. of natural gas was imported as liquid from Algeria and Canada in 1972. In addition, it states that 47.9 billion ft^3 of LNG was exported to Japan from Alaska during 1972. Therefore, 50 billion ft^3 of natural gas in liquid form was involved in import-export commerce in 1972. By applying a conservative $1 per thousand std ft^3, it is possible to estimate a value of $50 million for the LNG import-export trade.

LNG Produced for Internal Consumption. We may estimate the value of LNG produced for internal consumption from the gross liquefaction capacity of peak shaving and satellite liquefaction facilities presently operating. Although LNG is generally not considered a *commodity* in peak shaving operations, it is nonetheless possible to estimate its value from the size of the national liquefaction capacity by assuming the market value of LNG at $1 per thousand std ft^3 equivalent. "Gas Facts" [29] cites *gross* liquefaction capacity of 206 million ft^3 per day which computes to be 75 billion ft^3 per year with a dollar value of $75 million.

LNG Ship Building Construction. There are presently 16 LNG ships under construction in the U.S. [30]. It is assumed that these ships were ordered in the period 1973-1974 for delivery in the five year period 1975 to 1980. We estimate each ship's value at $90 million [31]. Assuming that these 16 ships will be delivered over the five-year period mentioned, we thus derive an average yearly value of $288 million for LNG ship construction.

LNG Storage and Peak Shaving Plant Construction. Hale [32] states that up to 10 or more LNG peak shaving plants will be built each year for the next 10 years. Further more, there are 19 applications pending before the Federal Power Commission for permission to import LNG or to liquefy and store it for *interstate* use alone. These applications are not trivial. To illustrate, one peak shaving facility in Iowa is estimated to cost $23 million. The import terminals proposed by Western LNG is estimated to cost $1.7 billion, and the El Paso-Alaska export terminal to supply part of the west coast (including 11 ships and a pipeline) is estimated to cost $5.6 billion. Hale [32] cites a recent Northern Natural Gas Company plan for a $20 million facility. With his value as a conservative average, we may estimate investment in peak shaving facilities to be at a level of $200 million per annum. The size of the U.S. LNG industry is therefore approximately:

Component	Value, $ M/yr
1. Import-Export Trade	$ 50
2. LNG produced for Internal Consumption	75
3. LNG Ship Construction	288
4. Peak Shaving Plant Construction	200
	$613 M

Therefore, the approximate size of the cryogenic industry in the United States is $1,403 million plus $613 million or $2.016 billion.

2.5.3.3 Research and Development

None of the above includes research and development, or any estimate of the future. There are a few indicators in this area:

About $26 million per year is spent on superconductivity programs in the U.S. [33]. This total includes: $3 to 4 million for electrical generators; $3-1/2 to $4 million for electrical power transmission; $6 million for electrical propulsion systems; $6-1/2 million for energy storage, magneto-hydrodynamics and controlled thermonuclear reactors; $7-1/2 million for high energy physics experiments; and $2-1/2 million for basic research on superconducting materials.

The importance of helium is noted in the Energy Research and Development Administration (ERDA) legislation, which directs the Administrator to conduct a study of the potential applications of helium, and to report his recommendations to the President and the Congress within six months of enactment. These recommendations will concern the management of the helium program from the standpoint of energy R&D [34].

The Institute of Gas Technology reports that the natural gas utilities feel the need to demonstrate to their investors that they have prospects for participating in a "perpetual" energy industry, not subject to depletion. They see hydrogen as a substitute fuel gas to move through their pipelines [35].

Many feel that cryogenics may be to the second half of the twentieth century what high temperature processing was to the first half. We at NBS certainly agree that at least it is an important, large, growing and dynamic industry.

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

3.1 Impact of Measurements

3.1.1 Functional, Technological, and Scientific Applications

The impact of cryogenic measurements may be illustrated by some examples where cryogenics plays a crucial role in the advancement of national programs. In the examples below, the measurement infrastructure supports the commerce in cryogenic fluids, although measurements *per se* may be peripheral to the applications listed. They are mentioned primarily because of their inherent interest.

In the area of health: blood for transfusions can be stored at liquid nitrogen temperature for extended periods of time, while storage for over 2 weeks at 4°C is the maximum allowed with conventional technology. Recently, the Food and Drug Administration has approved such blood as a commodity for interstate commerce.

Biological samples (like tissue, cancer cells, tumors, cornea, and bone marrow) can be stored without serious degradation for study and interlaboratory comparison. The National Cancer Institute maintains just such an archive.

There are several applications in agriculture, but one of the most noteworthy is that more than 50% of all cattle are bred by artificial means with the bull sperm stored and transported at liquid nitrogen temperature.

Another agriculture related use of liquid nitrogen is in food freezing, a well established technology--over $50 million worth of liquid nitrogen is used for this purpose annually. Since the use of liquid nitrogen has been so advantageous, developments are underway to extend its use further back into the food chain. For instance, sweet corn and sweet peas are being harvested experimentally with the aid of cryogenics. This process is said to enhance their value by retaining the "field sweetness" of the produce. Soybeans, a valuable source of protein, are being cryogenically harvested also. It is said that the objectionable (to some) flavor of soybeans is due to the highly perishable nature of the newly picked beans. Cryogenic harvesting is said to enhance the value of this product several times over by helping to retain the highly desirable fresh-picked flavor.

In transportation there are already a limited number of cars and trucks using LNG and hydrogen, but the auto industry does use cryotechniques extensively, including oxygen for steel making, grinding paint pigments, and deflashing parts at low temperatures. In addition, float glass is inerted with gaseous nitrogen. Even the reclamation of scrap metal from old cars and tires uses cryogenic technology--cooling to low temperature permits fracturing and component separation.

The aerospace industry is committed to cryogenics and about 40% of the National Aeronautics and Space Administration's budget is cryo-related.

In research, the National Accelerator Laboratory (NAL) has recently purchased 15,000 lbs. of NbTi ingots at a cost of approximately $500,000 to build a superconducting energy doubler. This amount of material is enough for only 1/6 of the magnets around the 4 mile ring, or $3 million worth of raw NbTi. Other scientific applications of cryogenics were discussed extensively in Section 2.2.5.

The Navy is building 3000 HP superconducting motors and generators for ship propulsion and has design studies underway for a 30,000 HP version. These motors could revolutionize the use of hydrofoils and even conventional ships.

In some of these examples, the NBS role is rather diffuse and indirect, while in other cases, our aid is quite explicit. In all cases, cryogenic measurements are central to the infrastructure that supports the technological and scientific applications mentioned.

3.1.2 Economic Impacts--Costs and Benefits

Some examples of the value of cryogenic measurements were given in Sections 2.2.2.2 and 2.5.2. We shall highlight a few of these values again below, and conclude with a specific case study sponsored by The Instrument Society of America.

- Approximately 2,000 cryogenic flowmeters are in use today with a value of over $3 million, making approximately 400,000 custody transfers per year. Flowmeters are considerably less numerous and less widely used than other cryogenic instruments.

- In terms of rate of growth, the industry as a whole, of which cryogenic measurements are a part, ranked 59th out of 130 industries surveyed by the Department of Commerce during 1973-74. The average growth rate was 7%.

The two principal subcodes within this group are 3821 and 3822. Projections [36] through 1980 are shown in table 3-1.

A specific example of benefit-cost estimation may prove useful at this point and help bridge the gap between instrument and user. Our example shall turn around the cryogenic flowmetering program, especially the summary report [37] prepared by The Instrument Society of America Ad Hoc Committee mentioned in Section 2.2.1.1.

As mentioned, NBS contributed to this report and excerpts are given below:

"The previous section has developed some of the needs for cryogenic fluid flow measurement and standards. However, it is one thing to have needs and another to economically justify the solution of these needs. Since this was part of the charge to the Ad Hoc Committee, an attempt was made to come up with an economic justification. As in many situations such as this, this economic justification is not easy to prove and verify by actual numbers because so many intangibles must be considered as part of the economics of such a problem. However, using statements and estimates from various Ad Hoc Committee members and other interested contributors, plus statements and estimates gathered from technical papers, letters, and telephone conversations, a brief report has been prepared in an attempt to at least demonstrate the economic magnitude of cryogenic fluids. For the purposes of this section of the report, the cryogens of concern at this time are oxygen, nitrogen, argon, hydrogen, and liquefied natural gas."

The report continues in this realistic fashion and estimates the value of cryogenic fluids. It continues:

Table 3-1

Instruments for measurement, analysis and control:
projections 1973-80
(value of shipments in millions of dollars)

SIC code	Industry	1973	1974	Percent increase 1973-74	Percent increase Low	Percent increase High
3821	Measuring and controlling instruments-------------	1,800	1,920	7	4.8	6.0
3822	Automatic temperature controls----------------	740	780	5	5.2	6.5

"A study of this table indicates that if the custody transfer of these fluids were in error by only one percent (present codes allow two percent), a billing error could amount to more than 15 million dollars. This point is emphasized in the table below."

Year	Possible Billing Error/Yr
1966	$ 2,158,000
1971	5,705,000
1976	15,372,000

In Section 2.2.2.2, we estimated that the total value of flowmeters in service in 1971 was about $3.1 million. One can choose for himself whether or not to divide the figures above by one another. If he does, a ratio of between 2 and 4 to 1 is obtained.

The report continues on another tack:

"Previous discussion has outlined the economic worth of the cryogenic fluids in terms of custody transfer. However, this is not the only place where an increased cryogenic fluid meter calibration certainty would be desirable. For example, in the aerospace industry an increase in fluid meter calibration certainty would go a long way to guarantee engine performance. Present uncertainties in the factors involved in mixture ratio trim cause approximately a 2% uncertainty in guaranteed engine performance. Accordingly, guaranteed engine performance is downgraded by 2% in order to insure overall mission success when engine and vehicle are mated. Any decrease in this 2% uncertainty would raise the mission capability by some corresponding amount.

"In the case of one oxygen-hydrogen engine under development, the 3σ error in flow measurement is 0.433 and 0.541% for fuel and oxygen, respectively. The corresponding percent error in mixture ratio (3σ) is 0.727%, which is clearly a substantial portion of the overall 2% uncertainty.

"If a facility were available that could reduce the flowmeter calibration uncertainty to 0.2% each, the corresponding percent error in mixture ratio (3σ) would be reduced from 0.727 to 0.282%. Hence, the uncertainty in engine performance is reduced by 0.444%. If the specific impulse of the engine is around 350 seconds, the corresponding increase in engine performance certainty is (350) (0.444%) or 1.56 seconds.

"In the special case under consideration, each second of additional guaranteed performance is equivalent to a 25 lbs increase in payload for a given booster. Accordingly, the improvement in flowmeter calibration assumed here reflects an increase in payload capability of (1.56) (25) = 39 lbs for a given booster.

"The value of increased flowmeter calibration certainty may be reflected in other ways. The above example indicates an increased payload capability of nearly 40 lbs. This also means that for a given payload, the booster has a payload capability of 40 lbs more than necessary, due to flowmeter calibration uncertainty. By decreasing this uncertainty to the levels assumed, the booster size can be decreased by 40 payload-lbs equivalent.

"In a typical system, each pound of payload requires some 60 lbs of additional propellant. Decreasing the flowmeter uncertainty means that, in this case, the booster size could be reduced by (40)(60) = 2,400 lbs of propellant. Corresponding reduction in tankage, lines, valves, engines, launch facilities, personnel, liquefier capacity, test sites, booster transportation, etc., occur.

"If the economic worth of cryogenic fluids, the possible billing error to consumers, the improved rocket performance, the improved regulatory agency relations, the improved customer relations, etc., are considered, it is safe to assume that the net value of improved flow measurements in custody transfer, diagnostics, and standards is a multi-million dollar per year proposition."

Please recall that all of the above is quoted from the ISA report.

3.1.3 Social, Human, Person-on-the-Street Impacts

We have already mentioned in Section 2.2.5.1 that 15 Nobel prizes in physics were awarded for work in or related to cryogenics. While these are hardly "man-on-the-street" impacts, it must be recognized that cryogenics has had significant impact on basic research and education, which does affect us all.

A much more down-to-earth educational need involves the plant operators, truck drivers, police and fire departments. The following statements have been collected to help reinforce this point.

"There is a broad feeling among those responsible for the measurement of LNG that much needs to be learned as to the best methods for measuring and calibrating flowmeters, tank level gauges, and densimeters. Plans for LNG measurement techniques and standards, at this point, are nebulous. It is probably a case in which operating experience is expected to focus attention on the need for specific programs in this area by the operating companies." M. H. November, Potter Aeronautical.

"It is a responsibility of the program of the NBS to train county personnel in the proper procedures of inspection." W. Watson, California Bureau of Weights and Measures.

"---that a committee or organization (possibly such as the CGA) work closely with the regulatory agencies and cryogen producers to educate both to the problems and to develop any necessary guides for product handling and metering." G. C. Nubel, Air Reduction Company.

"The cryogen producers also need more information for fire prevention codes. This information is needed by the public, such as fire department and police department officials." W. Spencer, American Cryogenics.

To cite educational needs (almost everyone agrees to education) is one thing, but to meet these needs is another. These needs are not essentially simple ones easily met by bulletins, pronouncements, or regulations, but rather they are complex ranging from technical and scientific down to operational. Some of these complex educational needs include: (1) study of safety practices; (2) education of police and fire officials; (3) education of driver-operator in proper procedures -- the why and how of these procedures, and so forth. Measurements are needed to help develop educational programs, specify codes, etc., which have the direct human/man-on-the-street impact.

The point of the cryogenic measurement system is to foster and help develop a new technology, the infrastructure technology of cryogenics itself. It is generally accepted that such technological innovation can help us expand our markets at home and abroad, strengthen old industries, create new ones, and generally provide more jobs in the labor market.

The direction of private technological activities is determined in large measure by thousands of private decisions -- and this should always be the case -- but we cannot ignore the fact that federal policy, such as undergirding a new technology, also has a profound effect upon what happens in the private sector.

3.2 Status and Trends of the System

Several special studies have been prepared to characterize the cryogenic measurement system (See Section 4.5.1).

The Overview. Two overviews have been made to document the infrastructure position of cryogenics in large national programs (space, health, transportation, etc.) and to identify leading indicators of trends of the health of cryogenics.

Applications for Specific Customers. Once the network of cryogenics in technology as a whole had been defined and tested, it was useful to look at specific functional relationships between terminals in that network, or the leverage of cryogenics in specific applications. Such studies were made on the application of cryogenics in atomic energy programs, transportation, biology, and water pollution abatement.

Applications to a Specific National Need - Energy. Technology assessments have been prepared in three energy areas -- LNG, hydrogen, and superconductivity.

Analysis of Major Technical Threats. Since cryogenics is a rather well bounded and self contained technology, it is not likely to be replaced by a competing technology. The principal threats are from among the rivals within the technology itself, as from abroad. Two foreign technology assessments have been made.

Analysis of Major Technical Barriers. The question of reliability and cost is always raised whenever a commercial application of cryogenics is suggested. Accordingly, a survey of the state-of-the-art of commercial refrigerators was first published in 1969 and updated in 1973.

Analysis of Major Technical New Opportunities. Assessments of cryoelectronics, superconducting engineering and the commercialization of cryogenics have also been prepared.

The synthesis of these studies is that the major developments in cryogenics in the next few years that will have significant impact on the technology of the country and its balance of trade are the widespread international use of liquefied natural gas potential uses of hydrogen, and applications of superconductors. These developments are a result of the national sense of urgency regarding energy problems and the established trends toward the uses of: (1) liquefied natural gas to meet local peak energy requirements (peak shaving) and to accommodate the transportation of natural gas in the dense cryogenic form; (2) liquid hydrogen as a potential synthetic fuel of the near future; and (3) superconductivity in applications for electric power generation, transmission, and storage. The cryogenic measurement system must respond with design data, metrology, and related applied cryogenic research.

Along with this "commercialization" of cryogenics comes a new role that gives even greater leverage to the measurements and data, and which is one way to assure the effective transfer of measurements into the hands of the users. This new role is a partnership between cryogenics and the regulatory agencies. For instance, results of the NBS flowmetering program (e.g., tolerances and basic property data) have been adopted into NBS Handbook 44 as a result of cooperative work with the states of California and New Jersey. The Maritime Administration and the U.S. Coast Guard are interested in new, inexpensive, but safe materials for seagoing tankers. The Federal Power Commission (FPC) needs cryogenic measurements and data on the cryogenic safety and design aspects of current applications before the FPC for authorization of LNG terminal and storage facilities. Underlying and supporting each of the specific technologies of LNG, hydrogen, and superconductivity is the necessity of: (1) establishing and providing an information base for cryogenic measurements and properties of materials at low temperatures; and (2) characterizing the behavior of materials at low temperatures by definitive studies involving mechanical, thermal, and electrical property measurements. Some of the strengths and weaknesses of the current cryogenic measurement system are described below.

Liquefied Natural Gas (LNG). Over 30 percent of the basic energy supply in the U.S. is provided by natural gas. The demand for this relatively inexpensive, ecologically satisfactory fuel has substantially exceeded the domestic supply. Even with responsible conservation and development of alternative sources, large quantities must be secured not only through foreign importation, but also from Alaska, by 1985. Domestically, major facilities have been established in large population centers to permit peak shaving and redistribution. These large scale applications require handling the natural gas in liquid form. New measurements and data are required to permit the U.S. to participate successfully in domestic and imported liquefied natural gas programs in order to develop; (1) advanced concepts, (2) environmental impact statements, (3) regulations, (4) economics, (5) safety, and (6) reliability. Accordingly, a complete and comprehensive physical measurement system for LNG needs to be developed.

Today, quantity gaging in storage and ship tanks is uncertain and requires accuracy statements and traceability yet to be developed. Flowmetering for commodity transfer and equity in trade has been developed for more conventional cryogens (Handbook 44). An equivalent program for LNG will be unique in conception because it will require the integration of mass and heating value measurements. Nonetheless, traceability to national standards (NBS) is already written into existing international agreements (El Paso Gas-Algeria and Algonquin Gas-Algeria) with little or no technical basis in fact.

Basic measurements of the thermal and mechanical properties of structural materials are the key to realizing the potential of LNG as a major source of fuel. For instance, the fatigue crack growth rate and fracture toughness of many potential construction materials have not yet been measured for cryogenic applications. Such data are essential to ship construction as well as to stationary storage of LNG.

Hydrogen. Hydrogen is a prime candidate to satisfy many long-term national (and international) fuel requirements. It seems no longer necessary to justify the relevance of hydrogen fuel research since hydrogen is a clear contender for the synthetic fuel market of the future -- only the time scale for implementation of this fuel is uncertain. Its use in the period 1985-2000 appears guaranteed. Thus basic measurements and data are required now.

Priority research elements that have been identified are: (1) improve hydrogen liquefaction efficiency, (2) evaluate methods of recovering liquefaction energy, and (3) evaluate hydrogen compatible materials of construction. Longer term priorities include the development of improved insulation systems and the establishment of instrumentation and measurement methodology for commercial exchange of liquid hydrogen.

Superconductivity. Cryogenic measurements and data are intimately bound together with the electrical energy industry through the application of superconductivity to power transmission, generation, and storage. All three applications have at least three problems in common. First, conductors tailored to each of the above areas are still under development, and their performance depends in part upon the rate of heat transfer to the helium heat sink under transient conditions. Second, the behavior of the entire helium refrigerant flow system, including responsiveness to instabilities must be known (pressure, temperature, and flow rate vs. time). Third, degradation, or aging, of the superconductor may result from the various different stresses -- thermal, electrical, or mechanical -- with long term reduction of system capacity. The problem areas -- refrigeration and superconductor behavior -- are common to each and every superconducting application and at present represent a weakness in the cryogenic measurement system.

Helium is, of course, the indispensable refrigerant for all known superconductivity technology. The importance of helium was recognized in the bill creating the Energy Research and Development Administration (ERDA), which directs the Administrator to conduct a study of the potential energy applications of helium and to report his recommendations to the President and the Congress within six months after the enactment of this Act. These recommendations will concern the management of the helium program from the standpoint of national energy research and development, and will undoubtedly have a profound effect upon the future of the cryogenic measurement system.

4. SURVEY OF NBS SERVICES

4.1 The Past

Ever since the Federal Government established the Bureau, NBS has been involved in cryogenic measurement science and has frequently been sought out to settle technical controversies or to solve problems whose sophistication lay beyond the capabilities of other agencies.

In fact, the NBS program in cryogenics itself dates back to 1904 when Congress approved the purchase of a hydrogen liquefier exhibited by the British at the St. Louis world's fair. A somewhat larger facility was established in Boulder in 1952 at the request of the AEC, and ever since then, the Cryogenics Division of NBS has participated significantly at the critical stages of planning and execution of every major national program using cryogenics. A brief historical background follows:

- Established the National Cryogenic Engineering Conferences, now in their 20th year.
- Assisted in the development of the first large liquid hydrogen bubble chamber, which won for Dr. Luis Alvarez the Nobel Prize in Physics in 1968 and also a commendation for the NBS team.
- Developed the OP catalyst essential to the long term storage of hydrogen.
- Produced the first text book in cryogenic engineering; co-edited the first journal of cryogenics and taught the first college accredited course in cryogenic engineering.
- Received the DoC Gold Medal for Measurement and Publication of Definitive Properties of Hydrogen.
- Assisted in 1970 in the investigation of the cause of the Apollo 13 cryogenic tankage failure and helped to establish the basis of safe redesign.

Thus it is apparent that NBS has provided cryogenic measurements, data, and services for nearly 70 years. The present holds every bit as much promise as cryogenics matures and finds more and more use.

4.2 The Present Scope of NBS Services

The present scope of NBS services to the cryogenic measurement system is indeed significant. We have already indicated that cryogenic measurement and data services are offered in nearly every field that NBS as a whole does: conceptual knowledge, instrumentation, reference materials, standard samples, reference data, and specifications (See Section 1.). Accordingly, it may be more edifying at this time to illustrate these services with our case study, the liquid nitrogen flowmetering program. We shall attempt to illustrate not only the NBS services, but also their uses and interactions through an Input-Output analysis. This matrix is essentially a four terminal network to describe the flow of information between NBS and various users.

Block I is "from NBS to NBS", or Internal Input.

Block II is "from the outside to NBS" or External Input.

Block III is "from NBS to the Outside" or External Output.

And Block IV, since it describes interactions "from the Outside to the Outside" and does not involve NBS *per se*, appears to hold little interest for us at the moment.

4.2.1 Description of NBS Services

A description of NBS services should not only include those services that NBS supplies to the outside, but to internal users as well. Accordingly, we shall subdivide this section into two parts: Internal Inputs--NBS to NBS; and External Outputs--NBS to the outside.

<u>Internal Inputs: NBS to NBS</u>. This block includes, for instance (Figure 1):

- The Institute for Basic Standards--whose statutory responsibility to provide basic measurements and standards made the program possible.
- The Office of Measurement Services - provided guidance on accuracy statements, and experiences in conducting round robins.
- Patent Advisor--guidelines for handling proprietary information on the performance of specific flow meters.

- The Office of Weights and Measures--publishes Handbook 44 and provides the secretariat to the National Conference on Weights and Measures (NCSM). Gave our program the direction and mechanism to make its results have the effect of law.
- Applied Math Division--planning experiments for statistical soundness and analyzing the results.
- Cryogenics Division--provided the essential technical base and resources.

For more detail on these Internal Inputs, see Section 2.4.1, especially NBS Infrastructure.

External Outputs: NBS to the Outside. The analogy has been drawn that basic measurements and standards are the "currency" or medium of exchanges in business. The analogy may be broadened by recognizing that a currency has no intrinsic value of its own, but is only as good as the user's confidence. The same is true for basic measurements and standards.

Standards as the "currency" of science can be a revealing analogy, for standards are the key to the commercialization of science. Each scientist works within a self contained system using "his" thermometer, "his" balance, and "his" meter, which could be the distance between two marks on a barn door, as far as he is concerned. As long as his measurement system is *internally* consistent, he has no need to refer to or compare against an external set of standards. Only when he steps out of his system to put his work into general use, to gain general acceptance, to put his work into circulation, as it were, does he need to refer to a set of external standards. Basic standards then are not the analog of currency, but are the currency of fact, since they are indeed the medium of exchange that causes the scientific work to become commonly accepted, used, and repeated. Thus, basic standards are the transfer agent from which the benefits of science are derived.

It is a paradox that "basic" has come to mean in the minds of some "undirected" or "exploratory", for indeed the sole need for standards is to communicate with others. In this sense, standards provide the dictionary of technology and commerce.

Standards are the means used to judge something as authentic, good, or adequate. They are the measures to determine what a thing should be, or whether it is correct. Thus, there are standards for measurements (property data) for performance (tolerance) and for products (type testing). In this program, these standards were embodied as "External Outputs" (Figure 2).

- Codes, Standards, and Recommended Practices, such as adopted in Handbook 44.
- Properties Data. The NBS property data for liquid nitrogen were also adopted in Handbook 44. See Sections 2.2.1.2 and 2.2.3.
- International Conventions. As mentioned earlier, the Compressed Gas Association was strongly motivated to deal with one national laboratory rather than fifty state laboratories. We extended this philosophy on an international scale via the IOLM. See Section 2.4.1.
- Performed type testing of meters of foreign manufacture as an integral part of the program. (See Tech. Note 624, "An Evaluation of Several Cryogenic Turbine Flowmeters".)
- Promoted and facilitated many visits by international observers. The result of one such visit was the direct translating into German of NBS Report 9778, "Cryogenic Flow Research Facility Provisional Accuracy Statement" to be used as a model by the PTB. For more discussion, see Section 2.4.1.

4.2.2 Users of NBS Services

The principal users of NBS services, in the representative sample chosen for illustration, can readily be identified by the inputs they had to the program. This may at first seem to be a backward approach, but it is surely the most direct way to identify those who needed the services the most - namely those who helped influence and "design" those services. We call these External Inputs.

External Inputs: Outside to NBS. The principal external inputs (Figure 3) came from regulatory agencies, and trade associations. Their role was fundamental in both initiating and guiding the program and was described in detail in Section 2.2.1.1. These included the Instrument Society of America (ISA) Ad Hoc Committee on Cryogenic Flow Metering, The Compressed Gas Association, and the State of California. There are three factors in common between NBS and these groups that bear further comment.

1. The regulatory agencies need a sound technical basis for their codes so that they are feasible as well as enforceable. The NBS, having no regulatory authority (and desiring none), needs the leverage of regulatory agencies for its basic measurements and standards to be adopted rapidly and uniformly.

2. Because the NBS has no regulatory functions, our basic measurements and standards must stand on their own merit. They must be the best in the country to be accepted, for they are not promulgated by law.

INFORMATION INPUT - OUTPUT MATRIX

From \ To	NBS	OUTSIDE
NBS	INTERNAL INPUT • IBS • OMS • Patent Adviser • OWM • Applied Math Division • Cryogenics Division	
OUTSIDE		

FIGURE 1. Internal input.

From \ To	NBS	OUTSIDE
NBS	INTERNAL INPUT • IBS • OMS • Patent Adviser • OWM • Applied Math Division • Cryogenics Division	EXTERNAL OUTPUTS • Codes • Standards • Recommended Practices • Properties • Measurement Techniques • Correlations • Literature Services • MAP • International Conventions
OUTSIDE		

FIGURE 2. External outputs.

(The analogy has already been drawn that basic measurements and standards are the "currency" or medium of exchanges in business).

3. Because of our unbiased outlook, the parties involved, each with his own self interest or view points, feels free to come to us as the impartial third party. The ISA specifically recommended recourse to a national laboratory. The State of California also expressed the need for traceability to a national standard, since they are obligated by law to perform type approvals. The CGA was strongly motivated to come to a central laboratory, for the alternative was to deal with fifty state laboratories.

Our responsibility lies not only in providing the competence in advance of need, *but also making that competence known to our customers,* and making it easy for him to do business with us.

4.2.3 Alternative Sources

We offer to the Cryogenic Measurement System essentially every service that NBS as a whole offers to the entire measurement system. Therefore, the list of every actual or potential alternate source is, for all practical purposes, endless. We have attempted to tether such a discussion by tying it to a specific scenario: namely, what would happen if NBS were to stop its cryogenic measurement services tomorrow? This scenario is developed in Section 4.3 "Impact of NBS Services", especially Section 4.3.1.

Here, we shall limit our discussion to means of identifying user needs possibly not being met, and the NBS role vis-a-vis such needs. One way to do this is to identify the Outside-Outside interactions. By definition, these interactions do not involve NBS, but perhaps they should.

Outside-Outside Interactions. The input-output functions of Block IV at first do not appear to interest us, for they do not involve NBS *per se*. They include, for instance (Figure 4):

Regulatory Agencies - California and New Jersey state weights and measures officials collaborating on a model code in order to facilitate trade among their states, as well as intra-state commerce.

Meter Manufacturers--an instrument maker planning his flow meter design and distribution to conform not only with U.S. convention, but also with that of the PTB, for instance.

Fluid Producers--especially those in interstate or international commerce.

Professional Societies--such as non-technical policy board meetings of the ISA.

Note that these examples are essentially non-technical policy level determinations, and accordingly appear not to be the concern of NBS. But note these common traits.

1. Vantage points of enormous leverage where the most fundamental decisions are made.

2. Opportunities of largest possible economic impact (it is more economical for everyone concerned to get a code that is feasible in the first place, rather than testing and re-writing the code after the fact.)

3. Taken as a whole, they represent the "Industrial Measurement System", a sub-set of the National Measurement System. (Figure 5).

This is the arena where decisions are the most fundamental, and where the opportunities and problems originate. Accordingly, it is not only in our sphere of responsibility, but also in our own interest, to consciously and systematically monitor and influence the course of technology in the political (people), technical, economic, ecological, and social environments. If we are to serve the cryogenic measurement system adequately, then we must continuously identify, analyze, evaluate and participate in the transactions occurring in this essential, but sometimes overlooked part of the measurement system.

4.2.4 Funding Sources for NBS Services

In Section 3.1 we identified the impact of our measurement services, and noted that in some of the examples given (health, agriculture) the NBS impact had been rather diffuse and indirect. In other cases (space exploration, LNG), the NBS cryogenic measurement services were explicit and direct. So it is with the funding sources for our services. Some services result in wide public benefit, meriting wide public support (e.g., appropriated funds). On the other hand, where specific beneficiaries can be identified, then these beneficiaries have paid, because "full recovery of costs" is the rule. A few specific examples may prove helpful and are given below.

Cryogenic Flowmetering. We have used this specific case study throughout our microstudy to help illuminate general principles. As discussed in Section 2.2.1.1, the Compressed Gas Association was a specific beneficiary, and the member companies most interested in the problem (see Table 2-2) contributed funds and helped provide program definition that allowed the program to proceed to its ultimate technical conclusion.

Reference Data. Accurate density measurements and analytical calculation methods for liquefied natural gas are essential to

INFORMATION INPUT - OUTPUT MATRIX

	NBS To	OUTSIDE
NBS	INTERNAL INPUT • IBS • OMS • Patent Adviser • OWM • Applied Math Division • Cryogenics Division	EXTERNAL OUTPUTS • Codes • Standards • Recommended Practices • Properties • Measurement Techniques • Correlations • Literature Services • MAP • International Conventions
From OUTSIDE	EXTERNAL INPUT • National Conference on Weights & Measures • Federal Agencies • Trade Associations (CGA, AGA) • Regulatory Agencies (State, National, International)	

FIGURE 3. External inputs.

	NBS To	OUTSIDE
NBS	INTERNAL INPUT • IBS • OMS • Patent Adviser • OWM • Applied Math Division • Cryogenics Division	EXTERNAL OUTPUTS • Codes • Standards • Recommended Practices • Properties • Measurement Techniques • Correlations • Literature Services • MAP • International Conventions
From OUTSIDE	EXTERNAL INPUT • National Conference on Weights & Measures • Federal Agencies • Trade Associations (CGA, AGA) • Regulatory Agencies (State, National, International)	• Regulatory Agencies • Meter Manufacturers • Fluid Producers • Consumer • Professional Societies (ASTM)

FIGURE 4. Outside - outside interactions.

INFORMATION INPUT - OUTPUT MATRIX

From \ To	NBS	OUTSIDE
NBS	INTERNAL INPUT • IBS • OMS • Patent Adviser • OWM • Applied Math Division • Cryogenics Division	EXTERNAL OUTPUTS • Codes • Standards • Recommended Practices • Properties • Measurement Techniques • Correlations • Literature Services • MAP • International Conventions
OUTSIDE	EXTERNAL INPUT • National Conference on Weights & Measures • Federal Agencies • Trade Associations (CGA, AGA) • Regulatory Agencies (State, National, International)	*INDUSTRIAL MEASUREMENT SYSTEM* • Regulatory Agencies • Meter Manufacturers • Fluid Producers • Consumer • Professional Societies (ASTM)

FIGURE 5. Industrial measurement system.

provide an unequivocal basis for custody transfer. These same data provide the basis for mass, density and heating value measurements throughout the fuel gas industry. A technical program to meet these needs is presently underway, funded and guided by a consortium of 18 energy companies (See Section 2.2.3 for technical description).

Hydrogen-Future Fuel. In the fall of 1972 the NBS Cryogenics Division NAS-NAE-NRC evaluation panel recommended renewal of a modest effort on hydrogen fuel technology. The scientific staff responded enthusiastically and a state-of-the-art evaluation was released in the summer of 1973. An economic analysis of hydrogen-fueled electrical utility systems was published in March 1974, and a benchmark literature bibliography was completed in June 1974. The work described below was initiated in July 1973, and efforts were accelerated by support of management at all levels of the NBS, e.g., Institute of Basic Standards Director's Reserve funds were made available to initiate this study.

The goal of this work is to provide innovative cryogenic technology so that hydrogen may be liquefied, stored, and distributed efficiently on an unprecedented scale and with safety and fairness to the consumer. Specifically, analyses and summary reports were prepared on the following topics: (1) cost and availability of hydrogen, (2) hydrogen in the electrical utility industry, (3) applications of hydrogen in transportation, (4) survey of materials for hydrogen service, (5) instrumentation for cryogenic hydrogen fuel, (6) transmission and distribution of energy, (7) solar energy -- liquid hydrogen, (8) industrial applications of hydrogen, and (9) hydrogen fuel literature.

These analyses demonstrated, among other things, that even now hydrogen appears attractive as an aircraft and aerospace fuel, in certain integrated utility systems (e.g., use of hydrogen to store solar energy), for transport of energy from nuclear or solar sea power plants and is already an essential ingredient in a wide variety of industrial processes (ammonia synthesis, hydrocracking, hydrotreating, and methanol synthesis). This example was chosen to illustrate how internal re-direction of funds by an alert management can quickly produce results not otherwise possible.

Liquefied Natural Gas. This present study of the cryogenic measurement system (now in its second year) has helped document for us the complete process that must be undertaken to provide a complete measurement service. Specifically, our LNG Budget Initiative submitted in the Spring of 1974 was deliberately constructed to include all three necessary elements: measurement science, data base, and technology transfer (includes safety, interstate and international cooperation, effective use of Office of Weights and Measures and training). Thanks (in part) to the National Measurement System study, new work proposals now use the guidelines so developed to assure a complete and comprehensive approach.

Even though this particular initiative did not survive the government budget process, we are nonetheless pursuing other avenues of funding, perhaps even multiple sources, but with the objective of nothing less than a comprehensive program. This example was chosen to illustrate the course of a new budget initiative pf potentially large public benefit, which could reasonably be assumed to merit public support (appropriated funds).

Thus the answer to "Sources of Funds for NBS Services" is: "It depends". Table 4-1 gives a more explicit answer.

Table 4-1

Funding by sources
Fiscal Year 1974

	Percent
NBS	
Direct appropriation	31
Postdoctorals	01
Standard Reference Data	03
Standard Reference Materials	01
NBS TOTAL	36%
OTHER AGENCY R&D	
National Aeronautics and Space Administration	11
Atomic Energy Commission	05
Department of Defense	23
Maratime Administration	05
Navy	01
Federal Power Commission	02
National Science Foundation	01
OTHER AGENCY TOTAL	48%
INDUSTRIAL ASSOCIATIONS	
American Gas Association	11
International Copper Research Association	01
Other	01
INDUSTRIAL ASSOC. TOTAL	13%
TESTING, CALIBRATION, SERVICES	03
GRAND TOTAL	100%

4.2.5 Mechanism of Supplying Services

Dissemination mechanisms are as varied as the services themselves.

Calibrations, and Maps were described in Sections 2.2.1.1 and 4.2.1 in conjunction with the cryogenic flowmetering program.

Reference Data, whether distributed in an unstructured way by individuals, or in a systematic way by the Cryogenic Data Center, were discussed in Section 2.2.3. Publications, special bibliographies, Standard Reference Data, and several Current Awareness services were described there.

Reference Materials were described in section 2.2.4. These included the Standard Reference Materials incorporated in the NBS program of that name. Also mentioned was the importance of corollary reference data and round robins utilizing "uncertified" reference materials.

National trade associations, other federal agencies, and international mechanisms were described in Section 2.4, "Dissemination and Enforcement Network".

These descriptions, while as complete and comprehensive as possible, nonetheless appear rather sterile compared to actuality. Supplying services is never "pure". Usually a mix of services, e.g., reference data along with reference materials, must be supplied to a mix of users, e.g., several laboratories in a round robin interchange. The cryogenic flowmetering program serves well again as an example of the mechanisms required in practice.

Figure 6 illustrates the truly staggering number of mechanisms for supplying services that came into play. Note for instance:

Regulatory Agencies--State
Regulatory Agencies--Foreign
Professional Societies
Industrial Meter Manufacturers--Domestic
Industrial Meter Manufacturers--Foreign
Industrial Producers--Domestic
Industrial Producers--Foreign.

Specific detail is given in Figure 6.

4.3 Impact of NBS Services

We shall attempt to examine the impact of NBS services by following a specific scenario: namely, what would happen if NBS were to stop its cryogenic measurement services tomorrow? For this approach, we are indebted to Professor Charles Howe, who is Chairman of the Economics Department at the University of Colorado. Professor Howe is a consultant to the State Legislature of Colorado and his specialty is establishing criteria for public supported programs. He has served as a consultant in this capacity to Ghana, Kenya, Botswana, and lately to the Cryogenics Division of NBS.

We shall try to follow this scenario down two roads, one leading to the potential economic impact; the other to the technological impact.

4.3.1 Economic Impact of Major User Classes

One possible scenario is that cryogenics would simply disappear. We believe, however, that cryogenics is here to stay; we have shown that it is an infrastructure technology

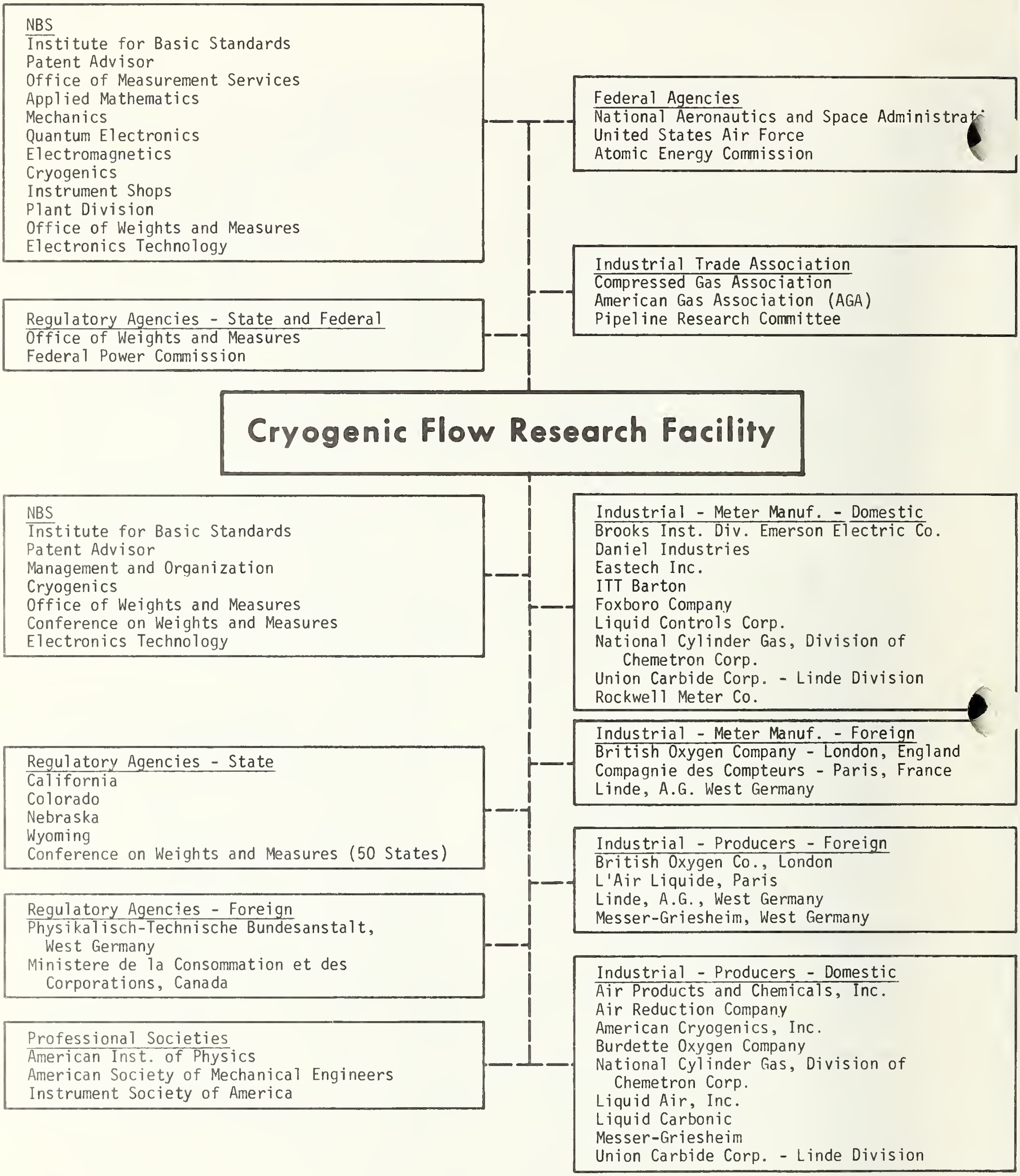

FIGURE 6. Liquid nitrogen flow program interactions.

that is used wherever it is more economical, or wherever it permits some higher level of performance. Accordingly, every user of cryogenics would create his own in-house competence a piece at a time. It follows that:

Such redundant facilities and data gathering would likely cause expensive and slow response to national needs, while at the same time wasting national resources.

It seems inevitable that such duplicate efforts would produce inconsistent design data which would prevent both process optimization and safety evaluation. The corrolary questions are: "Who is right?"; "Where is the arbiter to judge, and how does he decide?".

It is argued by some that while proprietary data of a *basic* nature may give its owner a slight edge for a short time, keeping data proprietary may sometimes impede national technological advancement and hence our ability to compete successfully in international trade.

In the absence of a centralized effort such as NBS provides, arbitrary or even conflicting standards could be adopted, leading to questionable practices in custody transfer and in safety evaluation. If a free enterprise economic system is to survive in a modern industrial society, buyers and sellers in the marketplace need to have as much confidence in the quantity and performance of goods exchanged as they do in the amount of moneys paid.

The government would find itself in the conflicting role of trying to regulate the very technology it is trying to promote.

A vague technical base inhibits both compliance and regulation, no matter how well-meaning or good intentioned either party may be.

If there were no centralized effort, both government and commerce would find themselves with a generally unsatisfactory basis for decision making and impartial judgments.

The key to impact of NBS services appears to lie in their centralized, coordinated nature. Our legislative mandate does indeed call for us to provide a base for a national system of measurement, and to furnish essential services. The congress has also wisely chosen language that calls for us to *coordinate* that system as well. Perhaps it can best be summed up that "no coordinated effort" would lead rather shortly to discordant and hence wasteful national programs.

4.3.2 Technological Impact of Services

Let us continue our scenario of: "What if NBS were not involved? What would happen if we stopped cryogenic technology tomorrow?" There would be no ready acceptance, no preferred alternative, and no centralized national effort. While this is true, it is neither very helpful nor very satisfying. We would like to be more specific and I believe we can be, by looking at some specific technological examples illustrating the points made above.

Redundant data/facilities cause expensive and slow response to national needs. The cryogenics measurement system is supplied reference data by many experimental systems. One of these is our Pressure-Volume-Temperature system for the thermodynamic properties of fluids, which was built up over many years by the National Aeronautics and Space Administration and NBS at a cost of approximately $1.6 million. If it did not exist, something like it would have to be built up many times over by every user who needs the data; and operated by scientists relatively "low" on the learning curve. As it is, it is available for any priority work regardless of its origin. It is, in fact, being employed now to produce industry wide data on LNG for the AGA.

Inconsistent design data prevents optimization and evaluation. Many times NBS has been called upon by the government to evaluate efficiency claims and production capacities projected by "paper studies". A complete and consistent set of design data is essential to this purpose. The National Aeronautics and Space Administration, for instance, specifies that NBS data be used in its proposals to provide a common, sound basis for evaluation. Similarly, NBS recommendations to the FPC would be open to question if it were not for our sound foundation of valid, consistent data.

Arbitrary/conflicting standards: questionable custody transfer and safety evaluation. The State of California, frustrated by their legal requirement to regulate the sale of liquid nitrogen, but with no technical backup, were forced to set arbitrary standards. Specifically, they set the same standard for liquid nitrogen as was then in force for gasoline. The suppliers demanded a technical demonstration of the feasibility of these standards. This impasse was resolved by the NBS liquid nitrogen flow program. The producers benefited dealing with one central laboratory rather than 50 separate state laboratories. The states benefited by not having to construct 50 times over such a complex cryogenic test facility. The public benefited by the rapid proof and adoption of the codes. As mentioned, we feel that this is a practical realization of the "New Federalism" at work - as NBS competence was directly transferred to the states.

Conflicting government role: regulate/promote technology. The federal government has occassionally found itself in the awkward position of attempting to regulate and promote a technology at the same time. The effective and safe use of atomic energy is perhaps such an example. Recently, the Atomic Energy Commission as such was abolished the regulatory functions assigned to a new commission, and the technology advancement functions assigned to a separate energy development agency.

The National Bureau of Standards, having no regulatory function, is free of this type of mission conflict.

Vague technical basis inhibits both compliance and regulation. A liquefied natural gas explosion in 1944 was not only the worst disaster in Cleveland's history, but it also helped to set back the use of LNG for 20 or 30 years.

One hundred and thirty-one persons were killed when one of the LNG tanks failed from low temperature embrittlement/fatigue. Neither the plant builders and operators nor the public safety agencies had an adequate technical basis (the properties of 3-1/2% nickel steel, in this case), although both were conscientious in their respective tasks.

Unsatisfactory basis for decision making/-impartial judgment. Because of the enduring energy shortage and the great potential of hydrogen as a future fuel, a large number of laboratories, both public and private, have moved speedily to verify the feasibility of hydrogen as a fuel, e.g., numerous graduate students have converted automobile internal combustion engines to run on hydrogen gas. While this has been interesting and has attracted a great deal of attention, we have preferred to produce a benchmark study that will be used as the technological base for all further programs of any agency or university on hydrogen: future fuel. This report will do much to remove most of the speculation from this area and to provide a sound and common basis for decision making.

4.3.3 Pay-off from Changes in NBS Services

Services provided to the National Measurement System for cryogenics will always be embodied in measurements, data, and technology; but the thrust of the effort may change with time.

As mentioned, major developments in the field of cryogenics are occurring at three distinct regions of the cryogenic temperature scale, namely: 110 K (liquefied natural gas), 20 K (hydrogen: future fuel) and 4 K (superconductivity technology). These trends are not only valid, but also are taking on added significance in the light of the national commitment and sense of urgency to achieve a greater degree of national energy self-sufficiency in the near time frame.

These trends represent our best informed judgment of our prime *technical* opportunities for service over the next five years. In addition, largely as a result of this present study of the National Measurement System *operational* opportunities are emerging. The historical role of cryogenics at NBS has been one of technical problem solving to complement the monolithic mission of other government agencies (e.g., Atomic Energy Commission, National Aeronautics and Space Administration), and we continue to look forward to this exciting and mutually beneficial partnership. We now see another role emerging that gives even greater leverage to our measurements and data, and which indeed assures the effective transfer of measurements into the hands of the users. This emerging role is a partnership with the rerulatory agencies. For instance, the results of the flowmetering program (e.g., tolerances and basic property data) have been adopted into NBS Handbook 44 as a result of our cooperation with the states of California and New Jersey. A metals combustion program resulted from an initial Department of Transportation request following an oxygen tank truck disaster in Brooklyn. Much of the present LNG program came from interests by The Maritime Administration and the U.S. Coast Guard in new, inexpensive, but *safe* materials for seagoing tankers. Consultation and advisory services are provided to the Federal Power Commission on the cryogenic safety and other technical design aspects of several current applications before the Federal Power Commission for authorization of LNG terminal and storage facilities.

Table 4-2 shows how the beneficiaries of our outputs are expected to change as a consequence of the trends mentioned above.

Some of the reasons behind the expected changes shown in Table 4-2 are:

- Services to specific manufacturing firms will increase, reflecting the fact that cryogenics in general and superconductivity in particular are coming of age. More practical devices and instruments, such as SQUID's, will be manufactured.
- Interaction with the service industries will also increase as we interact more with the public energy utilities (hydrogen fuel, LNG, applied superconductivity).
- We have little direct measurement contact with the consumer *per se*, and expect no significant change. Contact will continue to be made through service industries and regulatory agencies.

Table 4-2. Distribution of effort

Beneficiaries of Outputs	Percent of Cryogenics Division Total Effort Current	5 years from now
directly to specific manufacturing firms or industries	8%	10%
directly to specific service industries	5%	8%
directly to the individual consumer	1%	1%
to the Defense Department	30%	33%
to Federal regulatory agencies	2%	5%
to State government needs	1%	3%
to other Federal government agencies	43%	30%
to other NBS groups	5%	5%
to university research and other research at the frontiers of science	5%	5%

- Direct support of the Department of Defense mission will continue, reflecting the fact that the Department of Defense supports about half of all research in this country [38] and that the first practical applications of superconductivity will probably be to Department of Defense needs.
- Both federal and state regulatory needs will grow. The federal interest (Federal Power Commission, Coast Guard) will be in the safe and efficient handling of cryogens. The State's interest lies primarily in effective metering, sale and taxation of cryogens.
- Non Department of Defense agencies will show a decline of the total, primarily due to the growth of the regulatory agencies.
- "Other" will remain small and constant, as instruments become standards and as conceptual knowledge is developed to the point of useful research.

4.4 Evaluation of NBS Program

4.4.1 Evaluation Criteria

Needs for NBS services to the cryogenic measurement system fall into two major categories: those determined by our own studies and initiatives, and those brought to our attention otherwise, such as suggestions from within other units of NBS or requests from other agencies, both federal and state. In any case, however, a similar decision process is made, carefully accounting for a balanced program, internal capability and facilities, staff wisdom, and the promotion of the mission and functions of Institute for Basic Standards and NBS.

Programs in support of these needs, whether funded by direct appropriation or by transfer of funds from other agencies, must be chosen for the same basic reasons. The Congress has wisely chosen a statement of the Bureau's mission broad enough to allow the Bureau to respond to changing needs. By the same token, such a freedom of choice demands of us a continual appraisal of the most important problems to tackle. Of the criteria for choice, and therefore for action, four seem to be vital to success:

- Needs in Relation to Mission (what is the relevance on either a long or short range basis?)
- Technical Opportunity (is it timely to take on a new program; is there a good idea?)
- Resources (can we bring enough manpower and money to bear on the problem to ensure an adequate contribution?)
- Leadership (is there an energetic "ball-carrier" who wants to do the job?)

Unless all four criteria are met, any problem that is tackled is not likely to have striking success.

However, there are three characteristics of our other agency work that do set them apart from our own, and these evolve in the following way:

- We wish to promote the efficiency of government through effective utilization of federal laboratories. When approached for help by another agency, we consider what they would have to spend to achieve our existing capability.
- The applied measurement programs of other agencies give our staff practical experience with problems in the field, and thereby automatically enhance the relevance of their work. We give priority to problems that add to our capabilities to carry out our primary statutory functions.
- We provide technical assistance to agencies that issue regulatory standards. The appropriateness and fairness of the tests

and measurement standards that define such regulations are critically important to fair and rational management of the Nation's technology.

If further consideration is warranted, we proceed through checklists (sometimes formally and documented, sometimes informally) that include at least the following criteria:

Evaluation Criteria - External

- Appropriate federal role?[1]
- Match to NBS mission
- Potential high impact
- Leverage of NBS measurement and data services on given sectors of the economy
- Importance of these services to fields other than immediately represented by measurements and data
- Importance of these fields within the scope of national priorities
- Absence of alternative institutions who can provide this information

Evaluation Criteria - Internal

- Utilize unique facilities, competences, and staff wisdom
- Maintain and strengthen staff competence
- Provide scientific and technical expertise to NBS programs
- Provide Institute for Basic Standards and NBS programmatic coherence
- Implement long-range strategic plan

Admittedly, these are only qualitative guidelines, but since the process is iterative and open to discussion over a period of time, some arguments begin to take on weight and become demonstrable while others do not. For instance, a "must" is that the program be somehow quantifiable -- that it have milestones for measuring progress versus plans. The decision is ultimately the line manager's responsibility, and he must bear the consequences. We find the above guidelines invaluable and useful. They are especially useful as tie points to tether the arguments and to make the decision process open and visible.

[1] This is of course, a most vexing question. Guidance is found in the NBS and Institute for Basic Standards mission statements, several NBS internal Policy Guides, and Administration interest. Guidance is also found in the following statement by a previous administration: "The legitimate object of government is to do for a community of people whatever they need to have done, but cannot do at all, or cannot so well do for themselves, in their separate and individual capacities". (A. Lincoln, Springfield, Illinois, July 1, 1854).

The final key to our program evaluation is how well the proposed program fits the Division strategic plan. This strategic plan is established by the cooperative action of senior technical staff, Institute for Basic Standards and NBS management, and the Evaluation Panel. Planning is, of course, a continuous process, but this strategic plan is formally documented and articulated annually in the Division's Planning and Budgeting Document (usually prepared each fall in time for the annual Evaluation Panel meeting, and the initiation of the budget cycle).

In this part of the evaluation process, it is important to realized that <u>both</u> the plan and the program are tested. Sometimes we do modify the plan to fit the program, but if so, we try to do this consciously and systematically, to be fully aware of why the strategic plan needed changing and what the consequences are.

4.4.2 Evaluation Panel Role

The Evaluation Panel always plays an important role in this evaluation process. The background and affiliation of the members are perhaps more germane to this present discussion than the names of the members themselves. The affiliations of the Panel members over the last few years (1975 back through 1970) are given below:

Department of Physics,
University of Pennsylvania

San Diego Gas & Electric Co.

Mechanical Engineering Department,
University of California,
Lawrence Berkeley Laboratory

Department of Physics,
University of Connecticut

Director, Superconductivity and Cryogenics Programs,
Westinghouse Research Laboratories

Controlled Thermonuclear Reaction,
Lawrence Livermore Laboratory

Department of Chemical Engineering,
University of California

Department of Mechanical Engineering and Applied Mechanics,
University of Rhode Island

Los Alamos Scientific Laboratory

The Evaluation Panel is charged with both broad and specific responsibilities. The Evaluation Panel:

- Provides Bureau management assistance in planning
- Considers importance and relative priority of projects

- Makes recommendations on new program initiatives
- Identifies areas of redirection
- Provides forum for technical staff
- Identifies barriers to progress
- Provides communication link with scientific and industrial organizations

We find the Panel especially valuable in evaluating our strategic plan and promoting a certain degree of discipline in exposing our programs to critical review and evaluation.

4.4.3 Why NBS?

In Section 4.3, we discussed the impact of NBS services and gave some specific examples of the consequences of not providing those services. In this Section, we shall examine some of the factors that help make the NBS role crucial.

Part of the reason is historical. NBS has supplied data and services to the cryogenic measurement system for nearly 70 years (see Section 4.1). As a result, we have developed unique capabilities -- not just in facilities, but more importantly, in staff experience -- a resource difficult, if not impossible, to duplicate elsewhere.

Industry values the third party independence and integrity of NBS, i.e., our impartial judgment. Companies and industrial associations frequently plead with us to establish a first line measurement competence in their technical area, even though they may already have competent research laboratories. Those industries who know they have an excellent product want their customers to be able to make accurate and objective evaluations of that product. If their own product claims are based on measurements traceable to NBS, customer confidence is enhanced. This is important also in foreign trade, for the Bureau is regarded as highly abroad as it is at home. We call it neutrality and acceptance; "neutrality" in the sense of an independent third party; and "acceptance" in two ways. Not only does the integrity, competence, and independence of NBS often lead to the ready, universal acceptance of our work, but also we are able to accept proprietary data in confidence, which often facilitates the process of objective technical review and evaluation.

Providing a fast and timely response is possible in part to this ready acceptance. NBS is also able to respond rapidly and credibly because of the experienced staff, having diverse backgrounds, which is available to assist in problem solutions requiring many technical disciplines (as in the Apollo 13 and Staten Island LNG incidents).

NBS alone has the charter to provide both national standards and international standards through the aegis of the Treaty of the Meter.

The federal role of NBS is to provide the basic measurements, data, and standards that are required to support and enhance a diverse national technology --the infrastructure technology of cryogenics itself. NBS does this in part by providing a sound technical basis for regulations that will stand up in court. NBS was established by the Congress to be helpful, and this assigned function is a critical link between the basic research community and those who have to put science to work.

The coordination of such a nationwide effort as this is best centralized so that the Nation can have a strategic and integrated program rather than a piecemeal one, and can further benefit from the synergism that naturally occurs in a centralized, coordinated effort.

These principles are the lifeblood of the National Bureau of Standards and are strongly and deeply felt by each and every one of the Cryogenics Division's professional staff members, just as they are by every member of the NBS as a whole.

Table 4-3 summarizes the crucial role of NBS. (See page 53).

4.4.4 Program Evaluation

"We judge ourselves by what we feel capable of doing; others judge us by what we have done." Henry Wadsworth Longfellow.

The previous sections have described the evaluation *process*; the following gives the *results* of that process, in particular, the judgment of the Evaluation Panel appointed by the National Academy of Sciences/National Academy of Engineering/National Research Council.

The members of the Evaluation Panel are chosen by the above associations for recognized scholarly competance. The members of the 1973-74 panel were: Donald N. Langenberg, <u>Chairman</u>, University of Pennsylvania; Paul L. Hathaway, San Diego Gas and Electric Co.; H. Paul Hernandez, University of California; John L. Mason, The Garrett Corporation; John M. Prausnitz, University of California; Clyde E. Taylor, Lawrence Livermore Laboratory.

The following material quotes the summary and general conclusions of the 1973-1974 report.

<u>"Summary</u>

"The Cryogenics Division's coupling with outside client agencies, industries, and associations is good, though more effort should be made to achieve visibility at the highest managerial levels of these organizations.

"The Panel believes that all three of the Division's new program initiatives are timely, relevant, compatible with the Division mission and goals, and worthy of support. On the basis of the *immediacy* of the problems being addressed, rather than long-term importance or quality, the Panel ranked the initiatives as follows: (1) Liquefied Natural Gas Technology, (2) Cryotechnology for Superconducting Equipment, and (3) Hydrogen: Future Fuel. Within each initiative, portions of relatively higher or lower priority were identified and discussed.

"General Comments

"The Division's technical and managerial competence remains high. With the possible exception of certain aspects of its Liquefied Natural Gas (LNG) Program, it maintains a good balance between work related to its essential basic-standards mission and work that responds to national problems, such as the energy crisis. Even in the latter area, the proposals and activities are clearly within the basic mission of the Division.

"The Division effectively maintains close coupling with its counterpart industries and industrial associations. Because these interactions are essential and contribute to the Division's success, they must be continued and enhanced. The Division is well-known at the operational level in industry. However, the Panel does not believe that U.S. industrial leadership at the vice-presidential level is aware enough of the Division's capabilities in trouble-shooting and contributions to engineering research. It is to the Division's advantage to ensure that those individuals who are in a position to influence policy in government and in industrial research foundations know about its industrially important activities and well-earned international reputation. *Accordingly, the Panel strongly recommends that the Cryogenics Division consider ways to increase its visibility in general and especially in high-level industrial management circles.*

"An important Division contribution outside NBS has been its consultative services to industry and other government agencies. The Panel urges that as many permanent technical staff, including its younger members, as possible participate in this activity as a means of ensuring continued effectiveness and achieving more general recognition of the importance of this facet of its work."

The 1974-1975 panel members were Donald N. Langenberg, Chairman, University of Pennsylvania, Paul L. Hathaway, San Diego Gas & Electric Co., H. Paul Hernandez, Lawrence Berkeley Laboratory, Paul G. Klemens, University of Connecticut, James H. Parker, Jr., Westinghouse Research Laboratories, Clyde E. Taylor, Lawrence Livermore Laboratory.

The following sections are quoted directly from the panel's 1974-1975 report:

"THE ROLE OF NBS IN CRYOGENIC TECHNOLOGY

"The Panel was informed that the involvement of NBS (primarily through the Cryogenics Division) in cryogenic technology is sometimes questioned. The rationale for such questions is apparently that, since cryogenic technology is a primary concern of a variety of private-sector institutions, many of the cryogenic programs currently in progress within NBS might better be carried out in these institutions.

"It is the view of the Panel that the current activities of the Cryogenics Division in the area of cryogenic technology are entirely consistent with the goals and purposes of NBS and should not (and in many instances could not) be left to private sector institutions, particularly when the independent position and the high quality of the Division's work is recognized.

"Let us consider some examples:

"A. Liquefied Natural Gas (LNG). The Cryogenics Division is studying the thermophysical properties of pure components and of mixtures of the components of LNG. The purpose of this work is to develop the basic reference data and measurement techniques required to assure equity in the handling and transfer of LNG, an activity which is rapidly becoming a major factor (billions of dollars) in our fuel importation industry. The assurance of equity in trade and certifiable measurement of trade quantities is self-evidently an NBS function. If the LNG industry were to assume responsibility for this program, it could do so only be replicating, probably several-fold and at considerable cost in time and money, the unique facilities and expertise already in existence in the Cryogenics Division. We would then have one party to commercial transactions specifying reliability of the measurements involved, or two parties in conflict over the applicability of different measurement systems. This is just the sort of thing it is NBS's function to avoid. That all of this is fully recognized by the LNG industry is evidenced by the fact that it is providing major funding for the NBS program through its trade organization, the American Gas Association.

"B. Cryogenic Materials. The Cryogenics Division is studying the mechanical and electrical properties of a wide variety of materials for use in cryogenic environments. The purpose here is to develop bench mark data for use in design, a function which could be carried out elsewhere only at considerable cost in duplication and general credibility and acceptability. Here again, the special capabilities of the Cryogenics Division are recognized in funding supplied by the Advanced Research Projects Agency and the U.S. Maritime Administration.

"C. Cryoelectronics. Several divisions of NBS are engaged in developing applications of superconducting electronics. Here the primary and immediate import will be on the Bureau's own needs for precision measurements and standards. There simply is no other institution which is in a position to supply the technology needed for these special needs.

"D. Properties of Cryogenic Fluids. The Cryogenic Division has provided a unique public service in acquiring available physical properties data, in performing experimental measurements, and in formulating these data for use in thermal computations for such fluids as helium, hydrogen, nitrogen, methane and the like. The integrity of their work is recognized worldwide and has led to the broad acceptance of this basic data."

Evaluation Summary. Each year, the Panel is charged with specific responsibilities in addition to its overall duty, and accordingly, the response each year centers about a different theme. Nonetheless, some general conclusions may be drawn from the above reports. Others judge us as having good coupling with our outside clients; having a timely, relevant and balanced program; maintaining high technical and managerial competence; and making an important contribution through our consultation services. Our special capabilities are recognized in funding supplied by counterpart institutions. We are criticized for having poor visibility at high level management circles. Correcting the latter deficiency could add leverage to our work.

On the whole, this outside review of our program is rather favorable.

Table 4-3. The crucial role of NBS

- Federal Role
  - Need for data and services to accomplish a specific government function, such as health and safety regulation
  - Importance of these data and services within the scope of national priorities
  - Leverage of NBS data and services on a given sector of the economy
- Diverse National Need
  - Lack of direct incentives to a single organization to perform the "services" needed
  - Diffuse benefit--high risk, low gain
  - Multiple beneficiaries
- Provide National Standards
  - Model established: measurement development, plus transfer of technology
- Impartial Judgment
  - Neutrality
  - Acceptance
- Unique Capability
  - Unique NBS capability in equipment, facilities, personnel, or experience
  - Past success; acceptance
  - Experience in related fields
- Fast Response Time
  - Ability to respond rapidly and credibly to a recognized need
- Technology Transfer
  - Needs identified by cryogenic community; well identified needs; well documented successes
- Preferred Alternative
  - Absence of alternative institutions who can provide this information
  - Mission orientation
- Acceptance
  - De facto standards of measurement, of quality, of performance, and of practices
- Coordinated National Effort
  - Importance of these data and services to fields other than those requesting the data
  - Other agencies conjoined; synergism

4.5 The Future

We have indicated that cryogenics is largely an infrastructure technology. It is by and large hidden from the casual observer, while at the same time occupying a central position of great potential leverage on the Nation's essential science and industry. The cryogenic measurement system is in turn, an infrastructure of cryogenic technology. Therefore, to anticipate the needs of the future, it is necessary to assess the state of cryogenic technology itself and the state of the measurement system within that technology. Such assessments are carried out periodically and systematically. The framework of the studies is discussed below.

4.5.1 Technology Assessments in Cryogenics

Overview. As mentioned briefly in Section 3.2, two overviews were made at the division-as-a-whole level to document the infrastructure position of cryogenics in large national programs (space, health, transportation, etc.) and to identify leading indicators of trends of the health of cryogenics.

The first, "Cryogenics and National Goals", [39] was in 1968. At the height of the space effort, it predicted the demise of that program, its need for hydrogen technology, and foresaw the growing importance of a practical helium technology and LNG as a fuel. It is perhaps interesting to note that the Oil and Gas Journal at that time said that "The U.S. is not generally regarded as an energy starved nation, and imports of LNG will never be significant."

The motivation for the second overview, "Trends in Cryogenic Fluid Production in the U.S." [40], was to verify and update the findings of the first. It seemed important to let a little time pass, and then test the structure and underlying assumptions of the first benchmark study. It was an experimental check of the 1968 study and did document the critical supporting role cryogenics plays in essential national industries.

Applications for Specific Customers. Once the network of cryogenics in technology as a whole had been defined and tested, it was useful to look at specific functional relationships between terminals in that network, or the leverage of cryogenics in specific customer applications. Four such studies were formally done and published.

"Superconductivity Programs of the AEC" [41], predicted the need for efficient cooling of long lines to helium temperatures for power transmission. There are now four major research groups involved in the development of just such superconducting power transmission lines in the U.S. Precise measurements (especially pressure measurements) are crucial to achieving the effective cool-down of such long lines.

"Superconducting Levitation of High Speed Vehicles" [42], was prompted by need of the Department of Transportation to decide between competing levitation technologies, such as the floating of trains above a track on an air cushion, or supporting it on magnetic cushions that may or may not use superconducting magnets. This study documented the precise role of cryogenics in high speed ground transportation and proposed several possible ways to anticipate and resolve potential cryogenic measurement problems.

"Current Developments in Cryomedicine" [43] was meant to define what role, if any, NBS should play in the field of cryo-medicine. There did not appear to be a unique opportunity for NBS in the field of measurement science in cryo-biology. Accordingly, no particular course of action was deemed to have a striking chance of success. A conscious decision was made not to enter this field.

"Water Pollution Abatement" (internal study by Chelton) was the Cryogenics Division's first systematic look at environmental problems. Again, a program was deliberately not recommended, although both the need and the technical opportunity (but for others) were present. Two technical conclusions were reached: (1) The most extensive potential application of cryogenics is that of supplying (liquid) oxygen instead of air to secondary waste water treatment plants to accelerate decomposition, and thus upgrade present plants and facilities; and (2) the most sophisticated application of cryogenics is the use of superconducting magnets for colloidal filtration of river water. Nonetheless, criteria for NBS entering the field were missing. Specifically, the first case was not really a cryogenic research problem, for the handling of liquid oxygen is a well established business. Neither was the second, necessarily, since the construction of large superconducting magnets has been accomplished at the national laboratories.

Applications to a Specific National Need--Energy. We have prepared technology assessments in three energy areas: LNG, hydrogen, and superconductivity. Measurement services and data to support these three technologies promise to be the main enterprise of the Cryogenics Division for the foreseeable future.

Liquefied Natural Gas was addressed at two levels -- simply its peculiarities as a cryogenic fluid, and as a commodity.

"LNG as a Cryogenic Fluid" [44] assumed that the Nation is just now entering an era of the large scale use of liquid natural gas. This report then predicted potential LNG problems, based on similar experience gained when the Nation just began handling liquid hydrogen as a commodity. It predicted specific instrumentation problems in measuring pressure, temperature, liquid level, and flow. It also predicted specific problems from property data that are insufficient, have had insufficient analysis, or are internally inconsistent. This study documented the practical utility of basic measurements and launched the American Gas Association program on LNG.

Since LNG was a significant commodity in trade, "Measurements of LNG in Commerce" [45] examined the measurement basis for purchase of LNG. This study found a six-step measurement process which has, at present, no quality control or quality assurance built in, and which is based essentially on a bid and barter system. For instance, tank volumes are fixed at room temperature by "strapping" the tank with a tape measure, and then establishing some functional relationship between liquid level and volume. This paper documents the advantage of basing the commercial custody transfer on modern mass flowmetering and property data instead. The goal is to establish an orderly, systematic, and scientific basis for LNG trade.

"Hydrogen: Future Fuel" [46] showed the many technical, economical, and ecological advantages that make hydrogen a prime candidate as a substitute chemical fuel of the future. It was the first step in documenting the needs for the present technical program.

"Superconducting Electrical Power Systems" [47] was an effort to accelerate the application of this technology to an old, established, and reliable industry. It found, among other things, that:

- Technological leadership in superconducting machinery in the United States can help to reduce generator imports by up to 50%.
- Technological leadership by foreign companies can help them to capture a larger share of the U.S. market.
- Superconducting generators may be essential to realizing the full advantage of the large fast breeder reactors.

Specific technical program plans were drawn to enable the development of superconducting electrical generators, in cooperation with the large electrical machinery manufacturers. This effort helped stimulate the development of applied superconductivity in this country, made public much privately held information, and has led to major new thrusts to provide adequate measurement services in support of this field.

Analysis of Major Technical Threats. Since cryogenics is a rather well-bounded and self-contained technology, it is not likely to be replaced by a competing technology, such as electrical measurements replacing mechanical or optical measurements, or TV phones replacing business commuting. The principal threats are from among the rivals within the technology itself, especially from abroad. Since cryogenics was "invented" abroad, we have never suffered the delusion of thinking that NBS has the world's supply. Instead, world-wide awareness is central to our supplying timely and essential measurement and data services to the U.S. cryogenics community.

The most recent systematic foreign technology assessment was the monitoring of applications of superconductivity in the USSR, Switzerland, W. Germany, France, England, and Japan (internal study). For instance, NBS staff visited the Fawley (U.K.) power station to inspect the 3250 HP superconducting motor; discussed national funding of private enterprise with the U.K. - National Research Development Council; discussed the German superconducting levitated train in Munich; and witnessed the Japanese 4-passenger demonstration superconducting train. We found foreign efforts to be aggressive, well ahead of our own, and funded in cooperation with their national governments. This study documented the magnitude of the foreign exploitation of U.S. technology and helped provide a sound basis for designing our own measurements and data program.

Analysis of Major Technical Barriers. The question of reliability and cost is always raised whenever a commercial application of cryogenics is suggested. Helium supply, management, and control lie at the heart of realizing practical superconducting systems.

Strobridge [48] documented that enough experience has been accumulated in the design and operation of low temperature refrigerators and liquefiers to safely assume that any cooling requirement can be met. This study frequently obviates proposals for new refrigeration surveys, or, in some cases, refrigeration development programs, and provides a common data base for refrigeration dependent technologies (e.g., accelerators and transportation).

We have seen that cryogenics is an infrastructure industry, serving in an indispensable way the needs of other industries. Similarly, the science of cryogenics is an infrastructure science. Seldom are the low temperatures themselves of interest, except perhaps to establish some record. Rather, their real importance lies in enabling the basic understanding of other phenomena, i.e., increasing conceptual understanding.

The essential point is that here, too, cryogenics plays an essential but invisible role. It is usually not the cryogenics *per se* under study,but rather that the ultra low temperatures cause basic physical phenomena to be greatly simplified and thus be more susceptible to understanding and use.

Accordingly, we conducted in 1969 an internal planning study to define needs in millikelvin research and propose specific action to meet those needs. This study recommended specific measurement and data needs in the millikelvin and sub-millikelvin range. These plans included the development and improvement of standards and measurement techniques, as well as techniques for obtaining and maintaining low temperatures.

Analysis of Major Technical New Opportunities. The studies above have in common the motivation of need in relation to mission. A parallel requirement of a sound program is the existence of a timely technical opportunity, and our formal technology assessments have not been without this component as well.

Cryoelectronics has been addressed in this fashion twice, in harmony with the notion of reviewing and checking our predictions periodically. The first was an internal planning study which documented developments in superconducting devices in d.c. voltage, direct current, magnetic field, RF current, RF power, pulse technology, RF noise, and temperature (internal study). It articulated a measurement role for NBS and formed a new organization to consolidate an NBS program in cryoelectronics.

"Developments in Cryoelectronics" [49] was published to document the development of new electronic instrument,s taking advantage of the unique properties of superconductors. It found that commercial activity has been in the nature of an investment in the future: very few devices have actually been sold yet. It suggested that computers, information transmission lines and magnetocardiography may become commercially significant applications of superconductivity.

It suggested that many other superconducting devices also perform specialized functions uniquely, and would repay the cost of development without necessarily generating a large market. This study is helping to provide the basis for future measurement and data programs.

An intense and in-depth effort on superconductivity was conducted at the request of the President's Science Advisory Committee (PSAC), which required the participation of many experts outside of NBS. In a sense, it was a conference-style Delphi exercise. The result was an oral briefing to PSAC on the current status and future promise of superconductivity. It covered such topics as new superconductors; magnets and their application to transportation, ore benefication, and water pollution; electric power generation and distribution; and cryoelectronics. As a result, the President's Science Advisor formally requested the Department of Commerce to take a leadership position for the exploitation of cryogenics and the creation of new industries.

As a result of this briefing, a plan was developed to help assure the successful commercial exploitation of cryogenics. The goal was to assist the Department of Commerce to create its own policy for the effective application of cryogenic technology for public benefit.

Summary of Cryogenic Technology Assessments. These studies have given visibility to our decision making, and invited staff participation by those most likely to be affected by the decisions. A stronger, more timely program has been the result.

4.5.2 Driving Forces

The overall goal of the National Bureau of Standards is to strengthen and advance the Nation's science and technology and to facilitate their effective application for public benefit. Accordingly, it is not surprising that we find both technical and societal driving forces at work, influencing the trends of our program.

Technical driving forces (applied superconductivity, hydrogen fuel, LNG imports, etc.) were noted in the specific technical sections above. In addition, as implied in the NBS Goal, we must continually give special attention to the public and private institutions through which our measurement and data services benefit people. Some noteworthy trends in such societal driving forces and our expected response to them follow below:

- Services influencing the manufacturing sector will increase, reflecting the fact that cryogenics in general, and superconductivity in particular, are coming of age.
- Interaction with the service industries will also increase as the interaction with the public energy utilities and the Energy Research and Development Administration increase.
- There is little direct contact with the consumer *per se*, and no significant change is expected. Contact will continue to be made through service industries and regulatory agencies.
- Both federal and state regulatory needs will grow. The federal interest will be in the safe handling of cryogens. The state's interest lies in effective metering, sale, and taxation of cryogens.

As a result, we shall have to maintain a balanced program supplying both measurement services and data to the cryogenic measurement system.

4.5.3 Emerging Technologies

We have seen that the major developments in cryogenics in the next few years that will have significant impact on the technology of the country and its balance of trade are the widespread international use of liquefied natural gas, applications of superconductors, and potential uses of hydrogen. Cryogenic measurement and data services are essential to meet the developing needs for metrology, design data and applied cryogenic research.

Figure 7 shows these technological trends and our response to them. The check marks are a qualitative representation of our present emphasis, which is in harmony with the timeliness (or urgency) of the technological trends. LNG is upon us now; superconductivity is a technology that is finding wider use; while the most pressing need for hydrogen -- Future Fuel is data for decisions. These emerging technologies will demand continued NBS support for the foreseeable future. See Section 5. for specific recommended actions.

4.5.4 Impacts of the National Measurement System Study

This study of the National Measurement System documented for us the complete process that must be undertaken to provide a complete measurement service. For instance, our LNG budget initiative submitted in the spring of 1974 was deliberately constructed to include all three necessary elements: measurement science, data base, and technology transfer (includes safety, interstate and international cooperation, effective use of the Office of Weights and Measures, and training). Thanks (in part) to the NMS study, new programs now use the guidelines so developed to assure a complete and comprehensive approach.

In addition, we have become more sensitive to the measurement system concept in all our programs, not just the LNG program. For instance, we are making an inventory of all of our measurement services. We also are documenting our operations throughout the dissemination network, e.g., regulatory agencies, state offices, central standard authorities, and education programs.

Left to our own devices, we would most likely have conducted a technological impact study (the science and technology profile of the cryogenics industry needs updating) and not an examination of our part of the National Measurement System. Left on our own, we would have benefited by documenting new and other needs and developing programs accordingly. We would have lost the understanding we now have of a "complete" program, and our role in the infrastructure of the National Measurement System.

5. SUMMARY AND CONCLUSIONS

5.1 Key Developments

This study has shown that there are three emerging technologies within the broad field Cryogenics with a need for a complete and

	TECHNOLOGY TRENDS ➧		
OUTPUTS ⬇	**Liquefied Natural Gas**	**Superconductivity**	**Hydrogen: Future Fuel**
Physical Measurement	√	√	
Materials Data Base	√	√	√
Cryoengineering Services	√		

FIGURE 7. Emerging technologies in cryogenics.

consistent system of measurements and data. Specifically:

Liquefied Natural Gas. A complete and comprehensive measurement system for the liquefied natural gas industry needs to be developed, with special emphasis on quantity gaging in storage and ship tanks, flowmetering for determination of both mass and heating value, and basic measurements of thermal and mechanical properties of structural materials.

Hydrogen. Basic measurements and data are required now to support the development of hydrogen as a fuel, in such areas as improvement of hydrogen liquefaction efficiency, evaluation of methods of recovering liquefaction energy, of hydrogen-compatible materials of construction, and development of improved insulation materials and an instrumentation and measurement methodology for the commercial exchange of liquid hydrogen.

Superconductivity. Superconductivity connects cryogenics measurements and data to the electrical power industry, for power transmission, generation, and storage. Knowledge needed includes heat transfer rates, behavior of helium refrigerant flow systems (including the response to instabilities), and the degradation of the superconductors with time and stress.

Superconductivity is also a means of employing cryogenics to develop new or improved measurement techniques in fields outside of cryogenics. The SQUID (Superconducting QUantum Interference Device) is demonstrating promising applications in magnetocardiography, geothermal prospecting, determining molecular constants, and spectroscopy of all kinds. Indeed, the SQUID appears to be as versatile as the Laser as a measurement technique, and is, of course, fundamentally a cryogenic device.

Some of the needs of each of these parts of the National Measurement System for Cryogenics are illustrated below.

5.2 Liquefied Natural Gas (LNG)

LNG is a Cryogenic Fluid (NBP 110-140 K) but unlike the simple fluids of our usual experience it is:

- A non-ideal mixture of five or more hydrocarbon fluids and nitrogen; no known mixing rules exist at this time, and therefore the mixture properties are not yet predictable; all must be measured.
- Furthermore, the mixture fraction varies with source-time-and storage treatment.
- LNG is primarily an energy storage media, because its energy content is about 600 times that of natural gas at atmospheric conditions.

Peak shaving accounts for the largest number of LNG facilities with 106 being completed within the U.S. This number includes 55 actual peak shaving plants (which include liquefaction, storage and gasification equipment), and 51 satellite facilities (which comprise a total storage capacity of approximately sixty-five billion cubic feet (equivalent gas volume) and a total liquefaction capacity of approximately 295 million cubic feet per day.

LNG presents not only a nationwide problem, but an international one. Contrary to popular opinion, the U.S. is *not* dependent upon just *one* source. Imports are planned from Malaysia, Australia and South America, for instance. We will also "import" from Alaska. In fact, the U.S. is presently a net exporter of LNG (to Japan) due to contracts signed in 1968.

Industry desires NBS assistance in this national problem. For instance, the president of the American Gas Association has written the Secretary of Commerce, requesting measurements and data assistance from the Department of Commerce and the NBS.

The Secretary gets many such letters, to be sure, but our study has shown that the Department of Commerce and NBS have been earmarked as the international and interstate connection agency. International contracts call out NBS as the measurement authority. In addition, we also have an inter-state responsibility to provide LNG assistance to a variety of federal, state and local authorities on the inter-state transfer of LNG.

LNG has grown so fast and to such a size and complexity that our NMS study revealed that it is now timely for the Department of Commerce to take steps to assure quality control and continuity in this part of the NMS.

The overall measurement and data needs for LNG identified in the course of this study include:

- Heating Value (Energy) metering for national and international trade
- Quantity gaging
- Thermophysical properties
- Properties of structural materials
- Instrumentation and data for Energy Conservation
- Safety Criteria

The needs for the safe and effective utilization of liquefied natural gas are most urgent. They include both tools and techniques for physical measurements as well as a data base for materials selection and use.

5.3 Hydrogen

With respect to hydrogen, there seems to be little doubt that it will become a major source of fuel for the future. Needs are centered about providing an adequate data base--reference data, reference materials and performance standards--to give a rational basis for decision making in this field.

Candidate Markets for cryogenic hydrogen, without regard to priority or imminency, are:

- Transportation--to fuel aircraft, autos and ships;
- Aerospace--rocket and spacecraft fuel;
- Energy storage and transmission--carrier of nuclear or solar energy from sea-to-shore or overland;
- Utilities--fuel for integrated gas-electric utility operations and a portable fuel for rural communities; and to a lesser extent:
- Superconducting and cryoresistive electrical power cables--to be used as a closed-loop coolant (electricity and hydrogen are delivered);
- Industrial processes--to provide high purity hydrogen gas upon demand.

Assuming that a future market exists for liquid hydrogen we must dispense the fuel in an efficient, fair and safe manner.

The efficiency of liquid hydrogen fueled systems can be improved on three fronts:

(1) lightweight, efficient and inexpensive insulation materials are needed, together with national insulation transfer-standards;

(2) data are needed on advanced construction materials that are lightweight, strong, inexpensive, resistant to hydrogen embrittlement and brittle fracture, and having low heat capacity and thermal conductivity.

(3) liquid hydrogen handling procedures, though highly developed and successful in the aerospace program, will have to be revised for commercial applications.

Liquid hydrogen enjoys an enviable safety record in the aerospace industry. However, the safe use of hydrogen in commerce will require thorough re-evaluation of: 1) compatible materials of construction, 2) handling procedures and regulations, and 3) explosion hazards.

We must also be able to guarantee equity in hydrogen commerce. Thus, traceable measurement standards are required for mass flow, pressure, temperature, and quantity-gaging. Liquid hydrogen instrumentation has not significantly advanced in the past ten years since the peak of the space program. Major efforts will be required to meet the needs of a commercial cryogenic hydrogen fuel market. Instruments suitable for aerospace applications are not usually appropriate for commerce and vice versa. Measurement standards are needed to bring all aspects of hydrogen instrumentation into quality control within the National Measurement System.

5.4 Superconductivity

Superconductivity was discovered at about the same time as the Wright brothers first flight, yet remains largely an undeveloped technology. This is indeed curious since the potential practical applications of superconductivity are staggering. For instance, it is widely held that superconductors could be used to advantage to transmit electrical power with almost no loss, to make magnets of a size not heretofore possible for energy storage; to upgrade low quality iron ore in magnetic mineral processing; to improve the quality of kaolin; to purify water via colloidal filtration; or to float high speed trains on a magnetic cushion.

Yet *none* of these possibilities are approaching commercial realization in the United States. The problem does not appear to lie with the superconducting wires themselves, as over 500 materials are already known to be superconductors. Furthermore, a dozen manufacturers here and abroad are producing superconducting wire and cables in nearly commercial quantities at prices approximately one-tenth that of copper wire for the same current carrying capacity.

The problem appears to lie instead in providing a reliable, safe and convenient supporting cryogenic environment. We need to provide the helium measurements and data base essential to the successful development of superconductivity. NBS need not address the applications of superconductors mentioned above, but does need to provide the supporting measurements and data on: 1) helium heat transfer and fluid dynamics; 2) instrumentation and measurement systems for helium management, and 3) data on the degradation of superconductors.

Since heat transfer and fluid dynamics are strongly interrelated, a thorough understanding of the fluid dynamic aspects is essential. The important consideration is that all flow irreversibilities ultimately show up in the form of heat, thus reducing the capacity of the helium to absorb other losses. We need to provide basic data and understanding on the properties and behavior of helium to provide engineering and process designs, predictions, and scaling of equipment.

Effective helium management will require, at least, sensors for pressure, temperature, quantity and flow rate. We need to provide such instruments through developments which take advantage of the low temperatures and optimize the instrument output. For instance, superconductors themselves may be used for thermometers and level gages. We need a new generation of instruments and measurement techniques tailored to liquid helium as a technical fluid.

The third consideration arises from the fact that practical superconducting systems will not operate under ideal laboratory conditions. They will be subjected to mechanical stresses during shop and field-site fabrication; they will, at least occasionally, be subjected to unduly rough handling; they will have unprogrammed excursions in current, temperature, and mechanical stress during fault conditions. Even more fundamentally, they will certainly show typical manufacturing variabilities and may show time dependent deterioration of their desired design properties.

The foregoing discussion has focused on the physical measurements, units, standards and essential technical data needed to support the needs of the National Measurement System for cryogenics. In addition, cryogenics itself may be used to advantage to develop new or improved measurement technology outside of the field of cryogenics. Specifically, the SQUID is being used to improve technology transfer from our physical measurements program to other federal agencies and industry; and to extend the impact area of the measurement program. Since physical measurements are almost always reduced to electrical measurements, the list of cryoelectronic applications is almost endless. Accordingly, it is particularly timely to open up the way for extensive new applications of cryogenics to physical measurements units and standards.

5.5 Summary

Our study of the National Measurement System for Cryogenics has shown that major developments in the next few years will occur in cryoelectronics, the widespread international use of liquefied natural gas, potential uses of hydrogen, and applications of superconductors. Major other federal agencies will doubtlessly continue to solve their specific cryogenic technological problems through a variety of means, including, but not limited to, soliciting the services of the Cryogenics Division. We regard this constituent of our total program as a necessity to maintaining our institutional health, and our sustaining a current awareness of national needs and goals.

However, no other instrument of the government has the prime responsibility to assure the proper functioning of the Nation's system of cryogenic measurement. The needs as discussed briefly above and documented within the body of this study, demonstrate that now, more than ever, it is time for a central, coordinated, coherent national effort on the part of NBS to bring and keep the cryogenic part of the National Measurement System into quality control.

METHODOLOGY OF THE STUDY

APPENDIX A.

One purpose of the Cryogenics Division study of the National Measurement System was to clarify and understand what is necessary to provide a "complete" measurement service, and to identify the role cryogenic measurements in the infrastructure of the National Measurement System.

We hoped by this process to document the way information was gathered, how conclusions were reached, and how the results were validated. Such hindsight could then be applied to the systematic development of new measurement services in the future, as well as to improving present services. In the following material, we shall examine our particular methodology in four categories:

1. Mechanism for Selection of Data Sources;
2. Transmission Mechanics, the means by which the desired data was conveyed;
3. Contact Mechanisms, used to obtain the desired data;
4. Sources of Information or Validation.

Table A-1 is a matrix designed by Dr. R. C. Sangster, National Measurement System Coordinator, that conveys at a glance much about the study. The blocks in the matrix are divided by a diagonal. The upper left corner refers to the process of obtaining results; the one in the lower right deals with the process of validating the results. "O-L-M-H" gives a rough quantitative estimate of the importance (to this study) of the results in terms of zero, low, medium, or high.

The following narrative describes each of the four tactical means listed above.

1. Mechanism for Seclection of Data Sources.

An analysis of NBS clientele was very important to obtaining data. Many of the clientele (state weights and measures officials and compressed gas suppliers) played an essential role in validating our results. In the case study cited in this report, our results were crucial to the commerce between many of our clientele. They were profoundly affected (by law) by the results, and therefore had a vested interest in promoting valid results.

The NCSL membership, *per se*, was not used because the Instrument Society of America (ISA) had already formed an Ad Hoc committee on a specific measurement, namely cryogenic flow measurement. This committee provided an extensive review and definition of the national needs for cryogenic flow measurements and standards, and we used this resource extensively to illustrate the practical realization of general principles.

Invaluable help was obtained from the Compressed Gas Association (CGA). The CGA is a nonprofit corporation which represents all segments of the compressed gas industry in the United States, Canada, and Mexico. They also have associate members in European and Asian countries. Among its membership are over 250 companies, including North America's largest firms, devoted primarily to producing and distributing compressed, liquefied, and cryogenic gases, as well as leading chemical industry corporations that have compressed and liquefied gas divisions. They contributed valuable insights to the mechanics of the National Conference on Weights and Measures, especially as to how a code is developed and promulgated through the documentary system. Perhaps prompted by the interest of the CGA and the states in "type approval" of meters, members of the instrumentation industry were very helpful.

The U.S. Department of Commerce (DoC) compiled and published many statistical summaries that were invaluable to this type of study. For instance, the SIC codes lead immediately to the "Current Industrial Reports", in our case Series M28C, which gives frequent and accurate summaries of the production of cryogens. The "Alphabetic Index of Manufactured Products" is a companion to the better known "Standard Industrial Classification Manual". Other useful Department of Commerce publications include "Industry Profiles", and the annual "U.S. Industrial Outlook". The latter is especially useful, for it not only summarizes statistical data, but also forecasts growth and the reasons (e.g., new uses for old products) for this growth. "Mineral Facts and Problems", published by the U.S. Department of the Interior, provides a resource similar to the "U.S. Industrial Outlook", but is even more exhaustive in its treatment of cryogenic gases.

Private compilations, such as the Dunn and Bradstreet's "Million Dollar Directory", while giving a brief overview of a particular company, also gives the SIC codes for the products manufactured by that company. For instance, "Cryostats" do not appear in the SIC Manual, but can be found in a roundabout way from Dunn and Bradstreet, if one knows even the name of only one firm in the cryostat business. Once the SIC code is found for a particular product, then this resource lists all firms reporting under that code. In this way, every firm in that business is

TABLE A-1. Means used to obtain and validate data.

1. MECHANISM FOR SELECTION OF SOURCES	OBTAIN	VALIDATE
Analyses of NBS Clientele	H	H
Analyses of NCSL Membership	0	0
Analyses of Instrumentation Industry	H	H
Analyses of Other, Similar List	H	H
Use of SIC Codes for Analyses	H	0
Staff Judgment/Wisdom	H	H
Analyses of Statistical Compilations	H	0
2. TRANSMISSION MECHANICS		
Published Literature	H	H
Formal Meeting Presentation	H	H
Organizational Statement	H	H
Personal Statement	L	H
Advertisements	M	0
Clientele Customer Lists	L	H
3. CONTACT MECHANISM		
Literature Search	H	H
Retention of Consultants	M	H
Conversation - Visitor to NBS	H	H
- At off-site location	H	H
- By telephone	H	H
- By visit to source's site	H	H
Correspondence	M	M
Formal Polling/Canvass/Questionnaire	M	0
Delphi Studies	L	L
Other Formal Forecasting Techniques	H	0
Special Conferences (NBS Sponsorship)	H	H
Trade Show Exhibits by NBS	0	0
Round-Robin/Inter Comparison	0	H
Training Courses	0	0
Construction of New Institution	0	0

TABLE A-1. Means used to obtain and validate data (continued)

	OBTAIN	VALIDATE
Attendance at Conferences & Meetings	M	M
Statistical Compilations	H	H
4. SOURCE OF INFORMATION OR VALIDATION		
Academic People & Institutions	L	M
Prof., Tech. Soc., & Publishers	H	H
International & Foreign Organizations	L	H
Documentary Standards Bodies	L	H
Ref. Data & Mat'ls Organizations	H	H
Instrumentation Industry	H	H
NBS Evaluation Panels	L	M
Other NBS Units	H	H
Nat'l Conf. WTs & Meas/St. etc. OWM's	L	H
Nat'l Conf. of Standards Laboratories	0	0
Stds & Testing Labs & Services	M	H
Governmental Regulatory Agencies	0	0
Other Federal Government Agencies	0	0
State and Local Governmental Agencies	H	H
Trade Associations	H	H
Trade Press	M	0
Private Companies	H	H
Consumer Organizations	L	0
Popular Press	0	0
Other (See Text)	H	H
Staff Wisdom/Previous Studies	H	H

revealed with certain of its vital statistics.

The use of these statistical resources led us immediately to corporate Annual Reports, which are required annually by the SEC, and whose accuracy must be unquestionable. We gathered a number of such reports, and they proved to be one of our most valuable resources of specific, fine-grained information, plus giving projections for the future. We plan to keep a comprehensive and current set of corporate Annual Reports as a ready reference to answer "who needs it", and "what are they doing with it?"

2. Transmission Mechanisms

When the State of California began public hearings on a code for fluid metering of cryogens, it was suggested that the Cryogenics Division of NBS provide "best values" data for inclusion in the California Code. The gases under consideration were limited to oxygen, nitrogen, argon, and hydrogen. At the request of both the Compressed Gas Association and the State of California, we generated skeleton tables, which were published in the California Code. In addition, the Cryogenics Division provided a source document, NBS Technical Note 361 "Saturated Liquid Densities of Oxygen, Nitrogen, Argon, and Parahydrogen" [1]. The latter document was produced specifically to allow traceability of the selected values. It was revised in 1972 to include compressed liquid densities, and again in 1974 in a metric format. These NBS property data are specifically called out in the California Code and accordingly have the same weight of law as the flowmeter calibrations and tolerances themselves.

Other transmission mechanisms include:

- Codes, Standards, and Recommended Practices, such as adopted in Handbook 44;
- Properties Data. NBS property data for several cryogens were adopted in Handbook 44. In addition, there is no doubt that the wide dissemination and knowledge of the NBS cryogenic fluid property work was the original factor leading the regulatory agencies and the CGA to come to NBS in the first place.
- International Conventions. At one time or another, we have cooperated with the International Organization of Legal Metrology (OILM) to facilitate the adoption of international codes; performed type testing of instruments of foreign manufacture as part of the program; and promoted and facilitated visits by many representatives from other nations, including Germany, France, and the United Kingdom.
- Steering Committee. In the case history used for illustration, the Compressed Gas Association formed a steering committee to help provide a degree of quality control to the program, but especially to help substantially by providing guidance and advice at critical stages of planning and implementation of the program. This committee met three to four times a year during the nearly eight-year life of the program. In addition, state weights and measures officials routinely attended these meetings, which provided an invaluable forum for the cooperative solution of vexing problems.

Advertisements and other trade literature were of moderate importance in locating meter manufacturers and documenting accuracy claims. They played no role in validating the results, unless one cares to note any changes in advertising copy that might have occurred after the program.

3. Contact Mechanism

Contact mechanisms may be viewed as the terminals of the transmission mechanics described above, and accordingly will not be re-addressed at any length here. Only a few observations may be in order:

- Conversations - especially face-to-face meetings, such as described under "Steering Committee" above were a prime source of really useful data.
- Forecasting plays a major role. For instance "Normative" forecasting was performed by the ISA Ad Hoc committee mentioned in the study. Goals, needs, and desires were specified, and the Ad Hoc committee then worked backwards to the (then) present to define what capabilities either existed or could be extrapolated to meet the goals. Section 4.5 described the major role forecasting plays in developing the Division's total program of measurement and data services.
- Round-robin intercomparisons are at the heart of transferring the NBS measurement capability to the states, producers, and meter manufacturers. For instance, the State of California has now calibrated no less than 58 out of the 60 meters used there in liquid nitrogen commerce by this means. To further facilitate such intercomparisons, NBS has built and is currently proving a transfer

standard of its own. Similar round-robins have been conducted for years on thermocouple materials. Section 2.4 describes other inter-comparisons accomplished through the use of other reference materials.

Numerous contacts were made within the NBS and described in Section 2.4.1, under NBS Infrastructure.

4. Sources of Information or Validation

Many sources of information were of necessity described in the previous three sections. Accordingly, the purpose of this section will be to summarize the above, and to comment in a general way on the utility of some of the sources.

For this particular study, the Popular Press, Consumer Organization *per se* the Trade Press, Federal Agencies (regulatory and otherwise), the National Conference of Standards Laboratories (NCSL) and academic institutions did not constitute a major resource, although they surely would in other types of studies.

Some groups ranked low as input sources, but were virtually indispensable to validating the results. Such groups include international and foreign organizations and documentary standards bodies (the NCWM provided little input, but was essential to codifying the results); the main contribution of the NBS Evaluation Panel was in providing an overview of the study as a whole and aiding in the technical quality control.

A third group could be ranked as "medium" on the input side, but "high" in terms of validation. For instance, especially in the earlier stages of the physical evaluation of our flow system, round-robins were conducted with industrial testing laboratories. This cooperation not only gave us a head start in our own facility, but also opened the door for eventual international agreement (via the OILM, for instance).

The fourth group ranks "high" on both input and validation, and accordingly was included in the previous sections. For completeness, they may be listed as: professional and technical societies (e.g., Instrument Society of America, Compressed Gas Association); reference data organizations (e.g., the National Conference of Weights and Measures for Handbook 44; and our own Tech. Note No. 361); the instrument industry (via the Instrument Society of America and instrument manufacturers). Other NBS units were invaluable in helping design the experiments (e.g., Applied Math Division), in codifying the results (e.g., Office of Weights and Measures) and in furnishing other essential services (patent advice). The role of state agencies, trade associations (Compressed Gas Association) and private companies (cryogen producers, instrument makers) have already been mentioned. The Annual Reports of these private companies have proven to be gold mines of documented needs and opportunities.

Finally, we come to "staff wisdom". This study of the National Measurement System is based on 20 years of work by literally hundreds of men and women in the Cryogenics Division of NBS. This resource, especially in terms of accumulated experience, would be impossible to duplicate elsewhere. Accordingly, "staff wisdom" was of inestimable value throughout the study.

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15. SUPPLEMENTARY NOTES

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

The Cryogenics Division of NBS has evolved as the nation's central laboratory for cryogenics, much as NBS itself has evolved as the nation's central laboratory with both broad and specific responsibilities. Cryogenic measurement and data outputs provide the common foundation for all the institutions and agencies throughout the nation employing cryogenics to solve their problems.

This Study of the National Measurement System showed that the Cryogenics Division of NBS provides almost every category of measurement and data service that NBS itself provides: not just an instrumentation system (including, for example, pressure, temperature, density, liquid level, flow rate, etc.), but also properties of fluids (both thermodynamic and transport properties); properties of solids (thermal, mechanical and electrical); an interface with the users through systems integration and advisory and consulting services; and a dissemination network through the Cryogenic Data Center.

This study documents the impact, status and trends of the cryogenic measurement system and specifically illustrates these characteristics wherever possible with a specific case study, a recently completed measurements and data program for the flowmetering of liquid nitrogen.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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