NBSIR 75-930

The National Measurement System for Fluid Flow

William C. Haight, Coordinator
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Institute for Basic Standards

Final

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S. DEPARTMENT OF COMMERCE
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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*
Edward O. Vetter, *Under Secretary*
Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

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THE NATIONAL MEASUREMENT SYSTEM FOR FLUID FLOW

William C. Haight, Coordinator
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December 1975

EXECUTIVE SUMMARY

Fluid flow is a diverse field concerned with the motion of a wide variety of fluids encountered both in daily life and in scientific applications. It encompasses movement of weather systems by atmospheric winds, travel and dispersion of air pollutants, flow around aircraft and spacecraft bodies, oil and gas pipeline flow, irrigation and waste water flow, and many others. The types of fluid motions encountered in descriptions of these phenomena include closed-conduit, open channel, supersonic, subsonic, steady, unsteady, laminar, and turbulent flow. Measurements of the properties of these flows are instrumental in the functioning of the nation's industries and the advancement of scientific technology, and impact the lives of every consumer.

This report presents the concept of the National Measurement System for Fluid Flow as it exists today and the activities and mechanisms it employs to generate and implement measurement data. The system structure is presented, and data and information gathered on the interrelationships between the identifiable parts are reported. To further the study, more than 200 contacts were made with trade associations, government agencies, private companies and universities.

The basic structural element of this measurement system is the combination of the fundamental units of mass, length, and time to describe fluid response to external forces. Such responses are generally velocity (m/s), mass flow rate (kg/s), or volume flow rate (m^3/s), but can include specialized quantities like Mach number and frequency of flow fluctuations. Also affecting this response are the inherent fluid properties, such as viscosity, density, thermal and electrical conductivity, and bulk modulus of elasticity.

Documentary standards for fluid flow measurement represent international, national, and commercial viewpoints, and are used voluntarily by all parties. International organizations such as ISO and IEC are active in fluid flow preparing measurement standards, meter performance standards, and recommended practices for making measurements and analyzing errors. Nationally, ANSI, ASTM, ASME, API, and AGA prepare standards for flow measurements commonly encountered in their application areas.

Measurements are made with a variety of tools, some of which have been in use for a great many years, and others which are innovatively new. These instruments operate on a variety of principles including differential pressure, force, convective cooling, sound transmission, electromagnetic effects, vortex shedding, and more recently light scattering. In particular, vane and cup anemometers, water current meters, and orifice flowmeters are among the most commonly used meters in meteorology, stream flow measurements, and pipeline flow measurements, respectively. A rapidly growing area of new instrumentation includes sonic anemometers, laser velocimeters, and electromagnetic meters, the latter being used in conducting fluids such as liquid metals, wastewater and water under certain conditions.

Current capabilities, facilities and ranges of services of numerous calibration and standards laboratories engaged in gas and liquid flow measurement are identified. These include:

(1) Air flow
- 80,000 scfm, 2,800 psig at the Colorado Engineering Experiment Station
- 3,000 scfm, 125 psig at NBS
- 2 to 150 mph at NBS

(2) Water flow
- 40,000 gpm, 21 psig at Alden Research Laboratory
- 10,000 gpm, 75 psig at NBS

(3) Liquid hydrocarbon flow
- 10,000 gpm, 40 psig at Brooks Instrument Division
- 2,000 gpm, 50 psig at NBS

Additionally, over 60 flow meter manufacturers have been identified that have submitted instruments for calibration at NBS over the last seven years.

The study indicates a trend of U.S. domestic business in which total sales dollars have increased for fluid flow measurement equipment from \$67.2 million to \$123.8 million in the period 1963 to 1973. The

annual volume continues to grow with mounting demands for accuracy and sophistication of equipment. In testimony before the Congress, the manufacturers of scientific instruments testified that about 25% of the annual value of flow meters and instrumentation sold by the industry is sold abroad. They believe that these export sales exceed imports by more than four to one, and they are the leverage for export sales of instrumentation and control systems valued at twice to three times the flow measurement products.

State-of-the-art changes and technological advancements in fluid flow include both improvements in traditional instrument designs and numerous new designs that are finding increased application. Inflated fluid resource values and increased operating costs in fluid transportation are forcing a general rise in the cost to flow a unit of fluid. Consequently, greater investments are being made in increased measurement reliability and accuracy and in the managing and controlling of fluid flow. Primary metering devices are becoming increasingly sophisticated. In general, the applications which impose the most urgent requirements on flow measurements are those which stem from the imposition of new Federal regulations in fields that include environmental air and water quality control, coal mine health and safety, occupational safety and health, and clean room and work station requirements. Implementation of these regulations will increase the requirements for consistent and reliable measurements of many flow quantities that cannot be measured adequately today.

Specific fluid flow measurement needs are identified that include: providing new flow standards, preparing and disseminating recommended practices, and evaluating and developing instrumentation for the measurement of low velocities and unsteady speeds of air; establishing a rational basis for demonstrating consistent flow measurements among laboratories, developing new instrumentation and standards for fluid metering, and reestablishing the validity of discharge coefficients for orifice meters; providing new flow standards, preparing recommended practices for in-place applications, and evaluating and developing instrumentation for the measurement of velocities and flow rates of supply water and waste water. A general trend has been discerned underlying these needs in which opportunities to implement measurement assurance and the transfer-of-measurement capability are becoming increasingly important.

NBS functions as an integral element of the fluid flow measurement system, conducting fluid mechanics research and development, contributing to flow standards, and generating engineering data on a variety of flows. Calibrations are offered for instruments to measure velocity and mass flow rate in air, water, and liquid hydrocarbons. NBS services impact government agencies concerned with health, safety, power, fuel resources, water resources, weather monitoring, pollution control, and military and space programs as well as major segments of private industry such as the oil and gas industry, power utilities, heating and ventilating, and transportation. These user classes share a common concern for adequacy, accuracy and reliability of the various aspects of flow measurements.

Fluid flow measurement technology today represents a constantly changing field, thus supplying the impetus for a number of improvements within the National Fluid Flow Measurement System. In particular, a need for a national fluid flow reference system was emphasized at the 1974 NBS Flow Measurement Conference. This need is underscored by discrepancies in flow calibration results, duplication of measurement efforts, the lack of a technical "third party" to arbitrate discrepancies in measurement, and the lack of facility certification.

New measurement capability is also needed in both the very small and very large rates of flow. For example, the automotive industry is targeting for fuel flow calibrations at approximately .08 g/s with ±0.2% accuracy. Also, very low velocity measurements are required in air and water flows in order to meet regulatory requirements being established for health, safety, and environmental quality. The nuclear power industry requires measurement of cooling water flows on the order of 60,000 to 120,000 L/s depending on plant power output. Such plants also must be capable of measuring 150 °C condensate flows of 1200 L/s with accuracies of 0.1%. Additionally, limited natural resources and increased competition for fresh water between power generation utilities, industrial users, and agricultural water suppliers requires improved accuracies of field measurements.

To meet these needs, the NBS fluid flow program includes extension of measurement capability with emphasis on flow ranges encountered in new regulatory acts, error analysis in field measurements, meter performance evaluation for improved accuracies, and maintenance of contact with users through conferences and correspondence.

1. INTRODUCTION

Fluids are required by every living thing for existence. They include the liquids we drink; the oil and gas we heat our homes with; the gasoline for our cars; water in rivers, lakes, and oceans; the air we breathe; even the blood in our veins. Water covers approximately three-fourths of the earth's surface; the atmosphere covers our entire planet to a depth of several hundred miles, 99% of which is confined to within 20 miles of the earth's surface; and the sun and stars are composed largely of gases. It is readily apparent that the quantities we call fluids constitute a major part of the known universe.

The motion of these fluids is equally all-encompassing. Movement of weather systems depend on atmospheric wind patterns, as does travel and dispersion of air pollutants. Electricity can be generated by the motion of falling water and by the impact of high-pressure steam on a turbine. Aircraft flight is dependent on lift generated by airflow around the wings. Even human life depends on adequate flow of blood to all areas of the body.

Fluid flow measurements affect our lives in many diverse ways. Each time a water faucet is opened in the home, the total flow of supply water and sewage effluent is affected, requiring accurate metering at water reservoirs and sewage treatment plants. Similarly, natural gas used for home heating and cooking requires accurate metering at the source for distribution. Interstate oil and gas transmissions rely on flow meters for assessment of pipeline fees to customers. Wind speed measurements are fundamental for weather prediction, and industrial ventilation, and are necessary for monitoring aircraft flight. One could continue with many more examples, but it suffices to say that fluid flow measurements are instrumental in our daily lives and in the functioning of the nation's industries.

This study defines the system used to measure fluid flows, and shows the interrelationships that exist within and between the identifiable parts of this system. In particular, the role of NBS in the overall measurement scheme will be presented, as well as the interaction of the fluid flow measurement system with other social systems.

The data gathered is helpful in recognizing major trends of future applications of fluid flow measuring devices. This data is also useful in identifying and understanding major problems of measurement and in developing recommendations of actions to be taken for improving the national fluid flow measurement system.

2. STRUCTURE OF THE MEASUREMENT SYSTEM

2.1 Conceptual System

2.1.1 Definition of Fluid Flow

A *fluid* is defined by Webster to be "a substance that alters its shape in response to any force however small, that tends to flow or conform to the outline of its container, ..." and *flow* is "to move with a continual change of place among the constituent particles or parts." The concept of a fluid is illustrated by the commonly observed phenomena of water in an open container taking on the shape of that container, no matter how irregular it may be; and by a solid object being moved through water at will provided sufficient force is applied.

More precisely, a fluid does not have a preferred shape, and can change shape without a change in volume. Unlike a solid, which under shear forces can undergo a finite deformation, a fluid deforms continuously. Deformation here is used to mean changes in shape and orientation as a function of time. Fluid flow is concerned with the motion of liquids and gases, and the deformation they undergo under the action of forces. In the context of this study, the phenomena are considered to be macroscopic, and the fluid is regarded as continuous medium, i.e., any elemental volume of fluid is always considered to be sufficiently large that it contains a great number of molecules.

Even more precise mathematical definitions of fluids and flow exist, in terms of material symmetries and deformation functions, but those presented here suffice to define the class of phenomena covered by this study.

2.1.2 The Science of Fluid Mechanics

Fluid mechanics is the science dealing with the static and dynamic behavior of fluids, including liquids and gases. Its principles are generally applied in efforts to understand, measure, and control liquids and gases encountered in nature and industry. The broad scope of fluid mechanics encompasses the fields of meteorology, hydrology, oceanography, aeronautics, astronautics, fluidics, bio-fluid dynamics, and many more.

Historically, fluid mechanics is rooted in early developments of hydrostatics, hydraulics, and hydrodynamics. Hydrostatics, dealing mainly with water at rest, was the first of these fields to be developed. Archimedes, the Greek mathematician born about 287 B.C., discovered the first known principles of hydrostatics when asked to verify that his king's crown-maker had used pure gold for a new crown. This had to be done, of course, without destroying the crown. Archemides suspended the crown in water and measured the subsequent displacement of water. The weight of the crown divided by the volume of water displaced yielded the density of the crown, which could be compared to the density of pure gold. The ratio of the density of the crown to the density of water gave the world the concept of specific gravity.

The science of moving fluids, due to the complexity of such fluid properties as viscosity, was slower to develop. Two basic approaches evolved. One approach, called empirical hydraulics, was based on practical experience in designing structures to control and use flowing water. The other approach was a theoretical one in which an attempt was made to mathematically formulate essential fluid behavior. This had its beginning in the 18th and 19th centuries with efforts to describe the behavior of "ideal" fluids in which viscous, elastic, and surface tension effects of real fluids were ignored. Subsequent theories have attempted to include the case of real fluids. These two approaches to fluid mechanics were synthesized in the 19th and 20th centuries, and developments have continued to the present time. At present, aerodynamic, hydraulic, and fluids laboratories of universities, government agencies, and private research organizations are active in the study and further development of the science of fluid mechanics.

2.1.3 Classification of Fluid Flows

Many types of flows are encompassed by the fluid flow measurement system. The more common types of geometrical configurations are closed conduit flows, open-channel flows with a free surface, wakes, jets, and flows around bodies. Flows are also classified as to whether they are laminar or turbulent. Laminar flow, usually observed at low velocities or with fluids of high viscosity, is flow in layers moving smoothly relative to one another. Turbulent flow, on the other hand, is an irregular flow with random, diffusive, and dispersive motions. Further classifications of fluid flows include whether their velocity is less than, equal to, or greater than the speed of sound, and whether they are steady or unsteady. The velocity relative to the speed of sound is generally characterized by the Mach number, which is a measure of the importance of compressibility effects in the fluid. A Mach number of 1 characterizes a flow with a speed equal to the speed of sound. Incompressible flows, i.e., low Mach number, in which the fluid density is considered constant in time, cover most liquid and some gas flows. Compressible flows, where fluid density varies significantly with time, occur in many applications including high-speed aircraft and spacecraft flight. Steady flow is a flow pattern that does not vary in time, while unsteady flows consist of time-dependent fluid motions, such as a pulsating flow in an automobile exhaust pipe.

2.1.4 Measurement of Fluid Flows

The measurement of fluid flows requires a knowledge of the fluid's physical properties. those most commonly used in flow measurement are (1) viscosity, the property of a fluid by virtue of which it offers resistance to shear stress; (2) density, the fluid mass per unit volume; (3) thermal conductivity, the measure of a material's ability to transfer heat; (4) electrical conductivity, the measure of a material's ability to transfer electrical charge, and (5) bulk modulus of elasticity, the measure of a material's compressibility. In place of viscosity, the kinematic viscosity is sometimes used. This is defined to be viscosity divided by density. In place of density, specific gravity may be used. This is the density of the fluid divided by the density of water. Other quantities affecting flow measurement are (6) pressure, the force per unit area applied normal to the fluid surface; and (7) temperature. The units used to characterize these quantities are shown in table 1.

The measurement of these fluid properties is covered under separate studies of the National Measurement System. The purpose of this study is to discuss measurement of the quantities describing the flow of fluids, given that the fluids themselves can be adequately characterized in terms of their fundamental properties.

Recalling the definition of fluid flow, it is seen that two things are involved. First, fluids must be subjected to certain forces or stimuli, and then their flow in response to these forces must be characterized. Types of stimuli include pressure, shear stress, and temperature; and responses are most fundamentally velocity and flow rate. Note that

Table 1. Definition of fluid properties

QUANTITIES DEFINING A FLUID	SI UNITS	CUSTOMARY UNITS
Viscosity	Pa·s=kg/m·s	poise $lb_f \cdot s/ft^2$
Denisty	kg/m^3	lb_m/ft^3 lb_m/gal
Thermal conductivity	W/(m·K)	cal/cm·s·°C
Electrical conductivity	$(\Omega \cdot m)^{-1}$	$(\Omega \cdot cm)^{-1}$
Bulk modulus of elasticity	$Pa=N/m^2$	lb_f/in^2 or psi
Pressure	$Pa=N/m^2$	lb_f/in^2 or psi
Temperature	K	°F and °C

throughout this report, the term "velocity" is used to mean either speed or velocity. Although this is not technically correct, it conforms to accepted terminology. For certain fluids, other responses may be of interest. For example, flows of compressible fluids are best described in terms of Mach number instead of velocity. For unsteady flows, the frequency and amplitude of the flow fluctuations are generally of interest. The characterization of these measurements is shown in table 2. Additionally, the relationship of flow measurements to basic quantities of mass, length, and time is shown in figure 1 for the case of anemometer calibrations.

Table 2. Characterization of fluid flow measurement

QUANTITY MEASURED	DIMENSIONS	SI UNITS	CUSTOMARY UNITS
Velocity (speed)	L/t	m/s	ft/s or fps
Flow Rates	M/t	kg/s	lb_m/s lb_m/h or pph
	L^3/t	m^3/s	ft^3/min or cfm and scfm ft^3/sec or cfs gal/min or gpm mgd or million gal/day

2.1.5 Structure of the Fluid Flow Measurement System

The National Fluid Flow Measurement System encompasses the characterization of fluid flows; the acquisition and standardization of flow measurements; the outputs, uses, and users of such measurements; and the benefits of fluid flow measurements. Its structure is viewed for the purposes of this report as consisting of a basic system with distinct subsystems for gas and liquid flow. This covers phenomena associated with air, other gases, water, and liquid hydrocarbon flows.

The structure presented here also encompasses other significant fluid flows, not covered in detail in this report. These include multi-phase or multi-component flows, for example, liquid-gas or solid-liquid mixtures. Such flows are often of great industrial and environmental importance, such as in the pulp and paper industry or in dredging of waterways. In some cases, the solid component of a solid-liquid mixture is so small that its main effect on flow measurement is to make the use of certain intrusive devices more difficult, while in other cases slurries are so dense that the very nature of the flow itself is affected. Another type of flow being encountered with increasing frequency is that in which minute amounts of long-chain polymers are added as a drag reducing agent. It has been found that these polymers severely affect the performance of many of the traditional measuring instruments, such as Pitot tubes and orifice meters.

Flow of cryogenic fluids is covered in a separate National Measurement System study report and is therefore explicitly excluded from this document.

Figures 2, 3, and 4 depict the basic system structure and the gas and liquid flow subsystems, respectively. The interconnections and interactions occur in various ways - sometimes strongly and sometimes weakly. Correspondingly, the involvement of NBS within the system varies widely. These figures comprise one representation of the infrastructure within which actions and activities of measurement take place. Reading from top to bottom of each figure, the system and subsystems are shown in terms of seven major interconnected branches of fluid flow measurement:

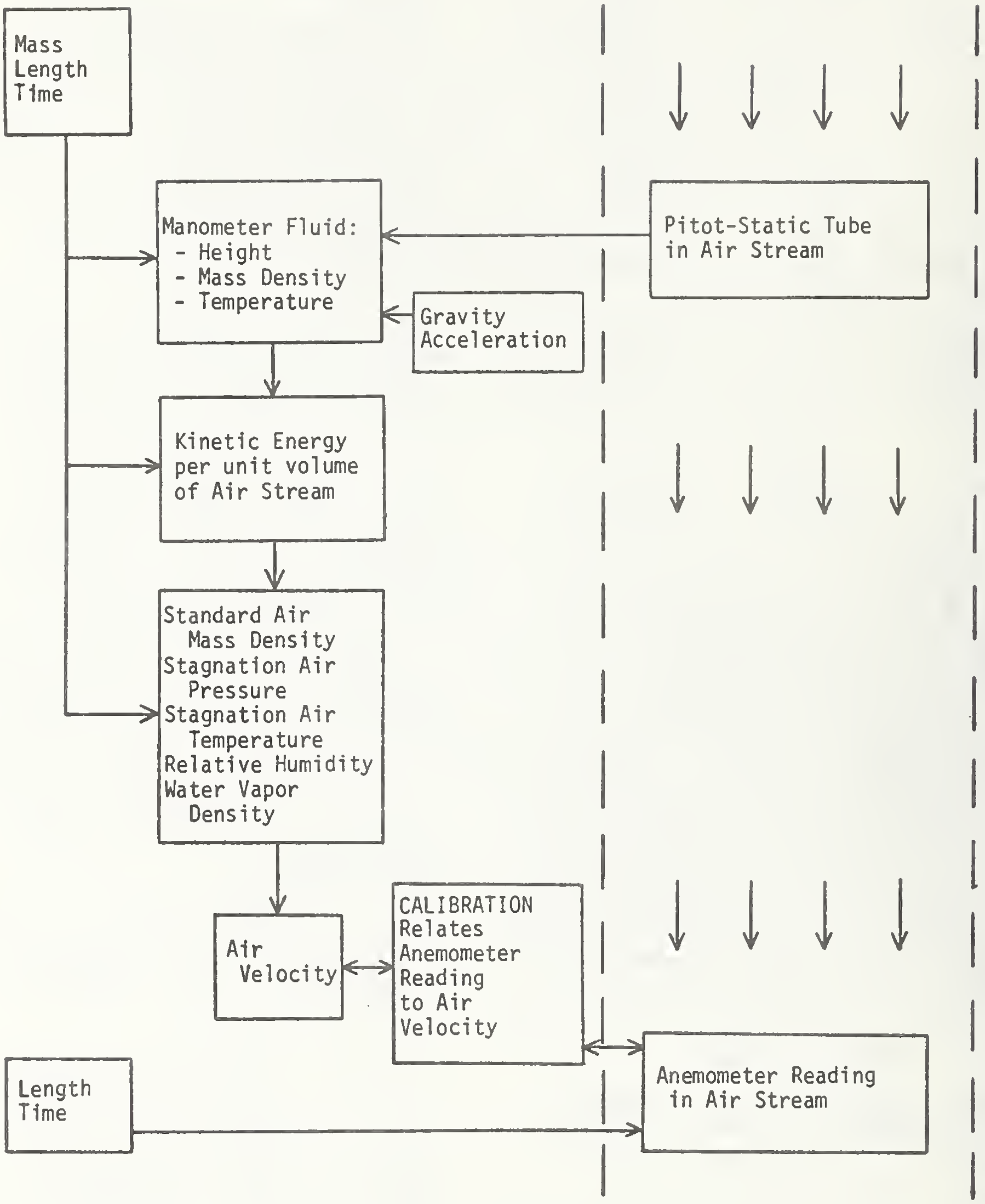


Figure 1. Relationship of anemometer calibrations to basic quantities

(1) Fundamental units, types of fluids and dimensions of measurement.
(2) Reference measurements.
(3) Transfer of measurement capability.
(4) Measurement outputs.
(5) Measurement uses.
(6) Measurement users.
(7) National concerns influencing and benefiting from measurement.

2.2 Basic Technical Infrastructure

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

Documentary standards are written specifications or agreements reached among the interacting elements of a given social system. In fluid flow measurement, most of these standards are the consensus of international, national, and commercial viewpoints, and are used voluntarily. Recently, mandatory standards have also entered the picture.

Internationally, the International Organization for Standardization, ISO, develops world-wide standards for use by member countries in world trade. ISO Technical Committee 30 (TC30) on Measurement of Fluid Flow in Closed Conduits, is concerned with standardization of rules and methods for closed-conduit flow measurement. Specific activity areas of TC30 include:

- Terminology and definitions;
- Rules for inspection, installation and operation;
- Construction of instrumentation and equipment required;
- Flow meter performance;
- Conditions under which measurements are to be made;
- Rules for collection, evaluation and interpretation of measurement data, including errors.

ISO Technical Committee 113 (TC113) also issues standards on flow measurement techniques and flow meter performance; for example, on the performance and use of propeller-type water current meters in connection with velocity-area traverses to determine flowrate, on venturi tubes, and on dilution methods of flowrate determination.

The International Electrotechnical Commission (IEC) is also active in fluid flow. IEC codes include procedures for field acceptance tests of turbines and recommendations for flowrate measurement with emphasis on the salt-velocity method, a tracer technique utilizing salt injections into water flows and measurement of subsequent travel time of the saline slug over fixed distances.

In a number of foreign countries, standards are published by national standards organizations. For example, the British Standards Institution has issued standards similar to those of ISO for venturi, orifice, and nozzle meters; for open-channel flow measuring devices, such as thin-plate weirs, broad crested weirs, and triangular weirs; for dilution methods; for velocity-area traversing; and for other techniques.

In the U.S., the American Society for Testing and Materials (ASTM) publishes specifications and test methods for materials, and undertakes research necessary to formulate these procedures. In fluid flow, ASTM is currently studying the relationship between the measurement and effective control of air pollution through a program aimed at validating methods for measuring contaminants in the atmosphere and in source emissions. This program applies an interlaboratory "round-robin" technique to bring together groups of competent laboratories for concurrent performance of tests under actual field conditions. As results are gathered, statistically analyzed, and evaluated, reports and specifications are prepared for general use by the fluid flow community. Additionally, ASTM currently has published standards for flowrate measurements with venturi meters, weirs and Parshall flumes, and has task groups working on improved standards in some of these areas.

The American Society of Mechanical Engineers (ASME) has a Committee on Measurement of Fluid Flow in Closed Conduits charged with standardization of rules and methods for measuring this class of flows. The committee's activity scope includes the following topics:

- Terminology and definitions;
- Rules for construction, installation and operation;
- Conditions under which measurements are to be made;
- Rules for collection, evaluation and interpretation of measurement data, including errors.

The standards developed under these procedures are intended to be submitted to the American National Standards Institute (ANSI) for approval as American National Standards.

The American Petroleum Institute (API) is the oil industry's major trade association

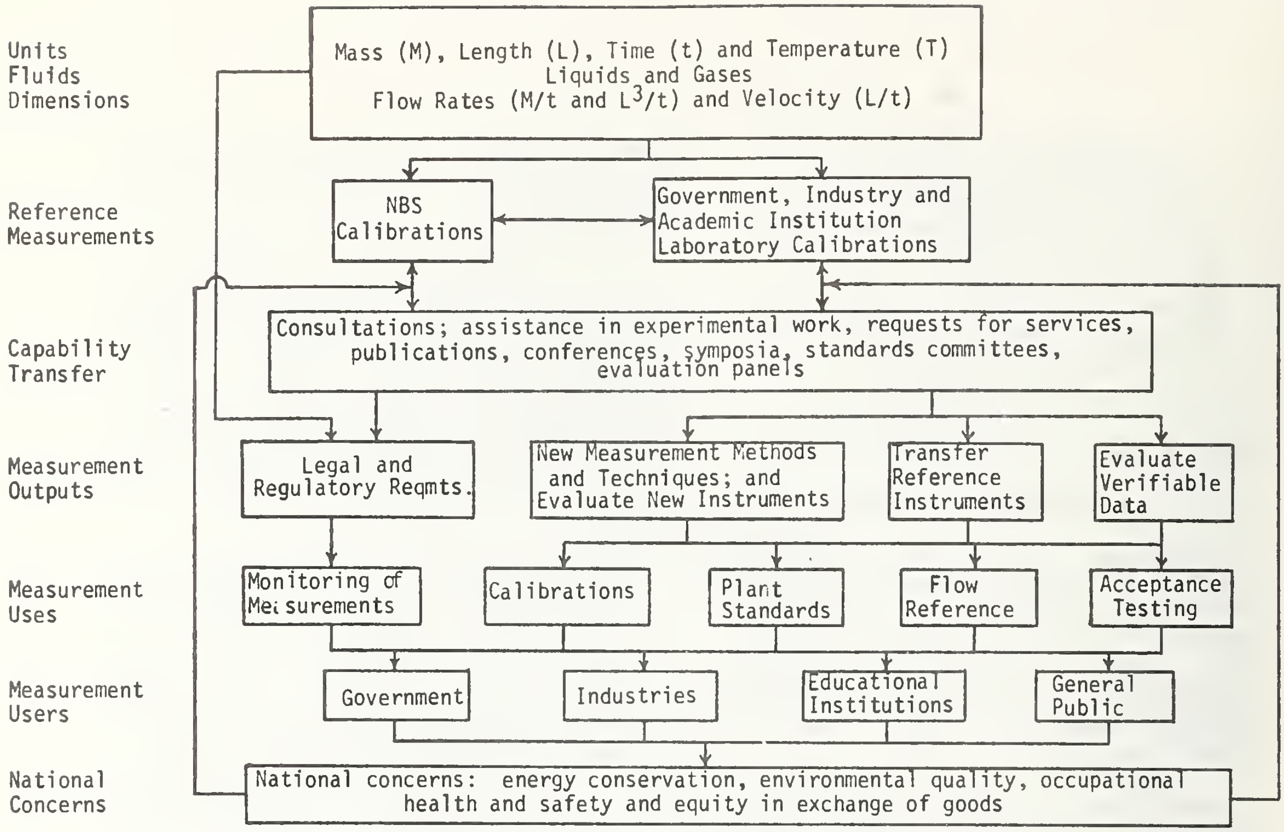
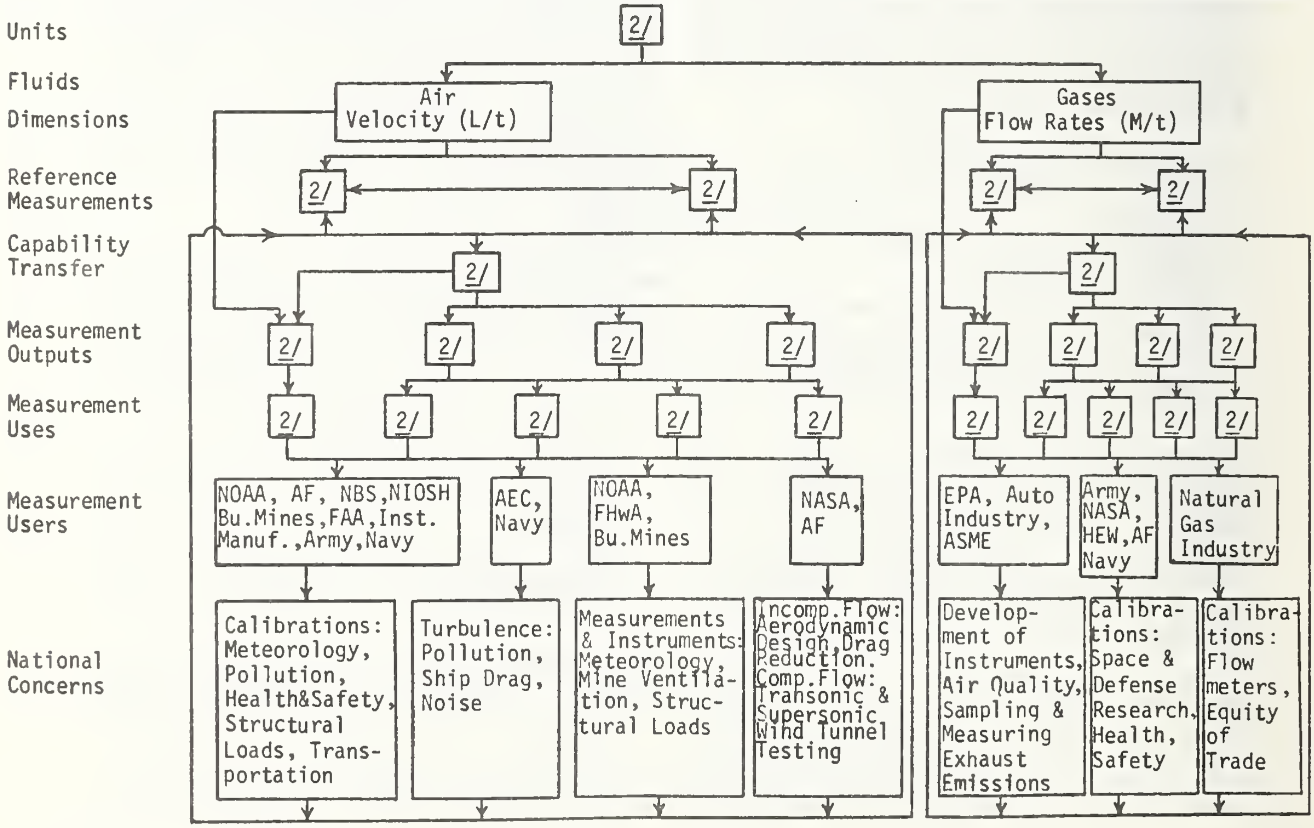
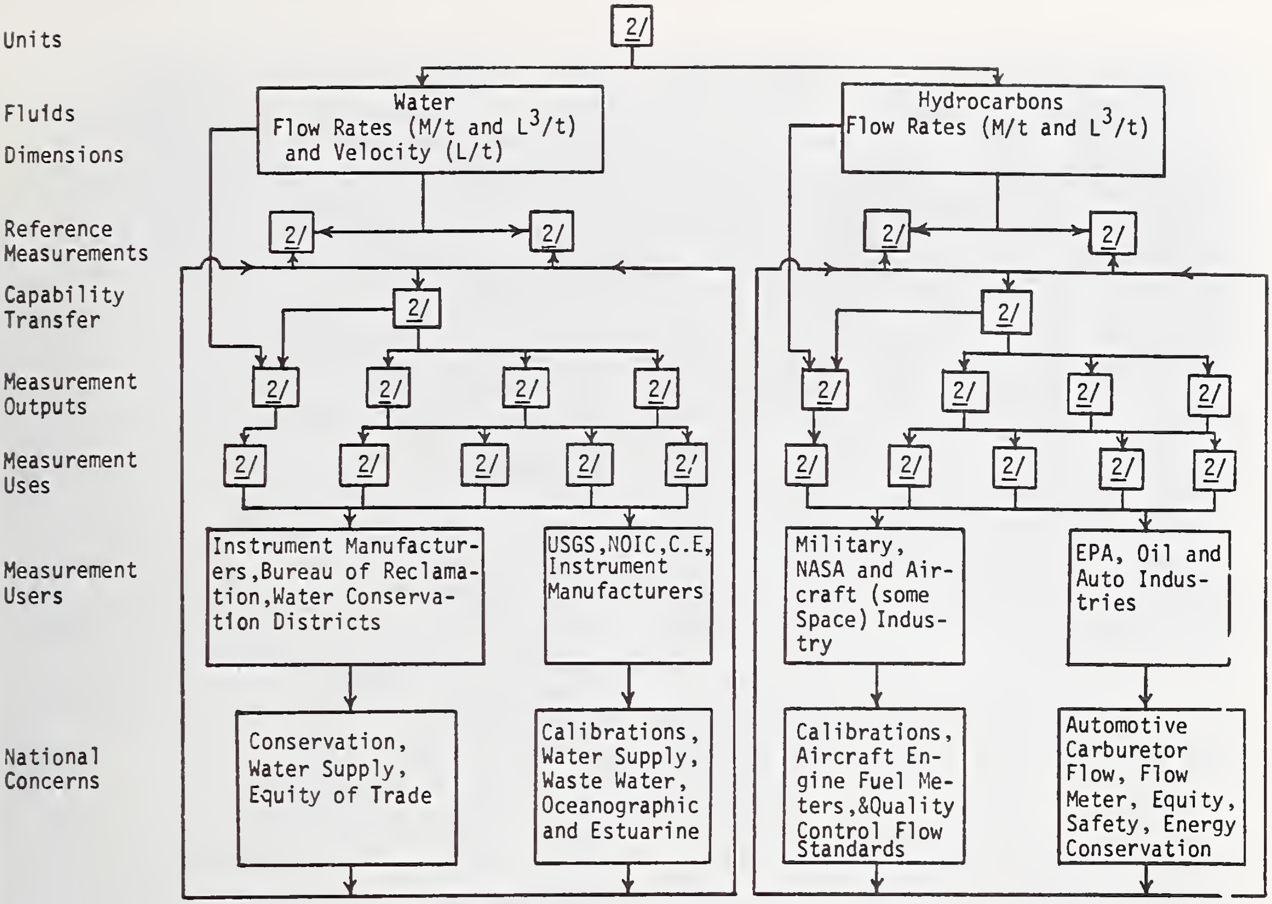


Figure 2. Structure of the national fluid flow measurement system



2/ Same as for figure 2

Figure 3. Structure of the national gas flow measurement subsystem



2/ Same as for figure 2

Figure 4. Structure of the national liquid flow measurement subsystem

Key to abbreviations used in figures 3 and 4:

Symbol	Name
AEC(ERDA)	Atomic Energy Commission (Energy Research & Development Admin.)
AF	Air Force
ASME	American Society of Mechanical Engineers
Bu.Mines	Bureau of Mines
C.E.	Army Corps of Engineers
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHwA	Federal Highway Administration
HEW	Department of Health, Education, & Welfare
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NIOSH	National Institute of Occupational Safety and Health
NOAA	National Oceanic and Atmospheric Administration
NOIC	National Oceanographic Instrumentation Center
USGS	U.S. Geological Survey

whose activities reach far and wide into three major areas: industry affairs, public affairs, and environmental affairs. In the first area, a Committee on Petroleum Measurement formulates standards on procedures and equipment for the measurement of petroleum and natural gas products. This work is carried out through voluntary committee and working group participation, primarily industrial with some government participation. It covers such areas as positive displacement metering and turbine metering, automated measurement methods, cryogenic fluid handling, and tank calibration and gaging. API standards are aimed at promoting increased accuracy in petroleum fluid measurement, and may be used by anyone. Their use as statutory requirements for trade purposes is left to the various users. There are close ties between NBS and this API committee, ranging from committee work to research project participation. The Committee on Petroleum Measurement also represents the API in international measurement standardization projects.

The American Gas Association (AGA) is the gas industry's major trade association in the U.S. Their Transmission Measurement Committee is a standing committee in the Transmission Systems Division of the Operating Section of AGA whose purpose is to provide the industry with all necessary technical guidance for commercial quantity measurements, pressure and volume regulation, and quality measurements of fuel gas in connection with gas production, storage, and transmission. This information is based on research, and the resulting fundamentals and recommended practices are published for general information in AGA Transmission Measurement Committee Reports.

Other flow measurement standardization organizations in fluid flow include the Society for Automotive Engineers, the Instrument Society of America, and several governmental bodies. The most important of the latter is the U.S. Geological Survey which operates the Federal Interagency Work Group on Designation of Standards for Water Data Acquisition under the auspices of the Office of Water Data Coordination. This group is currently developing recommended methods for acquisition of water data, and NBS is represented on some of its committees. Also, the Government-Industry Data Exchange Program, GIDEP, has collected 17,000 calibration procedures and 35,000 engineering test reports in a variety of measurement fields including fluid flow.

2.2.1.2 Survey of Documentary Standards

Universally used standards for fluid flow measurement that would constitute a national reference system do not exist. Such a reference system should include a system of laboratories using acceptable procedures with measurement accuracy verified by intercomparisons among the members, including NBS, and should form the basis for reliable field measurements. The need for this system in fluid metering was emphasized at the 1974 NBS Conference on Flow Measurements as Related to National Needs being actively promoted by the Process Measurement and Control Section's Fluid Meters Standards Committee of the Scientific Apparatus Makers Association (SAMA). SAMA points out that the need for a reference system of this type is underscored by (a) discrepancies in flow calibration results, (b) the loss of U.S. technical stature in not having an agency comparable to existing flow measurement centers abroad, such as NEL in England and PTB in Germany, (c) duplication of measurement efforts, (d) the lack of a technical "third-party" to arbitrate discrepancies in measurement, and (e) the lack of facility certification.

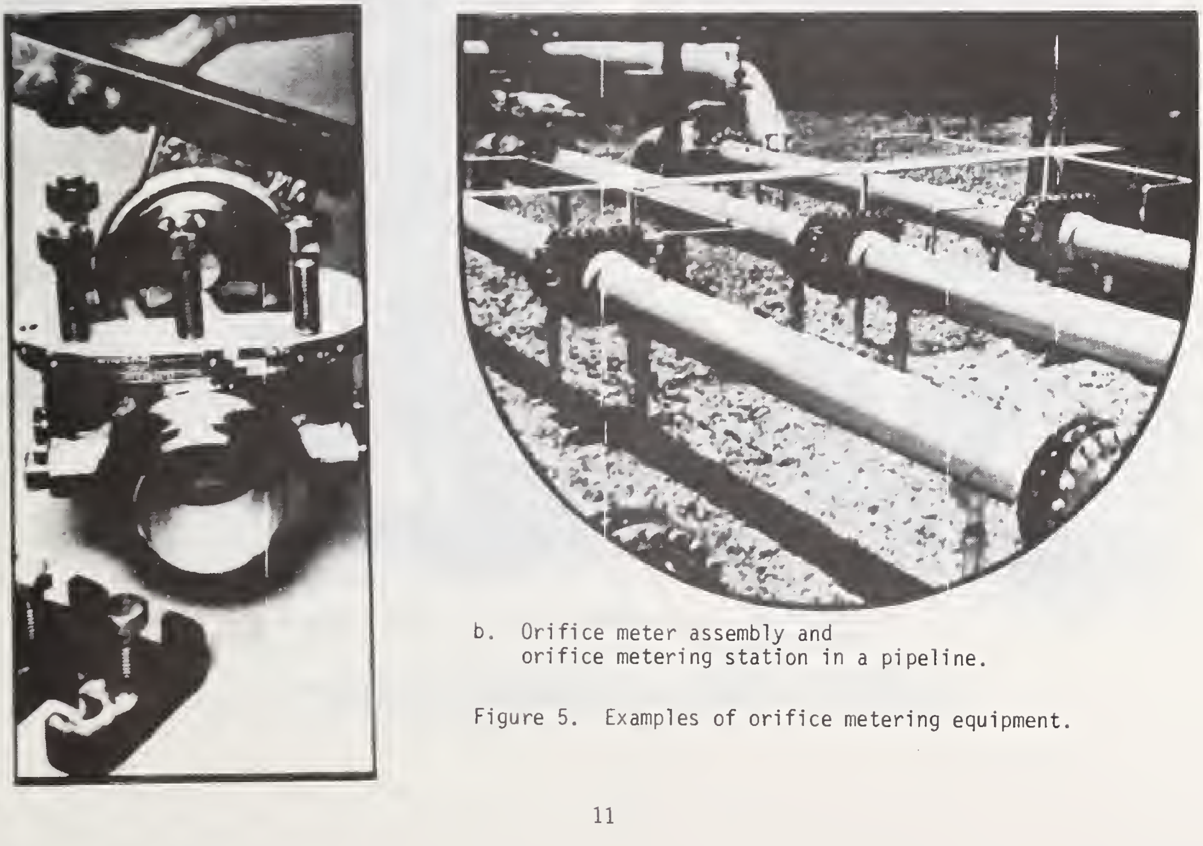
In lieu of a coordinated standards approach to flow measurement supported by the force of law, the U.S. fluid flow measurement industry has developed its own standards. In aeronautics, the FAA uses a number of SAE standards and specifications to regulate airspeed indicators in use on aircraft. In fluid metering, a number of coefficient tables for meter classes have come to be used as "standards," such as the American Gas Association (AGA) Gas Measurement Committee Report #3, the AGA-ASME Orifice Coefficient Committee report of 1935, the 6th edition of *Fluid Meters*, published by ASME in 1971, and the American Petroleum Institute (API) type standards. In open-channel flow metering of irrigation water and wastewater, certain published values of discharge data for measuring flumes and weirs have become widely accepted. These "standards" represent knowledge available from industry, manufacturers, and government. Similarly, the International Standards Organization (ISO), a nongovernmental organization, prepares voluntary standards for use by the flow metering community in many application areas.

2.2.2 Instrumentation System

2.2.2.1 Measurement Tools and Techniques

Instruments used for velocity, volume, and mass flow measurements in either gases or liquids use some definite and reproducible

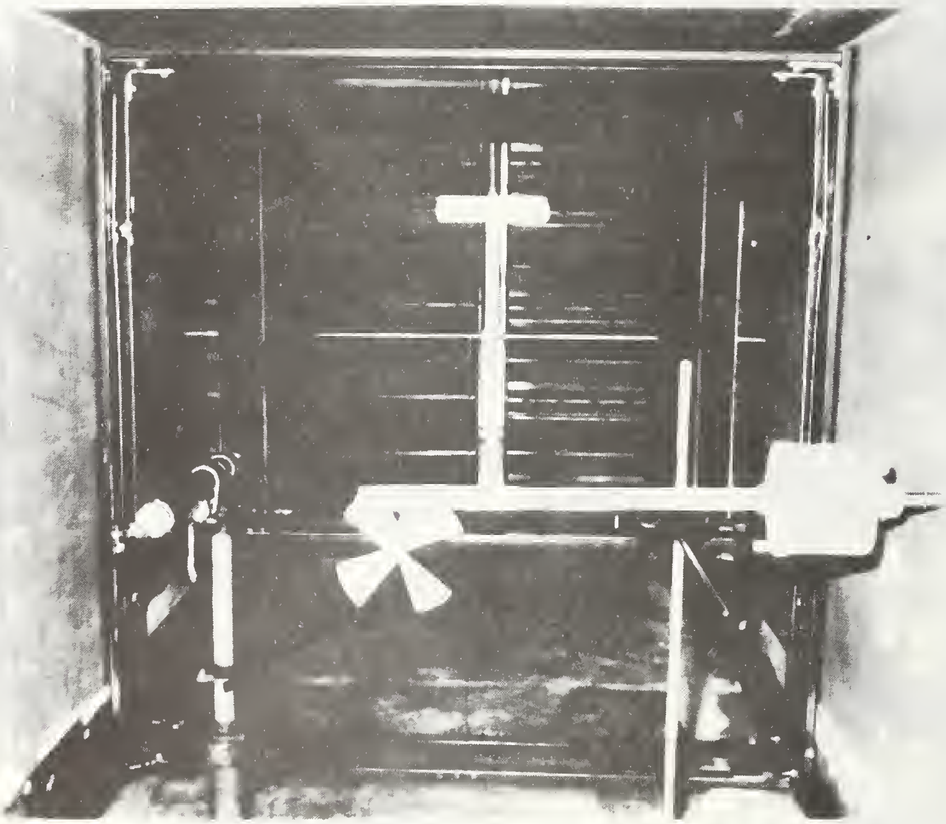
a. Orifice meter run and orifice plates



b. Orifice meter assembly and orifice metering station in a pipeline.

Figure 5. Examples of orifice metering equipment.

a. Examples of vane anemometers



b. Meteorological anemometer under dynamic response test in NBS unsteady flow facility

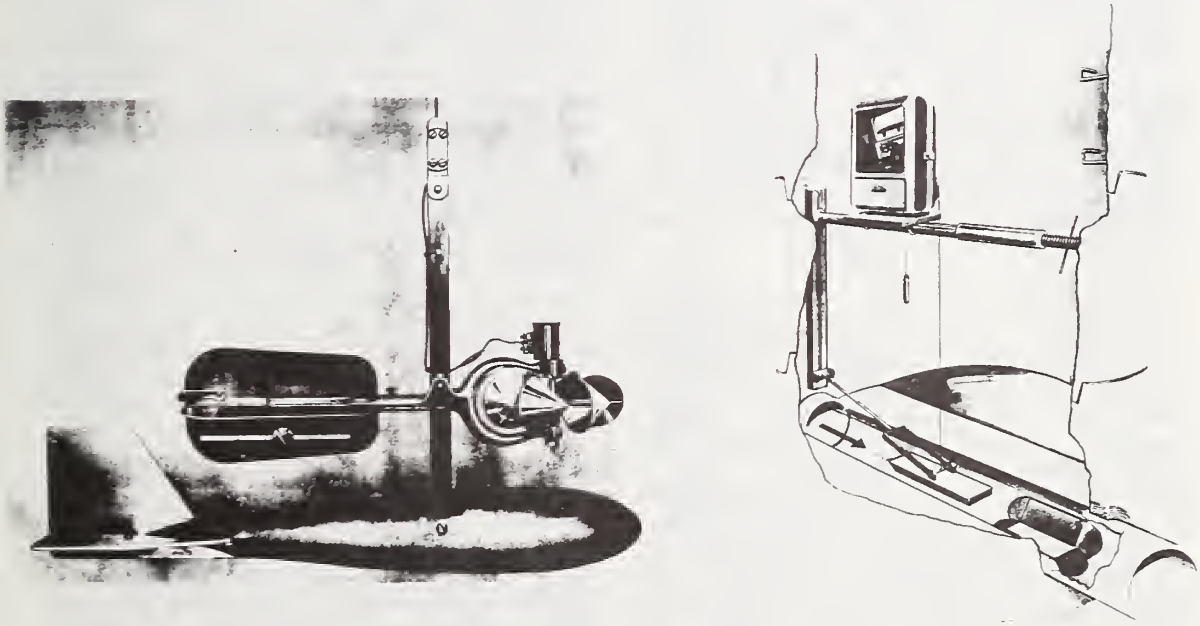
Figure 6. Examples of windspeed measuring equipment

effect related to the motion of the fluid such as differential pressure, force, convective cooling, sound transmission, electromagnetic behavior, vortex shedding, and more recently light scattering. A large number of instruments utilizing one or the other of the foregoing approaches are available for the measurement of steady and unsteady flows. The particular approach used depends for the most part on the accuracy required, the nature of the fluid, whether it is a local velocity measured at a point in the fluid, or a velocity averaged over an area characterizing the volume flow, and whether the flow is steady or unsteady.

The most widely used instruments make use of the differential pressure and force principles. Examples of the differential pressure type are the Pitot-static tube, laminar flowmeter, orifice meter, venturi meter, critical flow nozzle, and the variable-area free-float meter. Examples of orifice metering equipment are shown in figure 5.

Mechanical instruments, for example, vane, cup, and swinging-plate anemometers, positive displacement meters, water current meters, and turbine flowmeters utilize the force exerted by the fluid to produce a rotation or deflection of a moving member which is connected to an appropriate output device. For example, in a turbine meter, a passing fluid turns a rotating element at a speed proportional to the velocity of flow and each rotation of the element in a known cross-section represents a known volume passing through that section. Examples of anemometers are shown in figure 6, and an example of a water current meter is shown in figure 7a.

An additional distinction can be made for volume flows of liquids with a free-surface, in which velocity-area methods and critical depth devices are employed. In a critical depth meter, the flow rate is related to the height of the free stream surface upstream from a dam-like structure. The Palmer-Bowlus flume is an example of such a device, and is shown in figure 7b. Thermal anemometers, of which the hot-wire and hot-film anemometers are perhaps the most prominent examples, utilize convective cooling, i.e., the cooling of a heated body by the flowing medium.



a. A Price current meter with cable and weight suspension

b. A Palmer-Bowlus flume with scow float installed in a manhole (from Leupold & Stevens brochure)

Figure 7. Examples of hydraulics flow measuring equipment

All of the instruments discussed above have been in use for many years. A relatively new type of instrument for flow measurement is the vortex-shedding instrument. It is a hybrid type of instrument that depends on detecting by an appropriate mechanical or thermal detector a resulting fluid dynamical behavior such as the characteristic frequency-Reynolds number dependence of vortex shedding. Instruments of this type have been used for both wind-speed and volume flow measurements in air and water.

All of the forementioned instruments normally require some form of calibration. However, an appropriately designed Pitot-static tube can be employed, as is presently done by NBS, as a primary standard for the calibration of wind-speed measuring instruments such as non-standard Pitot-static tubes, thermal anemometers, cup, vane, and swinging-plate anemometers.

The outputs of many instruments are not directly in terms of velocity or flow rate. Many of the force-type meters such as cup anemometers, turbine meters, and water current meters have an analog or digital output in terms of a voltage or frequency. The relationship of these various outputs to the velocity or flowrate is determined by calibration. In addition, instruments of the differential pressure type require a coefficient to be specified by calibration. Instruments which are used in closed conduits for metering volume flows such as the laminar flowmeter, orifice meters, venturi meters, critical flow nozzle, and turbine meters are generally calibrated using timed volume or mass discharge methods or gravimetric measurement methods. Thermal anemometers, under well-established and restricted conditions, have been found to be particularly useful for making measurements in unsteady flows and turbulence, both in air and water.

The types of instruments referred to above represent the bulk of the instruments with the greatest commercial demand manufactured in the United States for general application to gas and liquid flow measurement. On the other hand, instruments utilizing electromagnetic effects, sound transmission, and light scattering at the present time have a much more limited market and may be regarded to some extent as special-purpose instrumentation, but their use is growing rapidly. For example, electromagnetic flowmeters are used for the metering of conducting fluids such as sewage sludges, liquid metals, and water if it has a sufficient threshold of electrical conductivity. (Liquid metals are being considered for use as heat transfer agents in nuclear systems.) Sonic anemometers operate on the principle of detecting the transit time of transmitted sound, and this principle has also been applied to flowrate meters. In principle, they have improved frequency response over most of the differential pressure and mechanical types of instruments which makes them particularly useful for the measurement of low-frequency unsteady flows. However, they are relatively expensive and to date have received limited use. The advent of the laser has made possible the development of the laser velocimeter which, operating on the principle of the Doppler shift of scattered light, is finding application to the measurement of multiphase flows in gases and liquids and to the measurement of very low velocities. Here again its use for the most part is confined to research activity.

Gasoline pumps, utility water meters, and utility gas meters are generally volume measuring devices. They are only occasionally used as flowrate devices, and hence are not within the scope of this study on fluid flow. Testing and regulating volume measuring devices normally falls under the jurisdiction of state and local offices of weights and measures or state and local utilities.

2.2.2.2 The Instrumentation Industry

Consistent and reliable measurements are the basis for questions of traceability that arise in connection with contracts. The determination of what constitutes traceability is made by the contracting agency and not by the National Bureau of Standards. In general any specified chain of intercomparisons that has an NBS calibration as its starting point, can satisfy the requirement. This is most often provided by the instrument manufacturer's certificate which cites an NBS test report by number and date. Numerous organizations, conducting their own measurement systems for inhouse purposes do not maintain traceability to NBS. These include the National Oceanographic Instrumentation Center of NOAA (NOIC), and the U.S. Geological Survey (USGS). The latter is discussed in more detail in Section 4.3.3.

Recent exploratory discussions between NBS and the above agencies could lead to highly desirable comparisons of water current meter calibrations between the USGS towing basin and the NBS water tunnel (under development), and also comparisons of evaluations of new current meters by NOIC and NBS. Of related interest is the plan by NBS to have its efforts pertinent to waste water measurement include the establishing of recommended procedures for determining the in-place performance of flow-rate meters and involve direct participation by NBS in field measurements.

Table 3 presents a list of fluid flow meter manufacturers that have had instruments calibrated at NBS over the past seven years. In preparing this information, two criteria were used: (1) an instrument maker is listed if he submitted at least one of his own instruments to NBS for calibration, and he either uses it as a transfer standard or supplies it to a customer; (2) an instrument maker is also listed if his instrument is submitted to NBS for calibration by a user although we may have no specific knowledge as to the use to which it is being put. No distinction is made in this table as to instrument function, i.e., whether it is used to measure velocity, volume, or mass flow, or whether they measure in gases or in liquids. They are grouped for convenience according to their operating principle. Multiple listings are provided when it is known that a manufacturer makes more than one type of meter, however not all types have necessarily been calibrated at NBS.

2.2.2.2.1 U. S. Domestic Business in Fluid Flow Meters, Status and Trends

Total sales are increasing annually for flow measurement equipment. Several forcing functions are operating here: (a) efficiency is being increased in industrial operations through improved methods and techniques of measurement; (b) productivity is being increased with improving accuracy of measurements in industries that rely upon quantitative measurements of production, e.g., the chemical processing industry; and (c) an increasing number of industrial business contracts include incentives and penalties for adherence, or lack thereof, relative to quantitative performance that is scheduled and must be measured in the production process.

No real perturbations are foreseen in presently projected volumes of sales of flow meters and related apparatus, although forecasts do indicate a lower annual rate of growth of sales for such equipment. It appears that the annual volume of total sales dollars will continue to grow with mounting demands for increased accuracy and related sophistication in the flow meters.

Department of Commerce, Bureau of Census, Current Industrial Report MA-38B estimates sales of industrial process flow and liquid level instruments alone (not including meteorological instrumentation, but including associated readout and control equipment, as follows:

Year	$M
1963	67.2
1964	72.6
1965	85.4
1966	90.4
1967	101.4
1968	95.9
1969	106.5
1970	107.2
1971	98.6
1972	109.8
1973	123.8

From the Journal of the Water Pollution Control Federation, "Equipment Market, Water and Wastewater," February 1972, meters and control equipment expenditures for water supply treatment and wastewater disposal treatment are reported to be:

Year	$M
1965	33.3
1968	35.1
1970	51.4

This kind of business data is proving to be very difficult to gather for flow meters per se, exclusive of associated equipment.

The following trends of industrial levels of business are examples of major domestic industries characterized by growing efforts to achieve improved accuracy of measurement of the indicated fluid:

a. From "Gas Facts - A Statistical Record of the Gas Utility Industry, 1973 Data," American Gas Association.

Year	Total Industry Revenues (10^9\$)	Net Gas Production (10^{12}ft^3)
1965	7.4	16.4
1966	7.9	17.6
1967	8.3	18.7
1968	8.8	19.8
1969	9.5	21.2
1970	10.3	22.4
1971	11.4	22.8
1972	12.5	22.8
1973	13.0	22.9

Table 3. U. S. manufacturers of flow measurement instrument calibrated at NBS

Force
Advance Instrument Corp.
Airflo Instrument Co.
Alnor Instrument Co.
Bacharach Instrument Co.
Bendix Environmental Science
Brooks Instrument Division
Cardion Electronics
Climatronics Inc.
Climet Instruments
Cox Instrument Division
Daniel Industries Inc.
Davis Instrument Manufacturing Co., Inc.
E G & G, Inc.
Electric Speed Indicator Co.
Fischer and Porter Co.
Flow Technology Inc.
Flo Tron, Inc.
The Foxboro Co.
General Electric Co.
W. and L. E. Gurley Co.
ITT Barton
Meteorology Research Inc. (MRI)
Quantum-Dynamics
Rockwell Manufacturing Co.
Scientific Instrument Co.
Specialty Electronics Development Corp.
Taylor Instrument Co.
C. W. Thornthwaite Associates
Weather Measure Corp.
Xonics, Inc.
R. M. Young Co.

Electromagnetic
Brooks Instrument Division
Fischer and Porter Co.
Taylor Instrument Co.
The Foxboro Co.
Thermo Systems Inc.

Displacement
American Meter
Industrial Measurement & Controls
Precision Scientific Co.

Differential Pressure
Airflow Developments Limited
American Standard Corp.
Brooks Instrument Division
Cox Instrument Division
Daniel Industries Inc.
Dwyer Instrument Co.
Ellison Instrument Division
Emil Greiner Co.
Environmental Instruments, Inc.
Fischer and Porter Co.
Fluid Dynamics Devices (Canada)
The Foxboro Company
Kollsman Instrument Corp.
Meriam Instrument Laboratories
National Instrument Co.
Pacer Systems, Inc.
Parker-Hannifin, Inc.
Taylor Instrument Co.
Teledyne Geotech
Testek, Inc.
Texas Instruments, Inc.

Sonic
E G & G, Inc.
Nusonics Inc.
Saratoga Systems

Thermal
Alnor Instrument Co.
Datametrics
Environmental Instruments Inc.
Hastings-Raydist Inc.
Reeves-Huffman Inc.
Weather Measure Corp.

Vortex Shedding
American Standard Corp.
Eastech, Inc.
Fischer and Porter Co.
J-TEC Associates, Inc.

Tracer
Badger Meter Co.
Hydrospace Challenger

b. From U. S. Department of the Interior, U. S. Petroleum Refinery Capacity and Utilization, July 1972 -

Year	Capacity (10^6 bbls/day)	Utilization (10^6 bbls/day)	Percent Capacity
1970	11.9	10.8	92.0
1971	12.7	11.5	90.6
1972	13.0	12.1	93.0
1973	13.4	12.7	93.9
1974	13.5	13.3	98.3
1975	13.6	13.9	100.0+

c. From Journal Water Pollution Control Federation, Water (municipal) and wastewater (municipal) expenditures and federal grants, February 1972 -

Year	Expenditures (10^9\$)	Grants (10^9\$)	Total (10^9\$)
1967	2.7	0.3	3.0
1968	3.5	0.6	4.1
1969	3.1	0.4	3.5
1970	2.9	0.8	3.7
1971	3.2	1.3	4.5
1972	3.7	2.3	6.0

Table 4 includes an estimate presented in Perry's Chemical Engineers Handbook as to the relative order of occurrence of flow measurements in the process industry.

2.2.2.2.2 Export-Import Business in Fluid Flow Meters, Status and Trends

Business outside of the U.S. is growing vigorously in fluid flow meters, and U.S. manufacturers of meters are engaged in aggressive programs to increase their sales abroad. Along with the growth of U.S. exports there is some increase of imports of meters into the U.S.

In testimony before the Congress, the Scientific Apparatus Makers Association (SAMA) testified in part, "about 25 percent of total flow meters and flow instrumentation sold by the industry are sold abroad. The industry believes that export sales of flow meters and flow instrumentation exceed imports by greater than 4 to 1. Of great significance is the fact that flow meters and flow instruments are the leading edge for a wide variety of controllers, control systems and control computers. They are the leverage for export sales of information and control systems valued at two to three times the flow measurement products."

Table 4. Relative order of occurrence of various types of measurements in the process industries (from Perry's Chemical Engineers Handbook)

Type of Measurement	Estimated Relative Occurrence Percent	
Temperature		34.7
Electrical Methods	20.5	
Mechanical Methods	12.4	
Radiation Methods	1.8	
Flow		17.5
Mechanical Methods	14.6	
Electrical Methods	2.9	
Liquid Level		11.8
Mechanical Methods	10.2	
Electrical Methods	1.6	
Pressure		11.7
Mechanical Methods	9.8	
Electrical Methods	1.9	
Chemical Composition		5.6
Electrical Variables (I,E,R, etc.)		4.6
Humidity		3.5
Speed (linear and rotational)		2.1
Density and Specific Gravity		1.8
Moisture		0.7
Others (viscosity), weight, color, etc.)		6.0

From Department of Commerce, Bureau of Census, Report No. FT-990, U.S. exports in scientific and technological instrumentation (scientific, medical, optical, photographic, and measuring and calibrating instruments) amounted to approximately 885 million dollars and imports were approximately 381 million dollars in 1971. From Department of Commerce, Bureau of Census, Report Nos. FT-410 and FT-135, for industrial process instruments (including flow meters):

Year	Exports (\$k)	Imports (\$k)
1970	21,700	188
1971	24,600	253
1972 (Jan. to June)	12,100	n.a.

Favorable balance in trade can be attributed to technological leadership, marketing aggressiveness, and reliability of instruments and service. However, export-import trade has become highly competitive and foreign manufacturers of meters are intensifying their efforts in both foreign and U.S. markets.

A foreign procedure of major concern to U.S. manufacturers of meters is the business enhancement programs which a growing number of countries have initiated. France, Japan, Germany, Canada and the United Kingdom have programs which offer a variety of generous incentives such as tax credits, accelerated depreciation allowances, low interest loans, and outright grants for the performance of research and development. The establishment of research associations and joint ventures among private firms and between a government agency and one or more private firms are generally encouraged and supported. Such arrangements avoid duplication of R&D efforts, pool resources, and spread the risks. These programs surpass anything comparable in the U.S.

Foreign countries are more frequently becoming third parties in buyer-seller deals leading to foreign sales by U.S. meter manufacturing companies. While accustomed to discretionary or voluntary use of standards in the U.S., our meter manufacturers find that standards are mandatory and legal requirements have to be met in a growing number of countries abroad where national agencies play a paramount role in the purchase of U.S. flow meters. U.S. companies are looking to the U.S. Government for help in negotiating differences between U.S. and foreign standards. A pertinent view expressed by Daniel Industries is that, "On the international scene the one weakness that is continually faced (by U.S. meter manufacturers) is the lack of a 'Bureau of Standards' approved method of measurement for presentation to the international standards groups...this results in difficulties for American manufacturers in getting their equipment accepted in foreign countries...".

Wherever practical U.S. flow meter manufacturers are resorting to maximum employment of local capability abroad. This includes manufacturing and competing locally with meters produced in the foreign countries. In an important sense the exporting from the U.S. occurs in the form of technical and management talents. U.S. companies use a variety of foreign organizational arrangements that include corporate offices, wholly-owned companies and subsidiaries, and licensing and sales agreements.

2.2.3 Reference Data

The basic reference data for fluid flow are the fundamental units of mass, length, time, and temperature. Measurement of these quantities is covered by separate studies in this report series.

In addition to these basic quantities, a number of publications contain data on physical properties of gases and liquids found in fluid flows. These include:

1. NBS Circular 564, "Tables of Thermal Properties of Gases."
2. "Fluid Meters," ASME, 6th ed. 1971, for orifice and nozzle coefficients, viscosity and other properties of liquids, design data on meters.
3. Physikalisch-Technische Bundesanstalt (PTB) tables for water density.
4. ASTM-IP Petroleum Tables.
5. Parshall flume and weir coefficients, appearing in many references, e.g., "Water Measurement Manual," Bureau of Reclamation,
6. Publications of Thermophysical Properties, Research Center, Purdue University,
7. U.S. Geological Survey Series, "Techniques of Water Resources Investigations."

2.2.4 Reference Materials

The following reference materials are used for instrument calibrations and tests in fluid flow:

1. Hydrocarbon liquid MIL-C-7024B-Type I (Normal Heptane, a calibration liquid simulating aviation gasoline).
2. Hydrocarbon liquid MIL-C-7024B-Type II (Stoddard Solvent, a calibration liquid simulating JP-4 jet fuel).
3. Hydrocarbon liquid MIL-H-5606C (hydraulic oil).

Specifications for these liquids are prepared by the Aeronautical Systems Division's Engineering Standards Division at Wright Patterson Air Force Base in Dayton, Ohio. These materials are used at NBS and other laboratories primarily for turbine meter calibrations.

Reference materials whose properties are well known are often used to good advantage to supplement air and water calibrations of flow measuring apparatus by extending the range of dimensionless similarity parameters. Examples of such materials include pure helium and glycerine.

2.2.5 Science and People

Fluid flow measurements are encompassed by the broad field of science called fluid mechanics. Virtually every major university in the U. S. teaches fluid mechanics as a part of its engineering curriculum at undergraduate and graduate levels. In addition, universities have made significant contributions to fluid flow measurement and the properties of flow.

Interacting with the university segment are research and development institutions, such as the National Bureau of Standards, which have interests in both properties and phenomena of flow, instrumentation development, and derived standards of flow. Department of Defense laboratories and contracting agencies have made significant contributions to flow measurement and fluid mechanics, and the National Science Foundation has supported much work in this field. Other federal agencies, notably the U.S. Geological Survey, the U.S. Department of Agriculture, the Bureau of Reclamation, the Army Corps of Engineers, and TVA, have made significant contributions to water resource flow measurements. These interactions often occur through professional societies such as the American Society of Mechanical Engineering's Fluid Meters Research Committee, the American Physical Society, the American Gas Association (AGA), the Transmission Measurement Committee of AGA, the American Meteorological Society, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, and the Scientific Apparatus Makers Association (SAMA).

2.3 Realized Measurement Capabilities

A comprehensive analysis is being conducted of the existing facilities and measurement capabilities of all laboratories within the national fluid flow measurement system. Information obtained to date is presented in tables 5, 6, and 7 for air flows, gas and liquid metering, and supply and waste water measurements, respectively. There is an ongoing effort directed to inter-compare the facilities and capabilities within these measurement areas to establish measurement system performance levels.

In applied meteorology, wind speed measurements up to 100 mph are generally made within about 5 percent accuracy. In water resource and wastewater measurements, the accuracies achieved depend upon the sophistication of the organization and on the cost of water delivery and/or wastewater treatment and on regulatory requirements. However, they are often no better than 5 percent when the flow is in open conduits, and the accuracy can, and often does, deteriorate sharply from that level. Major errors due to improper application of open channel measuring devices and poor maintenance can be frequently observed in the field. In pipeline measurements of liquid and gas flows, the uncertainties are the order of 1 to 3 percent, owing to uncertainties in discharge coefficients of the orifice meter. In the aircraft engine industry, calibration laboratories are maintained to within about 0.15% of NBS results.

An additional discussion on the general state of adequacy of measurement capabilities vs. needs can be found in Sections 3.2.1.1 through 3.2.1.4 under the topic of status of the fluid flow measurement system.

2.4 Dissemination and Enforcement Network

2.4.1 Central Standards Authorities

Over the years, a system of national measurement standards for the derived quantities characterizing fluid motion has evolved. At the center of this system, NBS is the central measurement standards authority serving the entire domestic flow measurement community. NBS has a collection of facilities capable of generating a wide variety of reproducible reference conditions in flows of air, water, and liquid hydrocarbons. These facilities have been tested and evaluated over many years, and through comparison with comparable facilities have been determined to operate within well-defined limits of accuracy. Instruments and calibration procedures are included, and they are applied as national reference standards. The use of this standards system, while not generally a legal requirement, is considered to be a desirable means of achieving coordinated measurement results from all segments of the fluid flow measurement system.

Other government agencies, in particular the U.S. Geological Survey and the National Oceanographic Instrumentation Center (NOIC), are central authorities for select classes of measurements or certain ranges of flows involving particular instruments.

2.4.2 State and Local Offices of Weights and Measures

State and local offices of weights and measures deal primarily with volume dispensing devices in fluid measurement. This includes gasoline pumps, household water meters, household gas meters, and the like.

Table 5. Examples of aerodynamics (air velocity measurement) laboratories facilities

Location	Type of Facility	Velocity
Low Velocity Southwest Res. Inst., Thermal Systems, Inc., universities and NBS (under development).	Flow ducts for research and calibrations. Laser calibrations at NBS.	0.15 to 50 fps and ± 1% uncertainty at NBS.
Subsonic Private companies, universities, government, and NBS.	Wind tunnels with pitot-static tube as primary standard.	270 fps max. and 0.15% uncertainty at NBS. Attainable at other locations.
Unsteady Flow Ill. Inst. of Tech., Texas A&M and NBS.	Wind tunnels with variable fluctuations of flow for research. Calibrations at NBS (under development).	90 fps max., 1 to 25 Hz freq. range, speed of 0 to ±50% of mean speed, and gusts and lulls at NBS.

Table 6. Examples of fluid meters (gas and liquid flowrate measurements) laboratories facilities

Location	Flowrate (Max.)	Pressure (Max.)
Air		
Col. Eng. Exp. Sta.	80,000 scfm (time limited)	2,800 psig
NEL, United Kingdom	10,000 scfm	1,000 psig
NBS	3,000 scfm	125 psig
Rockwell Intl.	800 scfm	1,000 psig
Water		
Univ. of Minnesota	145,000 gpm	8 psig
Fischer & Porter	40,000 gpm	10 psig
Alden Research Lab.	40,000 gpm	21 psig
Japan	22,000 gpm	25 psig
NBS	10,000 gpm	75 psig
Liquid Hydrocarbons		
Brooks Instrument Division	10,000 gpm	40 psig
Japan	3,100 gpm	
Fischer and Porter	1,700 gpm	100 psig
NBS	2,000 gpm	50 psig

Table 7. Examples of hydraulics (water velocity measurements) laboratories facilities

Location	Type of Facility	Velocity Range
Private Industry (research)		
Hydronautics, Inc.	Towing tank	0 - 20 fps
Government (research and calibrations)		
Army C. E., Bonneville, Ore.	Towing	0 - 12 fps
Natl. Oceanic Instr. Center	Water tunnel	0.05 - 0.10 fps (low veloc. range)
NBS	Water tunnel	0.10 - 40 fps
Naval Ship Res. and Dev. Ctr.	Towing tank	Down to 0.05 fps
USGS, Mississippi	Towing tank	0 - 15 fps
University (research and calibrations)		
Chesapeake Bay Inst., JHU	Water tunnel	Down to 1 cm/sec
M.I.T.	Towing tank	0 - 25 fps
Penn. State	Water tunnel	0 - 80 fps

Table 8. Standards laboratories within system - a summary

		Standards Capabilities						Services			
		Primary Only		Secondary Only		Both Standards					
Type Labs.	No. Labs.	Gas	Liq.	Gas	Liq.	Gas	Liq.	Parent Org. Only	Other Organizations	Calibr. on Fee Basis	Calibr. No-Fee Basis
Private	180	9	12	31	32	17	20	61	20	94	1
U. S.	26	6	4	5	7	4	3	13	7	5	-
State	12	-	1	-	1	-	1	-	-	5	6
Total	218	15	17	36	40	21	24	74	27	104	7

Since such devices are not used as flowrate measuring devices in these applications, they are excluded from this study. In irrigation water distribution, the state and local offices of weights and measures have little or no activity.

State standards laboratories for fluid flow are covered in section 2.4.3.

2.4.3 Standards and Testing Laboratories and Services

Numerous laboratories are engaged in the flow measurement of gases and liquids, and table 8 presents a summary of the laboratories identified to date within the fluid flow measurement system. This summary reflects a continuing NBS effort to understand the depth and scope of participation and contributions on the part of all calibration and standards laboratories within the system's infrastructure. Table 9 comprises a list of these laboratories as obtained in part from "A Directory of Standards Laboratories" prepared by the National Conference of Standards Laboratories, 1974 Edition, and including their standards capabilities and measurement services.

In table 9, measurement services are indicated by (P) for primary standards only, (S) for secondary and/or test instruments only, and (B) for both levels of services. Primary measurement standards are defined as those maintained at an echelon just below the principal standards of mass, length, and time maintained by NBS. In this table customers receiving services are indicated by (O) when limited to parent organizations only, (C) when others are served in special cases, (F) when calibration is generally available on a fee basis, and (X) when calibrations are conducted on a no-fee basis.

The functions of several laboratories in table 9 deserve mention. The U.S. Geological Survey calibrates its own water current meters in a towing tank and occasionally calibrates on a fee basis for customers. USGS also conducts research and development on water current meters and flumes. The National Oceanographic and Instrumentation Center calibrates and evaluates oceanographic current meters. They also share some facilities with USGS in Mississippi.

Note that table 9 contains several state offices of weights and measures for convenience and reference. While the Directory of Standards Laboratories considers these as providers of fluid flow services, an NBS sampling indicates these services are volumetric measurements, and not rate measurements, and hence explicitly not within the scope of this report.

2.4.4 Regulatory Agencies

A number of new federal regulations require increased consistency and reliability in fluid flow measurements for implementation. These regulations arise from the:

- Federal Coal Mine Health and Safety Act of 1969
- Federal Standard No. 209a for Clean Room and Work Station Requirements
- National Environmental Policy Act of 1960
- Occupational Safety and Health Act of 1970
- Water Pollution Control Act of 1972, and others.

Regulatory agencies charged with enforcing these and other laws include:

- Environmental Protection Agency (EPA)
- Federal Power Commission (FPC)
- Interstate Commerce Commission (ICC)
- Federal Aviation Administration (FAA)
- Bureau of Mines

2.5 Direct Measurements Transactions Matrix

2.5.1 Analysis of Suppliers and Users

Supplies and users of fluid flow measurement services are shown in table 10, the Direct Measurements Transactions Matrix. To identify and analyze these groups and to discuss their roles requires an understanding of just what is being supplied and used. The following categories encompass all of the kinds of goods and services that are involved in these transactions:

- End-use measurement data
- Reference data
- Other measurement services (e.g., calibrations or time and frequency broadcasts)
- Reference materials
- Measurement instrumentation and its associated software
- Measurement how-to information
- Measurement requirements specifications (e.g., laws, regulations, documentary standards)
- Measurement needs information
- Money to pay for the above.

In developing the matrix for this study, attention was focused on the functional information, goods, and services involved in the transactions. The last item, money, was ignored as a direct entry in these particular matrices.

Table 9. U.S. Standards Laboratories-gas and liquid flow
Obtained in part from "A Directory of Standards Laboratories prepared
by National Conference of Standards Laboratories, 1974 Edition.

O Service to Parent Organization ONLY
C Available to Customers in SPECIAL CASES
F Calibration Services Available on a FEE BASIS
X Calibration Services Available on a NO FEE BASIS
P Serivce for PRIMARY standards only
S Service for SECONDARY standards and/or test instruments only
B Service for BOTH primary and secondary services

Laboratories	Zip		Liq. Flow	Gas Flow
Aerojet Electro Systems Co.	91702	O		S
Aerojet Nuclear Co.	83401	C	S	S
Alden Research Laboratories 1/	01520	F	P	
American Electronic Labs.,Inc.	19446	F	S	
American Geophysical & Instr.	90247	F	B	B
American Meter Co. 1/	19116	F	P	P
Applied Physics Lab./JHU	20910	O	S	
Avco Corp. Lycoming Div.	29411	F	B	
Bailey Meter Co.	44092	O	B	
Battelle, Columbus Labs.	43201	O	S	S
Beckman Instruments, Inc.	92634	F	S	S
Beech Aircraft Corp.	67201	C	S	S
Bell Aerospace Co.	14240	C	B	S
Bendix Corp., Kansas City Div.	64141	O	B	B
BIF 1/	02893	F	P	
Black, Sivalls and Bryson 1/	73125	F	P	P
Boeing Co., Aerospace GP	98124	F	S	S
Boeing Co., Wichita Div.	67210	F	S	S
Brooks Instrument Div. 1/	30458	F	P	
Burroughs Corp.	19301	F	S	S
Cal Tech, JPL DSN	92311	O	B	
Collins Radio Co.	52406	F	S	B
Colorado Engineering Exp.	80302	F		B
Comsat Laboratories	20734	O	S	S
Cox & Company, Inc.	10003	C		S
Cummins Engine Co.	47201	O	S	S
Daniel Industries 1/	77001	F	P	P
Dow Chemical Co.	80401	C	S	S
Fischer & Porter Company 1/	18974	F	P	P
Fisher Controls Co. McKinney Div. 1/	75069	F	S	S
Flow Technology, Inc. 1/	85281	F	P	P
Foxboro Co.	02035	F	S	S
Gage Lab Corporation	19115	F	S	
Garrett Corporation	85034	O	P	P
General Dynamics Corp.	06340	C	S	
General Dynamics Corp.	92112	F	B	B
General Dynamics Corp.	92112	F	B	B
General Electric Co.	13201	F	S	
General Electric Co.	33733	O		S
General Electric Co. (NASA)	39520	C	S	S
Grumman Aerospace Corp.	11714	O	B	B
Harris-Intertype	32901	F	S	S
Honeywell Inc.	33733	C	S	
Hughes Aircraft Co.	90230	O	P	P
Hughes Aircraft Co.	92634	O	S	S
Koppers Co., Inc.	21203	O	S	S
Lake Center Indus.	55987	O		S
Lear Siegler, Inc.	49508	O	B	
Lockheed Aircraft Corp.	30060	C	B	S
Lockheed-California Co.	91503	F	S	P
Lockheed Electronics Co., Inc.	07061	F	S	S
Lockheed Electronics Co.(HASD)	77058	O	B	B
Lockheed Missiles and Space Co.	94088	F	B	B
Maintenance Mechanical Corp. 1/	77001	F	P	
Martin Marietta Corp.	21220	O	S	S
Martin Marietta Corp.	80201	C	S	S
McDonnell Aircraft Co.	63166	C	B	B
McDonnell Douglas Astro.	92647	F	B	S
McDonnell Douglas Astro. West	90406	F	B	S
3M Company -- 3M Center	55101	F		S
Monsanto Research Corp.	45342	O	S	S
NAR, Rocketdyne Div.	91304	F	S	B
Natural Gas Pipeline Co. of Amer. 1/	78355	F		S
Newport News Shipbuilding & Dry	23607	C	S	S
Niagara Mohawk Power Corp.	13202	O		B
North American Rockwell	90241	C	B	B
Northern Natural Gas Co. 1/	68102	F		S
Ohio State University 1/	43210	F	P	
Pan Am World Airways, Inc.	32925	C	S	S
Pan American World Airways	89023		S	S
Perkin Elmer Corp.	06810	O	S	S
Philco-Ford Corp.	92663	O	S	S
Phillips Petroleum Company 1/	73034	C		S
Raytheon Co.	01810	O	S	
Raytheon Co.	02154	O	S	S
Rockwell International	2803	F	B	B
Sanders Associates, Inc.	03060	F	S	S
Sandia Labs.	87115	O	B	B
Singer Co., Kearfoot Div.	07424	F	S	
A. O. Smith Corp. Mis. Div. 1/	16510	O	P	
Southern California Gas Co. 1/	92365	F		S
Sperry Electronic Tube Div.	32601	F	S	
SSCO Standards Lab.	48237	F	S	
St. Anthony Falls Hydraulic Lab., Univ. of Minn. 1/	55414	F	S	
Sybron Corp.	14601	O	B	S
Tennessee Gas Pipeline Co. 1/	77001	F		S
TRW Systems Group	90278	F	B	B
Union Carbide Corp.	37830	C	B	B

Laboratories	Zip		Liq. Flow	Gas Flow
United Aircraft Corp.	06108	0	B	B
Varian	94303	F	S	S
Westinghouse Electric Corp.	21203	F	B	B
U. S. Government Laboratories				
Aberdeen Proving Ground	21005	F	S	B
Aerospace Guidance & Metro. Cent.	43055	0	P	P
U.S. Army Metro. & Calib. Center	35809	C	P	P
U.S. Geological Survey 1/				
Harry Diamond Labs	20438	0	S	P
Lexington-Blue Grass Army Depot	40507	0	S	S
NASA	32899	C	B	B
NASA	35812	C	B	B
National Bureau of Standards 1/	20234	F	P	P
National Oceanographic & Instrumentation Center 1/				
Naval Air Rework Facility Norfol	23511	F	S	S
Naval Air Rework Facility	94501	0	B	B
Navy Calibration Lab.	98277	C	S	S
Navy Eastern Stds. Lab.	20390	F		P
Norfolk Naval Shipyard	23709	0		S
USAF Type II A Standards Lab.	95652	0	S	S
Type II Stds. Lab. Pensacola	32508	C	B	B
Western Standards Lab.	92135	0	P	P
State Laboratories				
Alabama Dept. of Agr. & Indust.	36109	X	B	
Alaska State	99503	X	S	S
Arkansas Weights & Measures Lab.	72209	X	S	
California Bureau of Wts.& Meas.	95814	F	S	S
Colorado Dept. of Agric.	80211	X	S	
Connecticut State Office Bldg.	06115	X	S	
Delaware Dept. of Agric.	19901	X	S	
State Dept. of Agri, Hawaii	96814	X	B	
Idaho Dept. of Agric.	83701	X	B	
Illinois State	62706	X	S	
Indiana State Board of Health	46206	X	S	
Maine Dept. of Agric.	04330	F	S	
Maryland Office of Wts. & Meas.	20740	F	B	S
Commonwealth of Mass.	02133	X	S	
Michigan Dept. of Agric.	48913	X	S	
Minnesota Dept. of Public Serv.	55403	C	S	
Nevada Dept. of Agric.	89504	C	S	
New Hampshire Bur. of Wts. & Meas.	03301	F	S	
New Jersey State	08625	X	S	S
North Carolina Dept. of Agri.	27611	X	S	
North Dakota Public Serv. Comm.	58501	F	S	
Oregon Agriculture Dept.	97310	F	S	
Commonwealth of Pennsylvania	17120		B	
Tennessee Dept. of Agric.	37204	X	S	
Wisconsin Dept. of Agric.	53705	X	B	S

1/ Added by authors.

The supplier-user categories have the following composition:

(1) The knowledge community consists of academic institutions, professional societies, scientific institutions, and others. Specific groups within these categories that deal with fluid flow measurement are listed in Section 2.2.5.

(2) Documentary specification organizations include international and national standards agencies, committees, etc. The specific composition of this group is discussed in Section 2.2.1.

(3) The fluid flow instrumentation industry is covered in Section 2.2.2.

(4) The National Bureau of Standards occupies a key role between the basic technical sectors and the dissemination and enforcement network. NBS is discussed in Section 4.2.

(5) The standards and testing laboratories for fluid flow are discussed in Section 2.2.1.1. Those of the Department of Defense are included, as well as any other sector described below in this list, but those of NBS and any sector described above are excluded.

(6) Regulatory agencies are discussed in Section 2.4.4. This entry in the matrix includes state and local regulatory agencies.

(7) The DoD agencies, excluding standards laboratories, are listed in table 9, and also include the U.S. Army Corps of Engineers.

(8) Civilian federal government agencies are listed in table 9, and include, for example, NASA.

(9) State and local government agencies are listed in table 9. This category excludes state and local regulatory agencies.

(10) The agriculture segment includes irrigation companies as well as individual farmers. Hence, farmers are excluded from the general public category.

(11) The transportation category excludes the aerospace industry, since aerospace is listed on a separate matrix line.

(12) The general public includes the individual consumer, the worker, organized labor, and consumer organizations.

The other categories are self-explanatory.

In constructing this matrix, every defined sector is entered as both a supplier and a user. There are several reasons for this. Some sectors--such as the regulatory agencies--are inherently or as a result of circumstances both significant suppliers and significant users. All supplier sectors are users of some sort of measurement good or service. All normal user sectors are at least potentially significant suppliers of measurement needs information. And, most importantly, all sectors may be suppliers to themselves of at least some of the measurement goods and services that they use.

The diagonal elements on the matrix--those for which the supply sector is the same as the user sector--display the nature of the measurement goods and services rendered by that sector to itself.

Standard Industrial Classification (SIC) codes are used to further define supplier-user categories where convenient.

The following ground rules were used in completing the matrix entries:

(a) Only *measurements* transactions are covered. Transfers of any other kinds of goods or services are excluded. The transfer of money is ignored.

(b) Only *direct* transactions are assessed. A may do something for B, and B may do something for C, so that A had done something *indirectly* for C, but no entry would be made in the A-C intersection box on the basis of this kind of transaction.

(c) A number is entered in the center of each intersection box to define the *magnitude* of the transaction that occurs between the given supplier and user, *how much* happens. "How important," "how well," and all other questions are ignored at this point. Quantitative data may be available to form a basis for these judgments, e.g., the dollar value of the transactions, the number of units sold, etc. Generally, however, the selection of the proper entry is based on experienced judgment.

(d) If the transactions for a given intersection are judged to be trivial in magnitude, all other potential entries for that intersection are ignored, and the zero for the cental entry suppressed to leave the box simply blank. A blank box means a

Table 10. Organizational input-output transactions matrix

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR FLUID FLOW — USERS / SUPPLIERS	KNOWLEDGE COMMUNITY (Science, Educ., Prof. Soc.& Publ.) 1	DOCUMENTATION SPECIFICATION ORGANIZATIONS 2	INSTRUMENTATION INDUSTRY (SIC Gp 38) 3	NBS 4	STANDARDS & TESTING LABS. AND SERVICES (SIC Gp 73) 5	REGULATORY AGENCIES (excl. OWM's) 6	DEPARTMENT OF DEFENSE (excl. Stds. Labs.) 7	CIVILIAN FEDERAL GOVERNMENT AGENCIES 8	STATE & LOCAL GOVERNMENT AGENCIES 9	INDUSTRIAL TRADE ASSOCIATIONS 10	AEROSPACE (SIC Gps 37,45) 11	PETROLEUM & NATURAL GAS (SIC Gps 13,28, 29,46) 12	UTILITIES - POWER GENERATION (SIC Gp 49) 13	UTILITIES - SUPPLY AND WASTE WATER (SIC Gp 49) 14	AGRICULTURE (SIC Gp 49) 15	HEATING, VENTILATION AND AIR CONDITIONING (SIC Gp 17) 16	TRANSPORTATION (SIC Gp 37) 17	GENERAL PUBLIC 18
1 KNOWLEDGE COMMUNITY (Science, Educ., Prof. Soc.& Publ.)	1 4	2 4	2 2	4 4	2 3	2 1 3 2	2	2	2	2	2 1 2	1 1 2	2 1 2 2	2 2 2	3	2 2	2	2 1 2
2 DOCUMENTATION SPECIFICATION ORGANIZATIONS	2	4	3 1 3 2	2 1 2 2	2 1 2 2	3 2 2 2	2	2	2	2 1 3 2	2 3 2	2 3 2	2 1 3 2	2 1 2 2	2	2 1 2	2 1 2	
3 INSTRUMENTATION INDUSTRY (SIC Gp 38)	2 1 2	2 1 4 2	2 1 4 2	4 1 3	4 1 3	4 2 3 2	2	2	?	2 2	3 3	3 3 2	3 1 3 2	3 2 4 2	2 1 3	2 1 4	3 1 3 2	
4 NBS	2 1 4 2	2	3	3 1 4 2	3 3	3 3 2	3 4	3 4	2 1 2	2	2 2	2 2	2 1 2	2 1 3	2 2	2 1 2	2 1 2	2 1 2
5 STANDARDS & TESTING LABS. AND SERVICES (SIC Gp 73)	2	2	2 1 4 2	2 1 3	2 1 2	2	3	2	2	1	2 ? 3	2 1 3 2	2 1 3 2	2 1 3 2	2 1 2	2	2	
6 REGULATORY AGENCIES (excl. OWM's)	2	1	2	3 1 4 2	2	3	2	2	3 1 3 2	1	2	3 1 3 2	3 1 3 2	3 1 4 2	2	3 1 3 2	3 1 3 2	
7 DEPARTMENT OF DEFENSE (excl. Stds. Labs.)	4 1 4	2 2	2	2 2	3	2	4	1	?		4	1	3	3	1	1	3	
8 CIVILIAN FEDERAL GOVERNMENT AGENCIES	3	2	2	2 2	2	2	2	3	2		4 1 4	1	2	2 2 3 2	3	3	2	2
9 STATE & LOCAL GOVERNMENT AGENCIES	1	3	3		2	3	2	1	3 2 3 2			1	1	2	2	2		
10 INDUSTRIAL TRADE ASSOCIATIONS	1	3	3	2 1 2		3		2		2	1	3	1	1	?	3	2	
11 AEROSPACE (SIC Gps 37,45)	2 1 4	1	2 1 4	2 1 3	2 1 4	2	3	2 1 4		1	4					2	1	
12 PETROLEUM & NATURAL GAS (SIC Gps 13,28, 29,46)	1	2 1 3 2	3	2 1 2	2	3	1	3	2	3	?	4	3			1	?	
13 UTILITIES - POWER GENERATION (SIC Gp 49)	1	3	2	3 1 3 2	2	3 2 4 2	2	1	2	1		3	2 1 4 2	2 1 2 2	2	1		X
14 UTILITIES - SUPPLY AND WASTE WATER (SIC Gp 49)	1	2	3	3 1 3 2	2	3 2 4 2	2	1	3	1			2 1 2 2	2 1 3 2	3 2 4 2			X
15 AGRICULTURE (SIC Gp 49)	1	1	2	2 1 2		2	2	3	2	?			2	3 2 4 2	2			
16 HEATING, VENTILATION AND AIR CONDITIONING (SIC Gp 17)	1	1	1	2 1 1	1	2	2	2	2	3	2							
17 TRANSPORTATION (SIC Gp 37)	3	1	3	2 1 2	?	2 1 3 2	?	2	?	2	?	1					3	
18 GENERAL PUBLIC						3			2									2

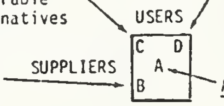
KEY TO MATRIX ENTRIES

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



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

judgment that the volume of the transactions for that box is trivial.

(e) On occasion, the authors felt able to make a reasonable assessment regarding "how much" happens for a given transaction intersection, but did not wish to record any judgments regarding any other aspects of the transaction. In such cases, only the central "magnitude" code number will be found.

(f) If any additional judgments are made, a number will be entered in the upper left hand corner of the intersection box to characterize the importance or criticality of the transactions, independent of their physical volume.

(g) The lower left hand corner is used to code in the rate of change of the magnitude of the transactions for that intersection.

(h) The inadequacy of the transaction in terms of providing the goods or services needed or desired by the user is coded into the upper right hand corner of the box.

(i) Normally, all zeros are suppressed to leave the table blank when they apply. Thus a blank spot in the table implies that there is no need for attention to it, and any entry signifies some need for attention. If a zero is significant for calling attention to a situation that needs changing, it is entered as such.

(j) Question marks may be entered at any of the information locations. They indicate a lack of knowledge by the authors combined with a judgment that the knowledge is probably of significant value for the purposes of this matrix.

(k) An X entered at any information location indicates that the study deliberately excluded efforts to develop information on that point.

2.5.2 Highlights Re Major Users

Measurement capabilities possessed by various segments of the fluid flow community are illustrated in tables 5, 6, and 7 for air flow measurement, gas and liquid flowrate measurement, and water flow velocity measurements, respectively. In addition, the NBS measurement capabilities in these three areas are discussed in Section 4.2.1. Needs exhibited by all categories of fluid flow measurement users are discussed in detail in Sections 3.2.1.1 through 3.2.1.4. In addition, Section 4.4 summarizes activity areas posed by the 1974 NBS Conference on Flow Measurements as Related to National Needs that were highlighted as a result of user needs.

Major users of water flow measurements are the water pollution-abatement sector, the domestic and agricultural water suppliers, the hydroelectric power generation industry, and the hydraulic engineering community dealing with navigation and flood control in rivers. An analysis of the users of all fluid flow measurement services covered by the matrix shows the instrumentation industry and regulatory agencies are the largest general users. Other major users of air, liquid, and gas flow measurements are the power generation utilities, the Department of Defense, and other federal government agencies.

Frequently the sectors of the water user community are in competition with each other for access to limited amounts of water, and the importance of flow measurements consequently is increasing. For example, nuclear and fossil fuel power plants use large amounts of cooling water. A significant portion of this use is consumptive due to loss through evaporation in the cooling towers. The agricultural community also needs large quantities of this water from the same supply for irrigation, creating a situation of competitive needs for existing resources.

The U.S. Geological Survey operates by far the largest number of stream gaging stations, providing many other organizations with their data through periodic publications. However, significant numbers of measurements are also made by the Corps of Engineers, the U.S. Department of Agriculture and the Bureau of Reclamation. Because these agencies have substantial hydraulic measurement capability and facilities in-house, the direct NBS measurement service to them is generally limited to water current meter calibrations for Agriculture and Corps of Engineers field stations. A significant transfer of information on needs and capability between NBS and these agencies does, however, occur.

Irrigation water is generally distributed to individual farms by irrigation water companies. The quality of the flow measurements made in this distribution process is believed to be variable, depending in part upon the size and capability of the company, and in part on the cost of the water. NBS provides direct measurement services in this area by calibrating water current meters, which the companies then use in turn to field calibrate other flow measurement devices or to make water balances of their system. However, few irrigation companies have been sending meters in to NBS for regular recalibration. The effect of this on their flow measurements, or the nature of any alternate procedures they might use, is not known. Unlike the situation in wastewater measurements, the location of most irrigation measurement activity is unfortunately so distant from NBS that personal observation of procedures is not convenient.

In the field of hydroelectric power, a measurement problem of great economic importance is that of flowrate through pumps and turbines. This flowrate is needed to determine compliance with contracted efficiencies on the part of the turbine and pump manufacturers. This area of flow measurement, characterized by flow through large closed conduits, receives considerable international attention from organizations such as ISO and the International Electrotechnical Commission. NBS has contributed to this area primarily by work on methods of computing closed-conduit velocity-area traverses and by serving on pertinent flow measurement committees.

3. IMPACT, STATUS AND TRENDS OF MEASUREMENT SYSTEM

3.1 Impact of Measurements

3.1.1 Functional, Technological, and Scientific Applications

The technology assessment of the National Fluid Flow Measurement System has identified many attributes that can be used to quantify this system. In particular, there are over 350,000 orifice meters estimated to be in use within the gas and oil industries alone, and it is believed that at least one million orifice meters are used in the U.S. to measure flows of liquid and gas in commercial, industrial, and scientific applications.

Minimum levels of air flow rates required in mine safety, industrial ventilation, and indoor circulation of ventilating air involve a broad area of applications in field measurements resulting from regulatory requirements. Measurements of air flow rates also include applications to ascertain the effects of wind loading on structures and buildings in an environment of variable winds, the gathering of climatological and weather data, and the measuring of atmospheric turbulence and transport properties in the assessing of distribution effects of pollution associated with determinations of air quality.

Additionally, every industry which discharges wastewater into a stream or lake is now required to have a discharge permit, the terms of which require monitoring the flowrate as well as the content of the effluent.

3.1.2 Economic Impacts -- Costs and Benefits

Refer to Sections 2.2.2.2.1 and 2.2.2.2.2 for a discussion of the costs involved in making fluid flow measurements in the U.S. and a discussion of impacts of this sector of the business community.

Errors in measurements can significantly alter the cost-benefit relationship for fluid flows. For example, orifice meters, among the most common used to measure pipeline flows, have uncertainties in the published values of their discharge coefficients ranging up to approximately 2% for water or other liquids and up to 3% for gas. These uncertainties can produce large economic inequities, for example, in the production of natural gas involving gas producers, pipeline companies, large manufacturing industries that use the gas, public utilities and finally the individual consumer. It is common practice for any large gas transmission company to trade as much as one million dollars a day across one metering station, and therefore an improvement of only 0.1% of uncertainty of measuring the flowrate would decrease the uncertainty of trading by one thousand dollars a day.

Long distance transfers of water are on the increase and accountability for all water is becoming more important. The California water project, a major interbasin transfer of supply water between northern and southern parts of the state, charges approximately $62 per acre-foot for irrigation water in the vicinity of Los Angeles. This compares to a charge of $5 per acre-foot for water used for irrigation in one part of Kansas. The California project has an uncertainty of flowrate measurement estimated to be 5% and extensive efforts are underway to decrease this possibly as low as 2%. This reflects a trend to account more accurately for all water supply throughout the National Fluid Flow Measurement System.

3.1.3 Social, Human, Man on the Street Impacts

In increasing numbers waste treatment plants have to assess individual jurisdictions and industries for their fair share of the costs to collect and treat sewage. Costs are increasing for the required treatment, and improved accuracy of flowrate measurement and sampling of waste water is a mounting need. Reasonable projections and equitable distribution of these costs will depend directly upon flow measurements. For example, the Virginia State Water Pollution and Control Board recently placed a limit of 18 million gallons per day upon the capacity of flow to be managed by a water pollution control and treatment plant in Fairfax County. This requirement in turn caused the authorities to place a moratorium upon the establishing of sewer connections of new family units to be served by the plant. Within operating conditions of an estimated 5% uncertainty of measurement by the plant and an estimated 400 gallons per day of flow of sewer water from each unit, the uncertainty as to whether the plant exceeds its mandatory capacity is equivalent to 2,200 family units. These exclusions raise a serious situation in which the community cannot go forward with the development of these units and their economic value to the community. Although this situation arises fundamentally from the treatment plant's limitation in processing sanitary throughput, it may be cost beneficial simply to reduce the uncertainty in the measurement of throughput. However, a complete analysis of this problem would require additional data gathering regarding costs and benefits of the processing.

3.2 Status and Trends of the System

3.2.1 Status of the System

3.2.1.1 General Status

The status of the fluid flow measurement is presented from several viewpoints in this report. Initially, the needs of flow measurement are examined, both in general and specifically for subelements of the overall measurement system. Later in this section, current trends of fluid flow measurement capability are discussed.

General needs of the flow measurement system that have been identified to date include: (a) disseminating old and providing new flow standards, preparing recommended practices, and evaluating and developing instrumentation for the measurement of low velocities and unsteady speeds of air; (b) establishing a rational basis for demonstrating consistency of flow measurements within and between laboratories, developing and disseminating new or improved instrumentation and standards for fluid metering and re-establishing the validity of discharge coefficients for orifice meters; and (c) providing new flow standards, preparing recommended practices, and evaluating and developing instrumentation for the measurement of low velocities and total flowrates of supply and waste water.

The needs have their origin in national concerns that both influence and benefit directly from better fluid flow measurements. In practice these concerns include the development and effective utilization of energy, improvement of the quality of our environment, occupational safety and health, and equity in the exchange of goods. Industry, government, universities, technical societies and trade associations are willing supporters of the importance of finding adequate answers to these needs. The impacted national concerns related to the measurement needs are undergoing continuing review and analysis. A representative summary in table 11 illustrates this relationship as it is viewed to date in the course of conducting this study.

3.2.1.2 Air Flow Measurement Needs

Accurate calibrations are not presently available for air speeds below 600 feet per minute. The uncertainty at 100 feet per minute is about 20% and reliable measurements are nonexistent below 100 feet per minute. Regulations are increasingly becoming more stringent as to minimum levels of air flow rates to be maintained for solving problems of health and safety in mines, industrial ventilation and indoor circulation. The National Institute of Occupational Safety and Health requires precise measurements of air velocities as slow as 50 feet per minute and the Bureau of Mines has similar needs for carrying out legislative responsibilities. Standards and calibrations are needed down to approximately 10 feet per minute with an accuracy of 1% along with evaluations of the performance and applicability of existing and new instrumentation for the measurement of low velocities of air. Methods should be developed for improving the behavior of these instruments under conditions of use in the field.

Suitable calibration facilities, capable of unsteady wind generation, do not exist for characterizing the dynamic response of wind speed measuring instruments, and existing meteorological instrumentation does not permit the accurate determination of instantaneous wind speed. There is considerable uncertainty in measurement of gust velocities, and errors are also introduced in the measurement of average wind speed in fluctuating winds. Existing instruments rarely survive gust velocities above 100 mph. All of this is of increasing importance in such national problems as the effect of wind

Table 11. Measurement needs and impacted national concerns

Measurement Needs	National Concerns	Application Examples
Transfer standards Orifice coefficients Waste water flow	Energy	Gas and petroleum trans. and distr. Power generation Process control
Low velocity air Dynamic wind speed	Health and Safety	Ventilation of mines Industrial ventilation Clean work bench Aerodynamic loading of structures Fire research
Low velocity air Dynamic wind speed Waste water flow Water supply flow	Environmental	Air and water quality Climatological data Stack emissions Monitoring and surveillance
Transfer standards Orifice coefficients Waste water flow Water supply flow Interlaboratory comparisons	Economic	Export sales of instruments International standards for instruments Equity in transfers of goods Process control Regulatory compliance

loading on structures and buildings during a variable wind, the gathering of climatological and weather data, and the need to understand atmospheric turbulence and transport properties in the atmosphere to assess the effects and distribution of pollutants. With the partial support of the Federal Highway Administration, NBS has started a study of the lag characteristics of wind speed measuring instruments to develop procedures and practices for characterizing their behavior in both the laboratory and the field. Calibration procedures will be developed for the dynamic response of wind speed measuring instruments. The performance and applicability of existing devices will be evaluated and methods will be investigated for improving their response. Referenceable measurement methods will be provided for air speed instruments operating in unsteady winds. The results of the Federal Highway Administration supported study will be used in formulating new design criteria pertinent to dynamic loading and design life of such highway structures.

3.2.1.3 Gas and Liquid Metering Needs

The products of American flow instrument manufacturers are encountering increased resistance for use abroad because there is no central authority that certifies measurement capability or performance. As more international standards are developed, they will serve as non-tariff barriers for our exports if they vary from domestic standards and practice significantly. Flow instrument manufacturers and users have indicated the desire for a meaningful system that will allow them to demonstrate that they are operable parts of a coherent and consistent national flow reference system.

New or improved transfer flow standards and validated methods for verifying measurements in the field are needed to monitor or comply with effluent discharge regulations, to measure stack emissions and to establish equity in transfers of custody. Nonintrusive devices that can serve as standards are especially needed for verifying the performance of the thousands of existing metering stations without disruptions in operations or altering the performance of the existing systems. Changing relationships between producers, transporters and users and new regulations on accountability for the product being flowed are unbalancing the previously equitable arrangements that were based on precise but not necessarily accurate measurements. Depending on the application, evaluations and improvements of acoustic, laser or electromagnetic type meters may meet the needs. Also, critical flow ventirus (or nozzles) can serve as low head loss standards in lieu of some existing devices after further development.

Present uncertainties in the published values of discharge coefficients for flow measurements with the orifice meter range up to approximately 2% for water or liquids and up to 3% for gas. Correspondence with major users of orifice meters shows that a growing number of them consider these uncertainties to be too high. Improvements are needed in this major field of flow measurement by reestablishing a reliable data base for flow meters, and developing analytical procedures for extending experimentally verified relationships of flow beyond the range of Reynolds numbers of existing calibration facilities.

3.2.1.4 Water Supply and Waste Water Measurement Needs

At this time, meticulous care is required to achieve uncertainties lower than 5% in measuring the flowrate of waste water in open channels. However, measurements of approximately 1 fps and lower velocities have become important for determining the ultimate disposition of heated power plant effluents and other waste discharges. Needed improvements are particularly difficult to achieve for systems of measurement in which remotely located velocity measuring instruments must operate unattended and on-station for extended periods of time as long as several months in harsh environments. The need for decreasing the uncertainty of measuring waste water is of increasing importance under operating conditions in which municipalities and sanitary districts impose sewer use surcharges based on volume rate and content of waste materials. The economic impact of such policies was discussed in Section 3.1. Existing methods for flowrate measurement in sewage handling and treatment systems must be evaluated and improved, and reliable field calibration procedures must be established for presently available flowrate devices.

Slow circulatory velocities of water play an important role in the quality of lakes, reservoirs, bays and estuaries as affected by influent wastes and other factors. Today's emphasis on steps that will result in better quality highlights the need to improve applications of water current meters to measure these low velocities and to determine volumetric flow rates by velocity-area integrations. Such meters are used also by water supply and irrigation districts to calibrate in situ open-channel measuring devices and for mass-balance or continuity checks on entire distribution systems of water supply. As water becomes more costly, its equitable division among users will become increasingly important. Some economic consequences of this fact were presented in Section 3.1. The trend to account more accurately for all water supply is on the rise throughout the national measurement system, and the need exists to both evaluate the performance of present current meters in their various forms and develop new current measuring devices with improved accuracy and performance.

3.2.1.5 Impact of Metrication

Fluid flow measurements are currently made primarily in customary units. In addition, a number of commonly used combinations of customary units have evolved to describe certain classes of flows. For example, in hydraulics, water storage is frequently measured in acre-feet, which is the volume of water needed to cover one acre of land to a depth of one foot. Similarly, supply and waste water flows are often measured in millions of gallons per day. A major portion of the metrication program in this area would thus be training the personnel who take these measurements to think metric. Calibration data per se can be reported in any system of units, and in some cases can be reported in dimensionless ratios independent of units. For field applications, however, conversion to physical units is necessary. To record flow data in metric units involves using the same instrument used to record data in customary units, but changing the associated readout equipment. Instruments with metric readouts are steadily becoming available for fluid flow.

3.2.1.6 Impact of Automation

Automation of fluid flow measurements is widespread in cases where a large number of meters must be monitored or where highly automated process control phenomena are encountered. Sewage treatment plants are becoming increasingly more automated as more complex process flow scheduling is required for multistage treatment of waste.

An interesting application of automation in waste water flow measurement concerns optimal use of treatment plants during peak load periods. Many large cities have combined sewer systems still in use, where commercial and domestic sewage and storm water runoff flow in the same lines. Periods of heavy rainfall seriously over-load treatment facilities in this type of system, and often force untreated sewage to be discharged into the nearest watercourse. Since economic and environmental factors prevent separating these sewers, attempts are being made in some municipalities to use sewer lines as temporary storage basins by implementation of computerized valving systems designed to route water flow into as much of the existing piping as possible before sending it to the treatment plant.

The impact of automation in hydraulics is currently being studied by the Federal Interagency Work Group on Designation of Standards for Water Data Acquisition, impaneled by the USGS's Office of Water Data Coordination.

The degree of automation in laboratory systems for calibration services is generally a function of the workload of that facility. Many flow meters provide output in parameters easily monitored by a computer. This fact, coupled with reduced prices of computer systems being brought about by advanced electronic technology, makes automation in many of these cases practical as well as desirable.

3.2.2 Trends of Measurement Capability in the System

The cost to flow a unit of fluid is generally rising. This trend is due largely to the disproportionate amount of inflation in the values of the materials being transported but is also a reflection of increased operating costs in fluid transportation. These cost increases are forcing greater investments to be made for both increased accuracy and the managing and controlling of fluid flow. Primary metering devices are becoming increasingly sophisticated and their basic accuracy of measurement is the cutting edge of improvements in the state-of-the-art and in advancements of technologies of measurement.

In both the very small and the very large rates of flow the scene is a constantly changing one of new dimensions. For example, the automotive industry is now targeting for fuel flows in calibrations at approximately 0.1 lbm/min with ±0.2% accuracy of readings and striving for even smaller rates at improved accuracy. Additional efforts are being directed to possible standardization of the industry through the application of transfer reference devices. The nuclear power industry requires measurement of cooling water flows on the order of 1 to 2 million gallons per minute, depending on plant power output. Such plants also require measurement of 300 ° F condensate flows at 20,000 gal/min with accuracies of 0.1%. Another example of the changing state-of-the-art in fluid flow measurement is the rate of 100,000 gal/min of conducting fluid that can be measured using electromagnetic flow meters with an accuracy that ranges to ±2% of full scale. These meters can be used with conduits as large as 96 inches in diameter. In both the oil and the natural gas industries a similar trend exists in the metering of larger rates of flow with advancements in the state-of-the-art of meters.

The more traditional designs with improvements and numerous new designs are finding uses in the application of flow meters. Orifice meters will continue to be used for a long time. Such meters are probably used more for flow measurement than any other instrument. The vortex shedder seems to be establishing a firm footing from which it can continue to grow in applications. The ultrasonic device is the newest device that is finding its place competitively with other flow meters. Light-scattering devices are relatively new but they are showing real promise in measuring the velocity of flow. Thermal devices, both hot-wire and hot-film, are finding increased applications for measuring flow velocities. Another item of note is the increasing use of the critical flow nozzle for calibrating gas flow metering instruments. Turbine meters are also being applied to the measuring of flow rates of an increasing range of fluids. The British have reported they can measure fluid flow using tracers with accuracy of ±0.2% in high pressure gas flow. The French report a similar experience. Although some use is being made of tracer techniques in flowrate measurements in the U.S., the current meter continues to be the major instrument for water flowrate measurement by velocity-area integrations.

Important technological problems have arisen from the use of electrically conducting fluids, and especially liquid metals, as the cooling medium, heat transfer agent or the working fluid in existing and proposed thermo-nuclear power and magnetohydrodynamic (MHD) devices. Methods and instrumentation should be developed to make reliable measurements of steady flow, turbulent flow and temperature in liquid metals, to provide data on the flow dynamics and heat transfer of electrically conducting fluids. These developments would provide the technical base for relating this information to the design, performance and operation of the critical components of liquid metal handling systems of advanced power-generating plants.

Instruments are required that will measure more accurately low velocities in air and water, and will also perform well under environmental conditions in the field. Low velocities are particularly important in water pollution control and are arbitrarily defined here as velocities between 0.1 and 1.0 ft per second with emphasis on the low end of this range. The new high-performance NBS water tunnel will provide reference velocities for 0.1 ft per second and higher. Technological problems in velocity measurement in the field include unattended low-velocity meters. Today's instruments (including sensor element, recording, and storage or transmission components) are not reliable enough for long-term (up to 2 months and often longer) use in place. Problems are associated with fouling, wind, waves, ice, debris and a generally hostile environment. At the other end of the hydrographic velocity spectrum, there is no adequate means of measuring flowrate in very high-velocity channels carrying heavy debris. This is a situation commonly found in flood channels. Many velocity sensors are affected by a vertically oscillating platform such as a bobbing buoy or boat. These effects generally take the form of erroneously high readings. A bucket-type meter, for example, can be seen to rotate in the positive velocity direction if it is moved up and down in still water. Closed conduits which are inaccessible for measurement present a difficult situation in which to obtain a flowrate measurement except at very high cost in a submerged pipe outlet. Difficulty is encountered in obtaining good depth or head measurements accurately in the field. The metering system depth sensing element is subject to fouling when used for wastewater measurements. Very careful maintenance is required and frequent recalibration is desirable of the head sensing and recording system. Some industrial outfalls have wastewater issuing at high velocity from a pipe protruding from a wall. Access is often difficult and the high momentum of the flow makes it almost impossible to insert a meter of any kind at the outlet. Use of the trajectory to deduce the efflux velocity does not always satisfy regulatory requirements. Such outfalls are also common for surface runoff. Maintenance of weirs, flumes and the associated head measuring instruments is often poor. Portability is essential for instruments or methods which are to be used by regulatory authorities in checking industrial waste water measuring systems.

Reliable hydraulic, thermal and other water quality data are needed in the technical decisions for selecting, developing and maintaining electric power generating plant sites. Effects of cooling water intake and discharge on the adjacent body of water are major factors in siting decisions. The hydraulic information is difficult to obtain on-site. Existing measuring instruments and systems are not adequate for this job. An economical measurement system consisting of an array of instruments needs to be developed to operate unattended over long periods of time in adverse environments, and at the same time either storing or transmitting data. Site selections for measurement instruments and the optimum schedules for series of measurements need to be guided by validated mathematical models of the river and/or lake systems.

4. SURVEY OF NBS SERVICES

4.1 The Past

Fluid flow measurement research at NBS has been instrumental in the development of the science of fluid mechanics in the last 60 years, and a number of pioneering contributions have been made by Bureau scientists.

4.1.1 History of Aerodynamics

The earliest work in aerodynamics at NBS began soon after Congress established the National Advisory Committee for Aeronautics (NACA), the forerunner of NASA, in 1915. The mission of NACA was to initiate and direct scientific studies in problems of flight, and they charged NBS with investigation of the physical factors in aerodynamic design.

In 1916, Dr. Robert A. Goddard presented his idea for a rocket gun to the nation's Astrophysical Laboratory, which subsequently called Dr. Edgar Buckingham, the Bureau's aerodynamics specialist, for consultation. The device was conceived for launching recording instruments into the upper atmosphere, but had obvious and significant military value. The Bureau aided with design of two models, and the first device was successfully tested in July 1918. Unfortunately, other wartime projects with more immediate prospects of utilization caused the rocket gun project to be terminated.

The first aerodynamic facility built at NBS consisted of a wind tunnel and an aerodynamic balance, designed in 1917 by Dr. Lyman J. Briggs, who later became the Bureau's third director. When the wind tunnel was placed in operation in 1918, there were only two others in existence in the United States; one at the Washington Navy Yard and one in Dayton, Ohio, belonging to the Wright brothers.

The Bureau's aerodynamic research during the 1920's was funded primarily by NACA, the Army Air Service, the Navy Bureau of Aeronautics, and, after 1927, the aeronautics branch of Commerce. The primary interests of the military were improved airplane design and dirigible model testing. Passing interest was shown in the innovative areas of helicopter and jet propulsion. Dr. Buckingham evaluated a two-foot helicopter propeller model in 1917, and worked out its aerodynamic equations. He reported that a one-man helicopter was practical, but it was 20 years before vertical flight was successfully achieved. Jet propulsion was studied in the 1920's at NBS, but the concept was considered to be impractical due to high fuel consumption and excess weight of materials needed in construction of high-temperature combustion chambers.

More recently, NBS has pioneered in revealing the fundamental processes in the transition from laminar to turbulent flow in boundary layers. In the 1940's the Bureau provided the first experimental confirmation of the linear theory of boundary layer stability proposed by the German school of aerodynamicists, which until such confirmation had been largely discounted as unrealistic. Subsequent investigations through the present time at NBS probed deeper and yielded important findings concerning further stages of the instability and transition process, and the factors influencing transition.

In the field of anemometry, NBS work has been concerned with instrumentation for measurement of steady and unsteady flows. Significant contributions were made to turbulence measurement, and to the behavior and performance of laboratory and meterological wind speed measuring instruments. This includes the pioneering work on the theory and application of hot-wire anemometers, published in 1929, with further contributions in 1946; studies of the effect of supports on vane anemometer performance, 1948; a study of lag characteristics of anemometers, 1954; and research on the heat-loss characteristics of hot-wire anemometers in transonic and supersonic flow, published in 1955. In the period of late 1940's to the early 1950's, investigations into the effect of damping screens on flow in duct systems were made at NBS. This led to the design and construction at the Bureau of the first low turbulence wind tunnel and served as the basis for what has become the standard wind tunnel design practice. The quantitative evaluation of the effect of screens on diffusing flow and flow irregularities has also found ready application to wind tunnels providing for improved performance and more efficient and economical design.

From the early 1950's to the present time, NBS has been actively engaged in the study of nonisotropic and isotropic turbulent fields, and has been a major contributor to the basic reference literature on this subject. This work has played an important part in our present understanding of turbulent structure and in the evaluation of theoretical ideas, and has contributed to a technology concerned with fluid mechanical design problems and fluid mechanical devices.

A previously unpublished historical account of aerodynamic facilities through 1956 and outstanding contributions in aerodynamics can be found in Appendix B.1 by Dr. Galen B. Shubauer entitled "A History of the Aerodynamics Section." Of the facilities listed in this account, only the supersonic wind tunnel is still in existence. Current aerodynamic facilities are described in Section 4.2.1.

4.1.2 History of Fluid Metering

Air and water flow measurement research began in about 1918 at NBS. Mr. Howard S. Bean joined the staff in 1920 and became involved in widespread measurement problems almost immediately. He was soon joined by Dr. Edgar Buckingham. This led to participation in research programs designed to improve flow measurement with the orifice meter, and later with nozzles and displacement meters. Activity in this area continued through the 1930's, and saw Mr. Bean on as many as six committees simultaneously. Most of the NBS work was in cooperation with the AGA and ASME. For instance, the Columbus Tests, held at the Hydraulic Laboratory of Ohio State University, Columbus, Ohio in 1932 to 1933, provided the primary data base for the hydraulic coefficient of discharge for the orifice meter. Some of the massive amounts of data gathered were still being processed in the 1940's, and most of it has been reviewed recently [119].

Mr. Bean and Dr. Buckingham contributed prolifically to journals and trade papers, as well as about fifteen NBS publications as a result of this work [120], [121], [122]. Especially notable is the analysis of the Columbus test results by the National Bureau of Standards made by Dr. Buckingham and Mr. Bean. The results of their work were transmitted by the Director of NBS to the Chairman of the Joint AGA-ASME Orifice Coefficient Committee in May 1934. Additional developments at NBS during this period include an improved wet test meter, a gas compressibility measuring device, the portable Stillman Standard, and a small constant head aspirator.

Prior to about 1940, flow measuring facilities at NBS consisted only of a 25 scfm, 90 psig air flow facility. Volume/time measurements were used as the calibration method. Much of the fluid metering research was done at other laboratories. The number of meters calibrated at NBS was modest, increasing from a few wet or dry displacement meters in the 1920's to about 12 per year in the 1930's, nearly all for government agencies. Completion of the Hydraulics Laboratory in 1932 added a water flow measurement facility with flows to 1000 gpm at 125 psig.

Some growth in the air and water calibration effort occurred in the late 1930's when private companies began requesting calibrations, followed by a decrease in calibrations that lasted until about 1950. Access to a larger air flow capability was acquired about 1950 (2000 scfm and 50 psi) and a water calibrated orifice meter was then used to calibrate larger capacity air meters. Increased need for more accuracy perhaps accounts for an increasing number of calibrations from 1950 to the present. The need for calibrations shifted from the wet or dry displacement meters to the head-type meters with larger capacity. A capability to flow and meter air with volume/time measurement at rates to 50 scfm and pressures to 500 psi was added in 1958.

During World War II and in the years immediately following, testing and research programs on devices for handling and metering fuels for aircraft resulted in development of technical expertise forming the basis for the liquid hydrocarbon fluid metering program at NBS. These programs included significant work on such topics as spray nozzle performance characteristics [123], and methods for correcting for density and viscosity of incompressible fluids in float-type flowmeters [124].

About 1954, the Navy and the aircraft industry became interested in flowmeter calibration methods and, as part of a continuing program under the sponsorship of the Bureau of Aeronautics, the performance of various liquid flowmeters as well as equipment and techniques for their calibration was investigated extensively [125]. This effort resulted in demonstrating uncertainties as low as 0.15% to be possible for calibration of meters, using interlaboratory comparison techniques to establish the bounds on possible systematic errors. This represented a significant improvement in the state-of-the-art at that time. NBS was one of the first laboratories to advocate use of turbine meters as transfer reference meters for liquid hydrocarbons and to document their advantages and limitations [126]. A direct reading viscometer (range 0.3 to 30 centistokes) was also developed and patented as part of this effort. During this time and to the present, members of the Fluid Meters Section have actively participated in professional society committee efforts involving fluid meters research and generation of flow standards. These include committees in the ASME, API, SAE and ISA.

In 1969 the flow measurement laboratories were moved from the Bureau site in Washington to Gaithersburg.

Additional historical information on fluid metering throughout the U.S. can be found in Appendix B.2 in an account by Mr. Bean titled "Comments on Fluid Metering Events Preceding and Following the Organization of the ASME Research Committee on Fluid Meters."

4.1.3 History of Hydraulics

Hydraulics as a discrete entity at NBS originated in 1930 when Congress authorized establishment of the National Hydraulic Laboratory. The goal of this laboratory, as dictated by law, was "...determination of fundamental data useful in hydraulic research and engineering, including laboratory research relating to the behavior and control of river and harbor waters, the study of hydraulic structures and water flow, and the development and testing of hydraulic instruments and accessories...". Work for any U.S. Government agency and any state or political subdivision of a state was also authorized.

Hydraulics research in the 1930's was spurred by construction of hydroelectric power plants, flood control, irrigation, inland waterways, shore protection, and harbor development. Hydraulics was basically an empirical science at the time, and fundamental research in all areas was vital. The new laboratory provided three basic services:

(1) Fundamental research. Problems in this area were generally those requiring continuity of effort over periods of time that were unprofitable to organizations interested in specific engineering problems.

(2) Special investigations and tests. This work was limited to solution of specific problems for immediate application, and generally used results of fundamental research.

(3) Information services. The laboratory served as an information center and clearinghouse for current documents on worldwide hydraulics research.

The Hydraulic Laboratory was opened in 1932 in the midst of the depression and equipment purchases and staffing were severely limited. Specific research projects in its early days included: open channel flow studies; flow in curved pipes with smooth and rough walls; study and prediction of flood waves - a project suggested by the Weather Bureau; and plumbing research - a project involving translation of design data into practical plumbing codes and recommended plumbing practice manuals. Special investigations and tests included: model tests of flood control dams, spillways, and spillway channels; tests of portable pumps for fire protection; and tests of plumbing fixtures for compliance with specifications.

Government agencies served in the early days of the laboratory were the Departments of Agriculture, Commerce, Interior, Navy, Treasury, and War, as well as the Government of the District of Columbia, the Federal Trade Commissior, the National Housing Agency, the Public Health Service, the Tennessee Valley Authority, and the Veterans Administration.

Hydraulics activity was suspended during World War II, and the laboratory building was entirely converted to guided-missile investigations. When hydraulics work was resumed after the war, the emphasis was generally on fundamental investigations. Pioneering work was done on stratified flows and on wind stress on water surfaces, mainly for the Army Corps of Engineers and the Office of Naval Research. After the fluid mechanics group moved to the Gaithersburg site in 1969, the hydraulics activity shifted to more measurement-oriented investigations required by national needs which have been described elsewhere in this report.

4.2 The Present - Scope of NBS Services

4.2.1 Description of NBS Services

4.2.1.1 Fluid Flow Measurement Capabilities

Fluid flow measurement services pertinent to this report are provided by three Sections within the Mechanics Division: Aerodynamics, Fluid Meters, and Hydraulics. The basic provisions of each section are, respectively, air flow services, gas and liquid metering services, and water flow measurement services. Facility descriptions in each of the three organizational areas are presented in tables 12, 13, and 14.

4.2.1.2 Fluid Flow Work Areas

Aerodynamic services at NBS are provided at present in six basic work areas. These are:

(1) Calibrations
   a. Steady flows - 0.15 fps to 270 fps.

(2) Aerodynamic Measurements and Instrumentation
   a. Steady flows - 0.15 fps to Mach No. 1.95.
   b. Unsteady flows - up to 90 fps

(3) Incompressible Flow
   a. Steady flow
   b. Unsteady flow

(4) Compressible Flow Characteristics

(5) Turbulence Studies

(6) Physical Modeling

In the areas of gas, liquid, and water flow metering, NBS work areas include:

(1) Calibration Services (see table 13)

(2) Meter Evaluation and Development

(3) Measurement Technique Development

Work areas for water flow measurements consist of:

(1) Evaluation and research on water current meters for low velocity flows and for open channel flow rate measurements.

(2) Evaluation and research on flowrate measuring flumes, particularly to improve on-site verifications.

(3) Supporting services to other government agencies.

(4) Publication of measurement techniques.

A significant contribution toward making accurate measurements under field conditions, a major problem in water flow studies, is the recent publication by NBS of a "A Guide to Methods and Standards for the Measurement of Water Flow" [118]. Need for such a guidebook is emphasized by recent water pollution control legislation and the need for a closer accounting of the disposition of our water

Table 12. NBS air flow facilities

Type	Test-Section Size	Capability	Uncertainty	Distinguishing Feature
Dual test-section	5' x 7'	150 fps (max)	±0.3%	Low-stream turbulence Adjustable pressure gradient
	4' x 5'	270 fps (max)	±0.3%	Low-stream turbulence
Low-velocity (under development)	3' x 3'	0.15 fps (min) 50 fps (max)	±1.0%	Laser-velocimetry
Unsteady flow	4.5' x 4.5'	90 fps (max)		Steady or fluctuating mode Simulate gusts and lulls (fluctuating flows - 0.1 Hz - 25 Hz) Amplitudes 50 percent mean (flow in 3 percent increments)
Supersonic	3" x 4"	Subsonic to Mach No. 1.95		Low turbulence

Table 13. NBS gas and liquid metering facilities

Type	Capability	Uncertainty
Air (Constant Volume Collection Tank)	3.8 lb/sec (3000 scfm)(max) 20 scfm (min) 125 psig (max)	±0.13%
Air (Bell-type Prover)	0.064 lb/sec (50 scfm)(max) 0.2 scfm (min) 500 psig (max)	±0.13%
Air (Mercury Sealed Piston Prover)	15000 cc/m (max) 50 cc/m (min) 500 psig (max)	±0.13%
Water (Collection in Weight Tank)	10,000 gpm (max) 0.1 gpm (min) 75 psig (max)	±0.13%
Liquid Hydrocarbons (Collection in Weight Tank) (Stoddard Solvent and Hydraulic Oil)	200 gpm (max) 0.03 gpm (min) 30 psig (max)	±0.13%
Liquid Hydrocarbons (Collection in Weight Tank) (under development)	2000 gpm (max) 200 gpm (min) 50 psig (max)	±0.13%

Table 14. NBS water flow facilities

Type	Test-Section Size	Capability
Open-circuit Water Tunnel	20-inch diameter	0.25 fps (min) 8 fps (max)
Closed-circuit Water Tunnel (under development)	24-inch diameter	0.1 fps (min) 40 fps (max) 3 psig (min) 35 psig (max)
Open Channel Facility (under development)	3' wide by 1.5' deep by 40' long	0 to 10 cfs

resources. Wastewater flow criteria and requirements in particular are now involving many engineers and technicians who have had little past experience in flow measurements. Getting this information into the hands of those who need and will use it is one of the major thrusts of measurement programs at NBS.

4.2.2 Users of NBS Services

Table 15 presents the users of NBS fluid flow services, listed by Standard Industrial Classification (SIC) codes and short titles. A "user" is any person or organization to whom the outputs of work at NBS make a positive difference--clients, colleagues, or constituents, i.e.,

- Who would care, or whose work would suffer, if NBS had not done what it has been doing, stopped doing it now, or quit at some future time.
- Clients - those who pay NBS to do work.
- Colleagues - those who use NBS outputs, often obtained through very informal interactions.
- Constituents - those who use our products or services directly;
  - the first layer of user,
  - those directly conscious of benefits they derive from NBS,
  - constituents even though third-party organizations provide liaison coupling, as long as some direct tie to NBS exists.

The SIC codes cover the total of the productive, wage-paying economy. They do not cover the various final consumption sectors. The four-digit code is the finest level of breakdown in the SIC code system. When all four-digit codes in a three-digit category are judged to be equivalent from the viewpoint of NBS programs, only the three-digit code is listed. When the primary output contact is with a trade or business association (SIC 8611) or professional membership organization (SIC 8621), the other SIC categories that these associations represent are listed when there is a significant focus on or contact with such categories. For example, output to the American Petroleum Institute is coded under 8611 and also under 1311, 1321, 1389, 2911, 2992, 3498, 492, 493.

4.2.2.1 Users of NBS Air Flow Measurement Services

Distributions of customers of calibration services for air speed measuring instruments for FY 72 to present were as follows:

Government	65 percent
Industry	35 percent

The following Government agencies submitted instruments for calibration: NASA, NOAA, HEW, NIOSH, FAA, Army, Navy, Air Force, Agriculture and Bureau of Mines. Manufacturers in the industry segment who submitted instruments for calibration are listed in table 3. In-house calibrations were also provided to other Divisions of NBS. These instruments impact upon meteorology, pollution, health and safety, defense, fire research, loads on structures and transportation.

Other services and their impact areas are shown in table 16.

Table 15. Users of NBS fluid flow services Listed by Standard Industrial Classification Codes and short titles

Code	Short Title
	B. MINING
11	ANTHRACITE MINING
12	BITUMINOUS COAL AND LIGNITE MINING
13	OIL AND GAS EXTRACTION
1311	Crude petroleum and natural gas
1321	Natural gas liquids
1389	Oil and gas field services, nec
	C. CONSTRUCTION
17	SPECIAL TRADE CONTRACTORS
1711	Plumbing, heating, air conditioning
	D. MANUFACTURING
20	FOOD AND KINDRED PRODUCTS
2082	Malt beverages
2084	Wines, brandy, and brandy spirits
2085	Distilled liquor, except brandy
28	CHEMICALS AND ALLIED PRODUCTS
2812	Alkalies and chlorine
2813	Industrial gases
2816	Inorganic pigments
2819	Industrial inorganic chemicals, nec (incl. inorg. nuclear fuels)
2821	Plastics materials and resins
2822	Synthetic rubber
2823	Cellulosic man-made fibers
2824	Organic fibers, noncellulosic
2831	Biological products (drugs)
2833	Medicinals and botanicals (drugs)
2834	Pharmaceutical preparations
284	Soap, Cleaners, and Toilet Goods
2851	Paints and allied products
2865	Cyclic crudes and intermediates (org.)
2869	Industrial organic chemicals, nec
2879	Agricultural chemicals, nec
2892	Explosives
29	PETROLEUM AND COAL PRODUCTS
2911	Petroleum refining
2992	Lubricating oils and greases
34	FABRICATED METAL PRODUCTS
3483	Ammunition, exc. for small arms, nec (incl. nuclear bombs)
3494	Valves and pipe fittings
3498	Fabricated pipe and fittings
35	MACHINERY, EXCEPT ELECTRICAL
3511	Turbines and turbine generator sets
3551	Food products machinery
3561	Pumps and pumping equipment
3563	Air and gas compressors
3564	Blowers and fans
3566	Speed changers, drives, and gears
3582	Commercial laundry equipment
3585	Refrigeration and heating equipment
3586	Measuring and dispensing pumps
3592	Carburetors, pistons, rings, valves
36	ELECTRIC AND ELECTRONIC EQUIPMENT
3634	Electric housewares and fans
3635	Household vacuum cleaners
37	TRANSPORTATION EQUIPMENT
371	Motor Vehicles and Equipment
372	Aircraft and Parts
373	Ship and Boat Building and Repairing
376	Guided Missiles, Space Vehicles, Parts
38	INSTRUMENTS AND RELATED PRODUCTS
3811	Engineering & scientific instruments
3822	Environmental controls
3823	Process control instruments
3824	Fluid meters and counting devices
3829	Measuring & controlling devices, nec
3841	Surgical and medical instruments
	E. TRANSPORTATION AND PUBLIC UTILITIES
45	TRANSPORTATION BY AIR
4582	Airports and flying fields
46	PIPE LINES, EXCEPT NATURAL GAS
49	ELECTRIC, GAS, AND SANITARY SERVICES
4911	Electric services
492	Gas Production and Distribution
493	Combination Utility Services
4941	Water supply
4952	Sewerage systems
4953	Refuse systems
4959	Sanitary services, nec
4961	Steam supply
4971	Irrigation systems
	I. SERVICES
73	BUSINESS SERVICES
7391	Research & development laboratories
7397	Commercial testing laboratories
86	MEMBERSHIP ORGANIZATIONS
8611	Business associations
8621	Professional organizations
	J. PUBLIC ADMINISTRATION
95	ENVIRONMENTAL QUALITY AND HOUSING
9511	Air, water & solid waste management
9512	Land, mineral, wildlife conservation
96	ADMINISTRATION OF ECONOMIC PROGRAMS
9631	Regulation, admin. of utilities
9651	Regulation misc. commercial sectors
9661	Space research and technology
97	NATIONAL SECURITY AND INTL. AFFAIRS
9711	National security

Table 16. NBS air flow measurement areas

Work Area	Agency	Impact Area
Turbulence	AEC Navy	Pollution studies, drag reduction, noise
Aerodynamic measurements	NOAA FHwA Bureau of Mines	Meteorology, loads on structures, mine ventilation
Compressible flow	Air Force	Transonic and supersonic wind tunnel testing
Incompressible flow	Navy NASA	Drag reduction and noise

4.2.2.2 Users of NBS Gas and Liquid Metering Services

Distributions of customers of flowrate calibration services (for air, water and liquid hydrocarbons) in FY 72 through FY 74 were as follows:

Industrial	
Space, Aircraft engine	30 percent
Instrument manufacturers	26 percent
Other	19 percent
Government (Army, NASA, HEW, Air Force and Navy)	25 percent

The number of gas and liquid meters currently calibrated is 90 per year, consisting mostly of transfer reference meters for interlaboratory flow measurement comparisons.

4.2.2.3 Users of NBS Water Flow Measurement Services

Customers for water current meters calibrated in FY's 72 through 74 are distributed as follows:

Water and Irrigation Districts	35 percent
Industry	30 percent
Government	35 percent

Current meters impact upon both water supply and waste water. Measurements of velocities of water flow are needed in streams and in irrigation and wastewater systems to calibrate flowrate measurement stations or devices. The meters are also used to measure the velocities of waste waters which enter relatively static bodies including lakes, reservoirs, estuaries and bays.

4.2.3 Alternate Sources

A large number of alternate sources for calibration services comparable to those provided by NBS are available. Laboratories in table 9 that provide calibrations from primary standards on a fee basis encompass the bulk of these. In some cases, organizations with large calibration work loads have found it practical to develop their own calibration facilities, as discussed in Section 4.3.3 for the USGS.

4.2.4 Funding Sources for NBS Services

Funds for fluid flow measurement programs come from three sources:

- calibration fees
- direct appropriations
- other government agencies.

Calibrations are done on a reimbursable fee basis. Other agency projects involve a number of constraints; basically the work must be relevant to national concerns and must meet the criteria set to establish that it is within the scope of the NBS mission.

4.2.5 Mechanism for Supplying Services

Fluid flow measurement services are provided through:

- calibrations
- publication of handbooks and guidebooks for field measurements
- publication of research papers
- correspondence with the flow measurement community
- fluid flow conferences
- consultations.

These services are discussed in detail in Sections 4.2.1 and 4.4.

4.3 Impact of NBS Services

4.3.1 Economic Impact of Major User Classes

The major user classes of NBS flow measurement services are listed in Section 4.2.2. The economic impact of the private sector is indicated in the sales data presented in Section 2.2.2.2.1 for industrial process flow and liquid level instruments.

It is evident from the variety and complexities of the instrumentation used in flow measurement that their use by government, industry, and academia covers a large cross section of the nation's technology involving goods, services, and research activities amounting to billions of dollars. Government agencies concerned with health, safety, power, fuel resources, water resources, weather monitoring, pollution control, military and space programs, etc., as well as major segments of industry sucn as the oil and gas industry, power utilities, aerospace, heating and ventilating, transportation, manufacturing and chemical processing, etc., are all concerned with the adequacy, accuracy and reliability of the various aspects of flow measurement. Not the least involved is the public whose vital interest is directly affected by the forementioned programs and ranges from the gasoline they buy, to the heating of their homes, to the weather report in the morning paper. In addition, the manufacturers of flow measurement instrumentation contribute in a major way to an area which at present has a favorable balance of trade and depends on a quality product in order to maintain this balance.

4.3.2 Technological Impact of Services

Major technologies supported by NBS services and impacts therein are discussed in Sections 4.2.2 and 4.3.1.

4.3.3 Pay-Off from Changes in NBS Services

A major change in NBS fluid flow calibration services occurred in 1964 when the U.S. Geological Survey undertook to develop its own calibration capability after it was encouraged to do so by an NBS administrative decision. This occurred when NBS moved to Gaithersburg, and was initiated by the large work load of USGS in water current meter calibrations. Calibrations for USGS were performed by NBS until 1969, at which time the Fluid Meters Section moved to Gaithersburg. This work load comprised about 98% of NBS water current meter calibrations at the time, and the shift emphasized that jobs of that magnitude were more properly handled by the user organization.

Similarly, the shift from a large towing tank in Washington, D.C. for current meter calibrations to a water tunnel in Gaithersburg reduced the NBS capability to calibrate and test large current meters used in oceanographic applications, but provided greater flexibility for a variety of current meter investigations.

The addition of the unsteady flow facility in aerodynamics increased the NBS capability to respond to national needs associated with these measurements.

4.4 Evaluation of NBS Program

The strength of the NBS fluid flow measurement program lies in the wide range of fluid mechanics and related expertise which is available to back up that program. Weaknesses in the water flow measurement area are associated mainly with the size, or capacity, of facilities. Work cannot be done in water at sufficiently high flowrates to fully assess scale effects. Also, closed-circuit flow facilities are not available for investigating flow measurements in the presence of a solid phase or other additives, or for study of chemical additive types of flow measurement.

Needs for new or expanded fluid flow measurement services at NBS are identified by establishing and maintaining contacts with the user community. Mechanisms of contact include facility visits, letters and telephone communications, and NBS flow measurement conferences. One such conference was held at NBS in 1974 and was instrumental in providing a common base for discussion of user-supplier problems in fluid flow. Of the many problem areas covered, several can be used to identify pertinent follow-on activities in both the near-term and future. These areas are listed in table 17 for air flows, gas and liquid metering, and supply and waste water flows.

Fluid flow programs at NBS are reviewed annually by a National Academy of Sciences-National Academy of Engineering-National Research Council evaluation panel. The National Academy of Sciences, a private non-profit organization of scientists established under a Congressional charter in 1863, is empowered by its charter to act as an adviser to the federal government in scientific matters. The National Research Council and the National Academy of Engineering share this advisory responsibility with NAS. Panel members are selected by NAS-NAE-NRC from among leaders in research and administration in industry and universities, and are charged with reviewing and evaluating the functions and operations of NBS. Specifically, they consider importance and relative priority of projects, staff quality, equipment needs, finance, and the relationship of programs to the NBS mission. Additionally, the panel offers inputs of the anticipatory type on flow measurement needs and broad research and development needs, based primarily on their contact with the academic and industrial communities. The evaluation panel does not, however, represent every major user group in the three fluid flow areas covered by this report.

Table 17. Activity areas identified by 1974 NBS Flow Measurement Conference

Air Flows

- Stack effluent flowrate measurements
- Accurate, simple and portable transfer standard for calibration of anemometry instruments
- Survey of response characteristics of new anemometry instruments
- Long-term unmanned operation of instrumentation systems used to measure winds on highway bridges
- Achieving higher sampling rates for air flow measurements

Gas and Liquid Metering

- Calibration of power plant water flow meters at Reynolds numbers of 5 million for application at Reynolds numbers in excess of 20 million
- National Reference System for flow measurement standards traceable to NBS and reproducible between laboratories
- Flow laboratory certification to assure accuracy
- International legal and regulatory standards for exported instruments
- Standards coordinating group in the U.S. to interface with comparable government agencies abroad
- Measuring, not calculating, the accuracy of flow measurements
- Fully automated meter reading integrated with electronic data processing in distribution gas flow measurements
- Large capacity gas flow meter proving facilities
- Accuracy of measurements of leaks from pipelines
- Approaching era of re-intensified cooperative and participative efforts including meter manufacturers, calibration and measurement services laboratories, and NBS.

Supply and Waste Water Flows

- Improved accuracy of flowrate measurements at point discharges
- Methods and practices of field measurements
- Evaluation of foreign matter degradation of flow meters
- Improvement in low velocity flow measurement accuracies
- Leadership by NBS in achieving and monitoring industry-wide flow meter performance standards

Facilities at NBS are currently adequate for the most urgent of today's flow measurement needs, with the completion of the new facilities listed in Section 4.2. Needs that require additional resources include:

- Large scale flows
- Multiphase flows
- Unsteady flows
- Flows of non-Newtonian fluids
- Electrically conducting fluid flow
- Capability for additives in self-contained facilities
- Capability to test large current meters
- High velocity debris-filled flows.

Multiphase flow is an emerging technology, particularly in hydraulic transport of solids like coal and transport of solid waste and sewage sludge. NBS currently has no program or facilities to address this problem.

Priorities among users are assigned in the direction of overriding need. For example, in hydraulics, this need has been flow measurement for water pollution abatement and related water resource needs. Service programs are monitored only by the evaluation panel.

NBS provides an essential service in identifying, evaluating, and disseminating good measurement practices. Agencies such as EPA would find it increasingly difficult to operate wastewater discharge permit programs if NBS discontinued its dissemination of field measurement practices. It is feasible for alternate sources to supply some services now provided by NBS, particularly where NBS facility limitations restrict capabilities. However, NBS can continue to serve as an expert but neutral third party, an approach to measurement improvement becoming increasingly important in view of the pervasive nature of regulatory requirements.

4.5 The Future

4.5.1 State-of-the-Art Advances

Advances are urgently needed in the state-of-the-art at NBS to develop a non-intrusive flow reference device or system for pipe flows, to remove important sources of ambiguities and uncertainties in the data for head-type meters (orifices, nozzles, ventures, etc.) and to establish a rational basis for flow measurement laboratories to demonstrate that their portion of the measurement system is within acceptable limits. Advances are also needed in the state-of-the-art at NBS to calibrate meters used in stack flow measurement and sampling and for measuring flow rates associated with automotive emissions and fuel rates under the severe environment of the automobile.

Improved field measurements of wastewater flows are urgently needed by thousands of industrial users to meet the requirements of their discharge permits issued under the terms of the Water Pollution Control Act Amendments of 1972.

There is an important need to characterize the behavior of wind-speed measuring instruments in unsteady winds. Flow measurements associated with unsteady flows will become increasingly important, for example, in problems associated with wind loads on structures, pollution monitoring, climatology, etc. There is a significant deficiency in the measurement of subsonic flows where compressible effects play a role, and in particular in the measurement of unsteady flows in this range. Such measurements are needed not only to obtain fundamental technical data but are also sorely needed for the design and construction of flow machinery that operates in this flow regime.

The dynamic characteristics of relatively new types of commercial meters, e.g., electromagnetic, acoustic, vortex shedding, etc., which are receiving increasingly more use, still await satisfactory evaluation. The interaction of such characteristics with the dynamic characteristics of the calibration facilities also awaits clarification.

The present state-of-the-art of laser velocimetry is adequate for NBS calibrations at low velocities in both air and water. The Pitot-static tube is an adequate calibration standard at the higher velocities of air flow.

Overall trends of the Fluid Flow Measurement System are discussed in Section 3.2, and NBS services will help in the understanding of the major problems of measurement that arise.

4.5.2 Impacts of National Measurement System Study to Date

Several accomplishments in fluid flow measurement at NBS throughout FY 73, FY 74, and FY 75 are directly related to the National Fluid Flow Measurement System Study. These include:

Preparation in July 1973 of an internal report entitled "A Survey of Flow Measurements in Water Pollution Control," describing a special effort to accomplish a contact survey to observe field work firsthand in the measurement of flowrate of water and wastewater and of low velocities of water at less than approximately 1 foot per second, with emphasis on 0.1 fps and lower velocities. This survey includes identifying problems encountered in situ, present instrument and measurement capabilities, and accuracies needed compared to accuracies attained. The survey provides a direct means to establish and improve communications with instrument users in the field.

NBS (Mechanics Division) sponsored a conference on "Flow Measurements as Related to National Needs" in February, 1974. The theme was practical flow measurements in the field and their relation to national needs. Audiences of over 170 and invited speakers represented views from industry and trade associations, Government, regulatory agencies, instrument manufacturers, standards laboratories and users of instruments.

"Wastewater Flow Measurement Interagency Group Discussion of Standards and Methods of Measurement" was hosted by the Mechanics Division in June, 1974. This group of invited Federal hydraulic experts identified for EPA the technically acceptable flow measuring instruments and practices for application in the field measurement of industrial wastewater discharge flowrates.

A meeting was held in September, 1974 with the Process Measurement and Control Section's Technical Committee 29, Fluid Meters Standards, Scientific Apparatus Manufacturers Association, to discuss plans to establish a National Reference System for Flow Measurement, traceable to NBS and reproducible between institutional and commercial laboratories.

NBS participated in an interlaboratory comparison directed to reduction in the uncertainty of the discharge coefficients for the orifice meter.

An analytical study of errors of flowrate measurement caused by departures from "standard" conditions for Parshall and other flumes was initiated.

Design was initiated of a tilting open-channel test facility for evaluating open-channel flowrate measuring devices, and for examining open-channel velocity traverse methods.

Evaluations were initiated, using a towing tank, of the performance and error sources of meters used to measure low velocities in the field, examining, in particular, their threshold velocities.

A guidebook to standards and methods for the measurement of water flow was published in FY 75 (see Section 4.2.1.2 for a discussion of this item).

Initial experiments to ascertain the level of interlaboratory consistency in pipe flow were designed and will be carried out by NBS with four or five industrial laboratories after more comprehensive experiments. These tests are expected to lead to one important part of a national flow reference system.

Communications were improved and expanded between NBS, instrument users, manufacturers and regulatory authorities.

4.5.3 Ongoing and Expected Future Impacts of National Measurement System Study

The Mechanics Division will initiate follow-on meetings and/or other activities as needed with the Wastewater Flow Measurement Interagency Group to assist EPA with its specific measurement problems and to benefit other measurement areas such as present and future voluntary national and international standards.

Extend NBS calibration capability down to 10 fpm velocity in air.

Complete the evaluation of dynamic response of one of a class of meteorological anemometers.

Establish NBS calibration service for dynamic response of windspeed measuring instruments.

Evaluate the effects of flow turbulence on wind-speed measuring instruments and on water current meters.

Establish NBS capability for measurement of liquid hydrocarbon flows at rates to 1500 gpm with uncertainty approaching 0.1%.

Conduct selected investigations to assist industry to reduce the uncertainty of the discharge coefficient and expansion factor for the orifice meter and in addition, provide a better determination of the functional relations of coefficient vs Reynolds Number for extrapolation to a high Reynolds Number.

Bring on-line a high performance water tunnel to be used for improvements in the state-of-the-art of low velocity measurements, and establish a low velocity reference flow in its test section.

Complete the design and construct the tilting open-channel test facility.

Complete the analytical and experimental evaluation of errors in fabrication, installation and field use of flow measuring flumes.

Complete the evaluation of the performance of selected hydrographic current meters at very low velocities.

Establish guidelines for velocity-area traversing of small artificial open conduits with current meters.

Evaluate characteristics of part-full flow in circular conduits for application to sewer flow measurements.

5. SUMMARY AND CONCLUSIONS

The science of Fluid Mechanics from which the National Fluid Flow Measurement System originated has been in development for over 2,000 years. Over the centuries, mathematicians, physicists, engineers, and natural philosophers have contributed to a firm and mathematically definitive understanding of fluid flow phenomena, from flows of water in irrigation and water supply channels to hypersonic flows around spacecraft bodies.

Despite this extensive technological base, fluid flow measurements today constitute a constantly changing field. More sophisticated metering devices are being developed that utilize rapidly emerging technologies, such as laser velocimetry, ultrasonic flow meters, and electromagnetic flow meters. Applications arise where existing metrology will not suffice in a new environment, as in the case of liquid metals being used as a cooling medium, heat transfer agent, or working fluid in nuclear power devices. This brings about a need for development of methods and instrumentation to make reliable measurements of such flows. Finally, more stringent federal regulatory standards increase the requirements for accuracy, reliability, and consistency of flow measurements in ranges that are not adequately handled today.

Advancing technology and changing need for procedural standards supplies the impetus for a number of improvements within the National Fluid Flow Measurement System. In particular, an operational scheme including reference standards for fluid flow measurement that would constitute a national reference system do not exist. The need for such a system was emphasized at the 1974 NBS Flow Measurement Conference, and it is being actively promoted by the Process Measurement and Control Section's Fluid Meters Standards Committee of SAMA. The need for a reference system of this type is underscored by (a) discrepancies in flow calibration results, (b) the loss of U.S. technical stature in not having an agency comparable to existing flow measurement centers abroad, such as NEL in England and PTB in Germany, (c) duplication of measurement efforts, (d) the lack of a technical "third-party" to arbitrate discrepancies in measurement, and (e) the lack of facility certification.

Over the years, a system has evolved that serves as the national standard for fluid flow. At the center of this system, NBS is the central standards authority serving the entire domestic flow measurement community. NBS has a collection of facilities capable of generating a wide variety of reproducible reference conditions in flows of air, water, and liquid hydrocarbons. These facilities have been tested and evaluated over many years, and through comparison with comparable systems elsewhere have been determined to operate within well-defined limits of absolute accuracy. Supplementing this capability, the U.S. fluid flow measurement industry, has developed its own sets of flow facilities and documentary specifications for practical flow measurements. These include SAE air-speed measurement standards used by the FAA, AGA-ASME orifice coefficient tables in use by the natural gas and petroleum industry, published discharge data values used for measuring irrigation and wastewater flows, and many others. Presently, the lack of coherence of this measurement system and the low levels of interactions between the centers of measurement competence and measurement users has resulted in a considerably less than optimal fluid flow measurement system.

Instrument calibrations provide an essential service needed to satisfy requirements for accuracy and consistency of measurements. In general, all flow measurement instruments in use today require some form of calibration. This may be achieved through satisfaction of geometrical requirements in construction of the meter; through comparison of the instrument's output against a known set of input conditions related to fundamental units of mass, length, time, and temperature; or through comparison of the instrument's performance to a primary standard. In connection with the latter case, NBS presently uses an appropriately designed Pitot-static tube for a primary standard for calibration of wind-speed measuring instruments. However, there is a need to provide a very low velocity calibration capability. Also, calibration capability for dynamic response of wind speed measuring instruments is needed at NBS.

Errors in measurements can significantly alter the cost-benefit relationship for fluid flows, and in some cases produce large economic inequities. For example, orifice meters, among the most commonly used meter to measure pipeline flows, have uncertainties in the published values of their discharge coefficients ranging up to approximately 2% for water or liquids and up to 3% for gas.

Sales of industrial process flow and liquid level instruments have grown from $67.2 million in 1963 to $123.8 million in 1973. Similarly, business outside of the U.S. is rapidly expanding in fluid flow meters, and U.S. manufacturers of meters are engaged in aggressive programs to increase their sales abroad. Along with the growth of U.S. exports there is some increase of imports of meters into the U.S. SAMA estimates that 25% of total flow meters and instrumentation sold by the industry are sold abroad, and that export sales exceed imports by more than 4 to 1. More importantly, flow meters and instruments provide leverage for export sales of associated information and control systems valued at two to three times the flow measurement products.

It is evident from the variety and complexities of the instrumentation used in flow measurement that their use by government, industry, and academia covers a large cross section of the nation's technology involving goods, services, and research activities amounting to billions of dollars. Government agencies concerned with health, safety, power, fuel resources, water resources, weather monitoring, pollution control, military and space programs, etc., as well as major segments of industry such as the oil and gas industry, power utilities, aerospace, heating and ventilating, transportation, manufacturing, chemical processing, etc., are all concerned with the adequacy, accuracy and reliability of the various aspects of flow measurement. The trend of increasing material and operating costs in fluid flow is forcing greater investments to be made in both increased accuracy and managing and controlling of fluid flow.

In both the very small and the very large rates of flow the scene is a constantly changing one of new dimensions, and new measurement capability is needed for both gas and liquid flow. For example, the automotive industry is now targeting for fuel flows in calibrations at approximately 0.01 lbm/min with ±0.2% accuracy of readings and striving for even smaller rates with improved accuracy. Primary metering devices are becoming increasingly sophisticated and their basic accuracy of measurement is the cutting edge of improvements in the state-of-the-art and in advancements of technologies of measurement. Automation of fluid flow measurements is already widespread in cases where a high volume of meters must be monitored or where highly automated process control phenomena are encountered. Sewage treatment plants are becoming increasingly more automated as more complex process flow scheduling is required for multistage treatment of waste.

Faced with limited natural resources, improvements in accuracies of field measurements of fluid flows are urgently needed. Competition between power generation utilities, industrial users, and agricultural water suppliers has significantly amplified the need for accountability of fresh water supplies. Wastewater flowrate measurements presently being made under field conditions range from good to deplorable. Implementation of regulations such as the Water Pollution Contract Act Amendments of 1972 (Public Law 92-500) require upgrading of many of these measurements.

The NBS fluid flow measurement program is actively addressing many of the pressing problems in fluid mechanics today. Some of these activities were posed by the 1974 NBS Conference on Flow Measurements as Related to National Needs. capabilities are being extended to cover flow ranges and conditions emphasized in regulatory acts, error sources in field measurements of wastewater flows are being identified and evaluated, meter performance data is being evaluated for improved measurement accuracies, and good field measurement practices are being published and propagated through conferences and personal contacts.

ACKNOWLEDGMENTS

The authors wish to recognize the participation in this study of Mr. Philip R. Compton, formerly of the Mechanics Division at NBS, who served as coordinator from June 1973 to November 1974. The background research performed by Mr. Compton and the contributions that he made are gratefully acknowledged.

APPENDIX A. METHODOLOGY OF THE STUDY

The National Fluid Flow Measurement System Study used a mechanism of contacts as the principal data gathering tool. These contacts, more than 200 in number, included trade associations, government (Federal, state, and local) agencies, private companies, universities and laboratories. Contact media included letters, telephone conversations, and facility visits, all directed toward learning the interests, views, and contributions of persons engaged in conducting fluid flow measurements. A partial list of the organizations contacted can be found in table A1. The time schedule of the study and the logic flow used is shown diagrammatically in figure A1.

An additional data gathering tool was the sponsoring by the Mechanics Division of a Conference on Flow Measurements as Related to National Needs in February 1974. Information gathered as a result of this conference and needs of the system subsequently uncovered are presented in the report.

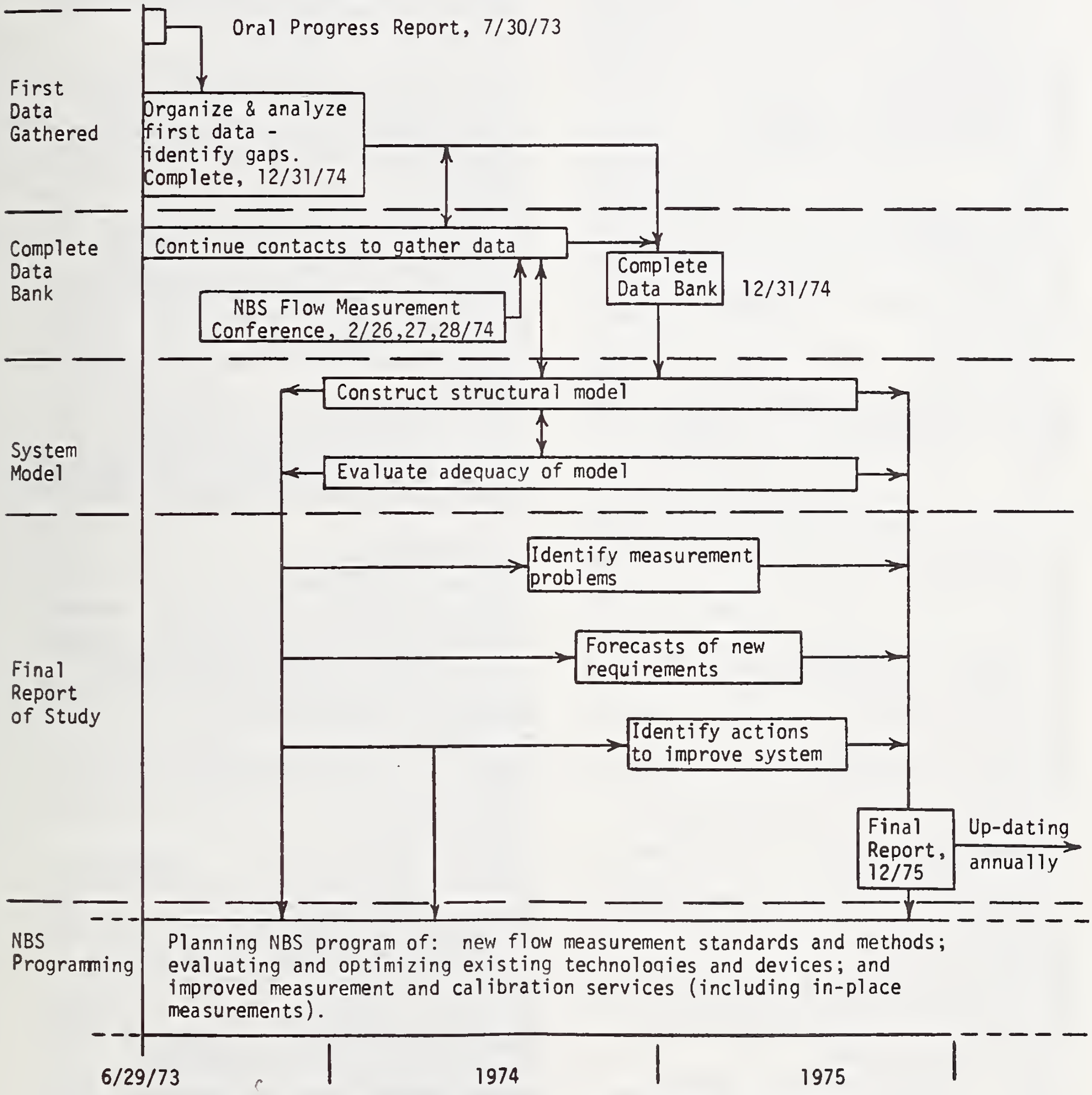


Figure A1. Time schedule of fluid flow measurement system study

Table A1. Contacts made in conduct of fluid flow measurement system study

1. Summary of Number of Contacts

	Associations	Governments	Private Companies	Universities	Total
Letters	22	5	35	2	64
Telcons	12	38	42	11	103
Visits	8	16	13	3	40
Total	42	59	90	16	207

2. Organizations Contacted (Partial List)

U.S. Government

AEC, Argonne National Laboratory
AEC, Directorate of Licensing
AEC, Site and Health Standards
Agriculture Department, Agricultural Research Service
Agriculture Department, U.S. Fish and Wildlife Service
Army Department, Corps of Engineers, Coastal Eng. Res. Ctr.
Army Department, Corps of Engineers, North Atlantic Div.
Army Department, Corps of Engineers, Waterways Exp. Sta.
Commerce Department, Census Bureau
Commerce Department, Domestic Commerce Bureau
Commerce Department, NOAA, Lake Survey
EPA, Air Quality Office, Durham, North Carolina
EPA, Air Quality Office, Ann Arbor, Michigan
EPA, Monitoring Office, Headquarters, D. C.
EPA, National Environmental Research Center, North Carolina
EPA, National Environmental Research Center, Ohio
EPA, Region VII, Kansas City, Kansas
EPA, Research and Monitoring Office, Applied Science and Technology Division
EPA, Research and Monitoring Office, Municipal Technology Branch
EPA, Water Quality Office, Combined Sewer and Stormwater Pollution Branch
EPA, Water Quality Office, Construction Grants Division
EPA, Water Quality Office, Municipal Waste Water Systems Division
EPA, Water Quality Office, Process Optimization Branch
EPA, Water Quality Research Laboratory, Edison, New Jersey
GSA, Transportation and Communications Service
HEW Department, National Institute for Occupational Safety and Health
ICC, Enforcement Bureau
Interior Department, Bureau of Mines
Interior Department, Bureau of Reclamation
Interior Department, U.S. Geological Survey - Tampa
Interior Department, U.S. Geological Survey- Water Resources Division
Labor Department, Office of Safety and Health Administration
National Science Foundation, Project RANN, Environmental Systems and Resources Program
Navy Department, Facilities Engineering Command
Navy Department, Pensacola Naval Air Station
NOAA, National Oceanographic Instrumentation Center
Transportation Department, Federal Highway Administration
TVA, Hydraulics Laboratory

State Governments

California Department of Fish and Game
California State Department of Water Resources
Colorado State Engineer Office
Delaware Office of Weights and Measures
Idaho Dept. of Water Administration
Maryland Office of Weights and Measures
Maryland State Department of Water Resources
Maryland State Public Service Commission, Engineering Department
Nebraska Central Public Power and Irrigation District
Pennsylvania Office of Weights and Measures
Virginia Institute of Marine Sciences, Dept. of Physical Oceanography and Hydraulics
Virginia State Water Control Board, Bureau of Surveillance and Field Studies

Local Governments

Dallas Water Utilities
District of Columbia, Department of Environmental Services
Fairfax County, Virginia, Lower Potomac Water Pollution Control and Treatment Plant
Manassas, Virginia, Occoquan Sewer Authority
Milwaukee Sewerage Commission
Montgomery County EPA
Potomac River Basin Commission
Washington Suburban Sanitary Commission

Private Companies

American Chain and Cable Co., Bristol Div.
American Electric Power Service Group
American Meter Company
A. O. Smith Meter Company
Arthur Brothers Company, Incorporated
Bacharach Instruments Company
Badger Meter Company
Bailey Meter Company
Baltimore Gas and Electric Company
Bendix Environmental Sciences Div.
Bethlehem Steel Corp., Sparrows Point
B-I-F Company

Bostwick Irrigation District, Kansas
Brandt Industries
Columbia Research Corp.
Consolidated Edison Company
Cummins Engine Company
Daniel Industries, Incorporated
Davis Instrument Manufacturing Company, Inc.
DuPont Company, Engineering Center
Duke Power Company
El Paso Natural Gas Company
EG&G Corp.
Environmental Services Corp.
Fischer and Porter Company
Florida Power and Light Company
Ford Motor Company, Fuel Systems Laboratory

Fresno Irrigation District
Friendswood Development Corp., Bayport, Tex.
F. B. Leopold Co.
Gamon/Celment Industries
General Motors Corporation, Fluid Dynamics Laboratory
General Motors Corporation, Proving Grounds
General Oceanics, Inc.
Helle Engrg. Co.
Hersey-Sparling Meter Company
Holley Carburetor Company
Hydrospace-Challenger
Industrial Bio-Test Laboratories, Inc.
Kahl Scientific Corporation
Kappe Associates
Katy Industries
Leupold and Stevens, Incorporated
Limnetics, Inc.
Liquid Controls Corporation
Marsh-McBirney Co.
Mead Instruments Co.
NB Products
Owens-Illinois Co.
Pacific Gas and Electric Company
Potomac Electric Power Company
Rockwell International Corporation, Gas Products and Water Meter Products
San Diego Gas and Electric Company
Southern California Gas Co.
Taylor Instruments Process Control Division, Sybron Corporation
Teledyne Gurley Co.
The Foxboro Company
Union Carbide Corporation, Technical Center

Associations

American Gas Association
American Petroleum Institute
ASME Research Committee on Fluid Meters
Gas Appliance Manufacturers Association
Instrument Society of America
SAE Carburetor Flow Study Group
Scientific Apparatus Makers Association
U.S.A. Committee for International Standards Organization, Technical Committee 30
Water and Wastewater Equipment Manufacturers Assoc.
Water Pollution Control Federation, Technical Services

Universities

Cornell University, Civil Engineering Dept.
Georgia Institute of Technology, Hydraulics Engineering
Michigan State University, Engineering Dept.
The Johns Hopkins University, Applied Physics Laboratory
The Johns Hopkins University, The Chesapeake Bay Institute
University of California, San Diego, Dept. of Applied Mechanics and Engineering Sciences
University of Cincinnati, Civil Eng. Dept.
University of Illinois, Civil Eng. Dept.
University of Michigan, Great Lakes Research Division
University of Missouri, Civil Eng. Dept.
University of Wisconsin - Extension, Dept. of Engineering
Virginia Polytechnic Institute and State University, Center for Environmental Studies
West Virginia University, Department of Electrical Engineering
Worcester Polytechnic Institute, Alden Research Laboratory

Other

Canada Centre for Inland Waters

APPENDIX B. HISTORICAL DOCUMENTS

B.1 History of the Aerodynamics Section
by Dr. G. B. Schubauer, March 1956
(Previously unpublished)

Soon after the United States entered World War I, the Navy requested the Bureau to design and build an aerodynamic balance. Dr. Lyman J. Briggs, who had just arrived on duty at the Bureau on loan from the Department of Agriculture, was assigned this task by the Director, Dr. S. W. Stratton. After the balance was completed, it was decided to keep it at the Bureau and to build a wind tunnel to go with it. Accordingly, Dr. Briggs' next assignment was to design and supervise the construction of a wind tunnel. In this he was assisted by Mr. Roy H. Heald who was working with Dr. Briggs in the Department of Agriculture, and who like Dr. Briggs was assigned to the Bureau on war work. Thus early in 1918 the Bureau got its first wind tunnel, located in what is now known as the South Wind Tunnel Building, No. 19. At that time there were only two other wind tunnels in the United States, one at the Navy Yard in Washington, D. C., operated by Dr. A. F. Zahm, and the other in Dayton, Ohio, belonging to the Wright Brothers.

The Bureau's tunnel was of the venturi type with room return and had a test section in the shape of a regular octagon 4-1/2 feet between opposite faces. It was powered by a 75 h.p. electric motor and could attain a speed of 80 miles per hour. The first investigations consisted of measuring the characteristics of airfoil sections used on planes in this country and also those copied from captured German planes. The staff consisted mainly of Dr. Briggs and Mr. Heald and later in 1918 included Dr. H. L. Dryden, who transferred to wind tunnel work from the Gage Section at the request of Dr. Briggs.

In 1919 Dr. Briggs had to make a decision as to whether to stay at the Bureau or return to the Department of Agriculture. He was induced by Dr. Stratton to remain at the Bureau to organize and head a new Division of Mechanics and Sound in which the wind tunnel group was to be set up as a section along with the Engineering Mechanics Section, Mechanical Instruments Section, Aeronautical Instruments Section, and Sound Section. The new section was called the Aerodynamical Physics Section, which name was retained until 1942 when the name was changed to Aerodynamics Section. Dr. Briggs was chief of the Section as well as of the Division until 1924, when Dr. Dryden was appointed chief of the Section.

In 1921, a 3-foot diameter wind tunnel was constructed on the second floor of the North West Building. This tunnel was later moved to the east end of the basement of the Industrial Building. The tunnel was powered by a 100 h.p. motor and could reach a speed of 180 miles per hour. In 1923 a 10-foot open-air tunnel was constructed on the north side of Van Ness Street. It was powered by a 200 h.p. motor and could reach a speed of 70 miles per hour. These constituted the principal facilities of the Section until 1938 when the original 4 1/2-foot tunnel was replaced by a return-circuit tunnel of the same size and power. This tunnel is now called the South Wind Tunnel.

Following World War I and continuing until 1926 the 4 1/2-foot and 3-foot tunnels were used principally for the investigation of speed measuring instruments and measurements of wind forces and moments on models of bombs. The 10-foot tunnel was first used for measuring yawing and rolling moments produced by rudders and ailerons in a study of stability and control of airplanes. Later, and continuing until 1931, the tunnel was used to investigate wind pressure on buildings and chimneys.

About 1922 investigations were begun into the factors affecting the validity of wind-tunnel measurements. Measurements in different wind tunnels in this country and abroad showed large differences in the drag of such objects as spheres and models of airship hulls. A year or so later the first attempts were made at the Bureau and in Holland to measure air turbulence by means of the hot-wire anemometer. Through such measurements it became possible to attribute the differences in drag to the turbulence of the air stream. Turbulence was found to affect the flow very close to the surface of a body in a region known as the boundary layer. This marked the beginning of basic research on turbulence and boundary layer flow which has continued to the present time. From 1925 on, the Section engaged in a steady development of hot-wire equipment for measuring turbulence in terms of velocity fluctuations, and the calibration of secondary devices such as spheres and cylinders. Along with this, studies were made of sources of wind-tunnel turbulence and means of reducing turbulence, and on effects of stream turbulence on transition from laminar flow to turbulent flow in boundary layers.

During the latter part of the 1920's investigations of airfoil characteristics at high speed were conducted using the jet of air from a 2-inch nozzle. Speeds up to and slightly exceeding the velocity of sound could be obtained. The equipment was located in the northeast end of the basement of the Industrial Building and in a small frame structure called the "High-Speed House" near the northeast corner of the Industrial Building. This was the first work on airfoils at high speeds to be done in this country.

The Section pioneered in a number of investigations and developments, some contributing directly to progress in aeronautics, and others opening new avenues of research. Up to the beginning of World War II such works included the high speed work on airfoils, development of apparatus for measuring turbulence and discovery of the importance of turbulence in aerodynamics, experimental verification of the laws of instability of laminar flow, demonstration of the effectiveness of damping screens for the reduction of turbulence, and measurements of decay of isotropic turbulence produced by grids.

Other major projects, illustrating the variety of work undertaken in the section up to World War II, are: Comparative tests of roof ventilators, early development of mufflers for aircraft, attempts to produce crash-proof gasoline tanks, investigation of engine fires and extinguishing systems, investigation of fatigue failure of aircraft propellers, study of thrust augmentors for jet propulsion, studies of the effectiveness of streamlining automobiles and locomotives, measurement of the characteristics of propeller-type fans, and determination of wind loads on buildings.

With the beginning of World War II all members of the Section went to work either on guided missiles or on wind tunnel investigations of bombs and projectiles. The first models of guided missiles developed at the Bureau were constructed in the South Wind Tunnel Building by members of the staff. This work was later placed in a separate section, but the wind tunnel work on bombs and projectiles continued.

The requests for wind tunnel measurements on bombs and finned projectiles increased to such proportion that it became apparent that more adequate facilities were needed. Accordingly $110,000 was appropriated by Congress in 1943 for the construction of a 6-foot wind tunnel (now known as the North Wind Tunnel, Building No. 73). Construction began in October 1943 and the tunnel was put into operation in 1945. This tunnel is powered by a 750 h.p. motor and reaches a speed of 190 miles per hour.

Following World War II renewed emphasis was placed on fundamental research on turbulence and boundary-layer flow. However, investigations of aerodynamic characteristics of missiles for the Armed Forces continued to be the principal activity in the North Wind Tunnel.

A Supersonic Wind Tunnel for speeds up to twice the speed of sound was acquired with the help of the National Advisory Committee for Aeronautics in September of 1950. On October 1, 1953 the Aerodynamics Section was combined with the Hydraulics Section to form the present Fluid Mechanics Section.

Summary History of Facilities:

South Wind Tunnel Building (No. 19) with original tunnel occupied early in 1918, original tunnel replaced with return circuit tunnel in 1938.

Three-foot Wind Tunnel constructed in 1921, first located on second floor of North West Building (No. 7), later removed to east end of basement of Industrial Building (No. 11), demolished in 1942.

Ten-foot Open-air Wind Tunnel constructed in 1923, located on north side of Van Ness Street, demolished in 1948.

North Wind Tunnel (No. 73) construction began in 1943, in operation from 1945 to present.

Supersonic Wind Tunnel, located in Hangar Building (No. 76), construction began in 1950 but not in operating condition until 1953; in operation from 1953 to present.

B.2 Comments on Fluid Metering Events Preceding and Following the Organization of the ASME Research Committee on Fluid Meters

Given at the Committee luncheon, in Detroit, Mich., November 14, 1973, by Howard S. Bean

1. Need for the Metering of Natural Gas and Development of the Orifice Meter

While natural fuel gas has been known, used and wasted in this country for over 200 years, the metering of it in a transmission pipe line is relatively recent. Sometime about 1890 (exact date not verified) Prof. Robinson of Ohio State University, built and installed a Pitot-tube meter in a pipe line to some town in Ohio. My recollection of the account of this, is he used a section of 3-inch brass pipe placing an impact tip at about one-fourth the tube length from the outlet end, and a static pressure wall tap located probably in or preceding the plane of the impact tip opening. Later other Pitot tube metering units were made, some of which were known as the Towl-type and others were referred to as the Oliphant Pitot tubes.

In 1904 Thomas Weymouth started a program of tests on orifice meters. He mounted his orifice plates between flanges, the flange sections of which were much thicker than the usual pipe flange. This enabled him to place his pressure holes in the flanges, at a distance of one inch each side of the plate. From talking with him later, it is my recollection a 4-inch pipe was used in these tests. He did not finish his test program until 1911 or later. At the annual ASME meeting in 1912 he presented a paper on the Metering of Natural Gas, but in that paper he did not give one bit of information about his orifice tests. The reason, I learned from him later, before that paper was either written or at least presented, he had sold his data to the Foxboro Company with all rights to its use, and he had become a consultant to that company. So it was that in 1921 Foxboro published their book *The Orifice Meter and Gas Measurement* by Brown and Hall. In this they give a curve, called the E-curve, of orifice efficiencies (i.e., coefficients) based on results of Weymouth's tests.

Later, I learned that some time between 1910 and 1920, one or two men in Pittsburgh, who apparently knew about Weymouth's test work, ran some tests on orifice meters. They also located their pressure taps at 1 inch each side of the orifice plate. However, whereas Weymouth had taken his static pressure from the outlet pressure tap, the inlet pressure tap was used at Pittsburgh. There was never any written report made of these tests, but the information I was given was that the results seemed to check with Weymouth's.

So thus we have, so far as I know, the origin of "Flange Taps."

Sometime about 1907, Professor Judd at Ohio State University made some calibrations of orifice meters for Mr. E. C. Bailey, owner of the Bailey Meter Company. In these tests Professor Judd located his high pressure tap at 1 pipe diameter preceding the orifice plate, and the low pressure tap at the vena contracta on the outlet side. Whether this was the first use of "Vena Contracta Taps" with an orifice is uncertain. In 1933 Professor Tuve and Ray Sprenkle had a paper in Instruments on the metering of viscous fluids with an orifice meter. In the tests they report on, vena contracta taps were used.

At the annual ASME meeting in December 1915, E. O. Hickstein gave a paper on "The Flow of Air through Thin Plate Orifices." The tests he reported on had been made at Joplin, Mo., with a gas holder as the reference measurement. Based on some work reported from Charlottenburg, Germany, Hickstein located his pressure taps at 2-1/2 pipe diameters preceding and 8 pipe diameters following the orifice plate. This gives the origin (at least in the U.S.) of "Pipe Taps." I do not know to what extent, if any, the Metric Metal Works, a gas meter company, helped Hickstein with his tests, but they used his results extensively, later.

It is interesting to note that by 1921 there was the Foxboro Company promoting Weymouth's flange taps, the Bailey Meter Company preferring Judd's vena contracta taps, and the Metric Metal Works (later a part of American Meter Company) with Hickstein's pipe taps.

2. NBS Inspections of Orifice Meters Used for Custody Transfer of Gas

In 1919 Mr. S. S. Wyer, a consulting engineer of Columbus, Ohio, became concerned about the accuracy of town border meters and fuel gas leakage in the lines to towns in Oklahoma, Kansas and Missouri around Joplin, Mo. Seems to me he had some connection at that time with a governmental agency on fuels. On the basis of that connection he went to the National Bureau of Standards and arranged for two men to go to Joplin and inspect the town border meters in the area. This inspection was made during the winter of 1919-1920 by M. H. Stillman (inventor of "A Portable Cubic-Foot Standard for Gas") and B. C. Page. Whether there was any improvement in town border meter accuracies and a decrease in gas leakage as a result of that work I never learned.

Along about June 1921 Mr. Wyer again went to the Bureau, this time as a consultant to the Lone Star Gas Company of Dallas, Texas. This time his request was for the Bureau to send men to check the town border meters of that company. I had succeeded Mr. Stillman the first of July 1920, so it became my job to go, taking Ben Page. All we could do was to check the recording gages, using a test gage or a deadweight gage for the static, and a water or mercury manometer for the differential, measure the diameters of the orifice plates, and to suggest the coefficient to be used based on the Foxboro "E-curve" of which we had a copy. This was no more than the gas company men could do themselves, it was not satisfactory to us, and it was made very plain to me it was not satisfactory to E. F. Schmidt, chief engineer of Lone Star Gas. But we had no data of our own to use or go by. So when we got back to the Bureau in my report to my division chief, I recommended that we should undertake a full scale study of orifice meters. Nothing came from that recommendation.

For some time, I do not know how long, Homer Pierce, an employee of the U.S. Indian Agency, had been in charge of the collection of royalties from gas wells in the Osage Indian Nation, in Oklahoma. Believing he should have official data for the measurements, he went to the Bureau of Mines office in Bartlesville, Ok., and asked them to provide him such data. It being a measuring (metering) problem the B of M staff considered the request should be referred to NBS. So it was that in September 1921, R. A. Cattell came to the Bureau from Bartlesville to transmit the request by Pierce, and in which the B of M concurred. Since I was in charge of gas metering Cattell was directed to me. (Incidentally, Cattell and I had been classmates at the University of California although we had not seen each other for over 5 years.)

3. NBS Study of Orifice Meters

Years later Cattell claimed he had not said if the NBS did not undertake a study of orifice meters the Bureau of Mines would. But if he did not say so directly he came near enough for me to report the request from Cattell that way to my division chief. My division chief took the matter up with the Director, Dr. S. W. Stratton. It was well known that Stratton was very vigilant concerning the prerogatives of the NBS in all fields of measurements. It was for that reason I had told my chief if the NBS did not, the Bureau of Mines would have to. It worked. The Director allocated $2,000 to start the job with the stipulation that Dr. Edgar Buckingham must be associated with the program. My chief remonstrated that gas measurement was Mr. Bean's responsibility and not Dr. Buckingham's. Dr. Stratton answered that by underlining that Buckingham be associated with the program. So that was that.

I am going to digress here to pay tribute to the late Dr. Buckingham. He had the remarkable ability to get more out of a set of data, even poor data, than anyone at the NBS. He had an unusual command of the English language, and could explain problems in a way that was easy to follow and understand. No matter what he might be working on he was always willing to give assistance and advice to others as well as myself. For 18 years he advised and assisted me on the several programs I was involved with after the first, and my regard and admiration for him increased throughout those years. I can join another former member of the Bureau staff in saying that our associations with Edgar Buckingham were more helpful than any graduate course we could have taken.

3.1 Tests of Orifice Meters at Edgewood Arsenal

Following allocation of the $2,000 starting fund I began looking up what could be found in the literature. Then early in 1922 set out on a trip to visit manufacturers and users of orifice meters. Those visited were Mr. Weymouth, Oil City, Pa.; Mr. Bailey, Bailey Meter Company, Cleveland; Mr. Jacob Spitzglass, Republic Flow Meter Company, Chicago, Professor Judd at OSU, Columbus; and Mr. T. H. Kerr of Ohio Fuel Gas Company In the meantime Dr. Buckingham had learned of some facilities at Edgewood Arsenal which the Chemical Warfare (War Department) would be glad to let us use. After a trip to Edgewood Arsenal I began laying out a test line and planning a program. By the end of September 1922 we were ready to make a few shake-down runs.

Learning that the Natural Gas Association of America was to hold meetings in Atlantic City, in October, I went to see if they could give us some suggestions for the program. Getting a chance to meet with Mr. H. C. Cooper, chairman of the committee on measurements and research, and Mr. Wm. Way, association secretary, I explained the Bureau's program and why undertaken. I then asked what conditions we should cover that the results might be useful to the natural gas industry. Mr. Way looked at me and said "Mr. Bean, if you want to know we would like to have the Bureau stay out of the gas metering business." So that ended the meeting.

The program at Edgewood continued through '23, '24 and was terminated in '25. A full description of the program and the results is given in NBS Research Paper 49 issued in 1929. Copies are on file in the libraries of most universities, many public and company libraries, as are many such publications.

3.2 Tests of Orifice Meters at Peoples Gas Light & Coke Company, Chicago

At the Atlantic City meeting of the American Gas Association (the manufactured gas industry) in October 1923, Mr. M. E. Benesh, Peoples Gas Light & Coke Company, Chicago, was appointed chairman of a committee on the measurement of large volumes of gas. On his way back to Chicago he called at the Bureau and asked for a conference with the Director and others including myself. He outlined a very extensive program that he proposed to conduct, and asked for Bureau assistance and cooperation, including having a member from the Bureau take part in the test work. So it was that I spent some 7 months of 1924 in Chicago. The tests were made at what had been a gas making plant. The test line was assembled in the ground floor of the station meter house, and included an orifice meter in a 24-inch pipe, a rotary displacement meter, a Venturi tube, a Thomas electric gas meter, and one of the stations rotating drum wet gas meters, the loop to this last could be blanked off. There were 14 orifice plates available, diameter ratios from 0.22 to 0.89. Calibration tests of the 4 lowest ratios, 0.22 to 0.55, and the Venturi tube were made using the upper lift of a large gas holder as the reference and source of water saturated air. Tests of the other meters were made by intercomparison. Pressure gradient measurements were made from 2-1/2 pipe diameters upstream to 6 downstream on 10 of the orifices, diameter ratios 0.22 to 0.77. These pressure gradient values are probably the most useful of the entire program. Unfortunately it was not until July 1931 that a complete report of the program was issued in NBS Research Paper 335.

3.3 Miscellaneous Orifice Research

In the summer of 1925 the Natural Gas Association set up piping to calibrate several orifices in 8- and 10-inch pipes. The tests were to be made with gas which could be discharged into a small covered holder located in Cleveland. The Bureau had been asked to take part in the tests, which accounted for my being there. The results of this program were not published separately.

In 1926 the Natural Gas Association Research Committee started their program on the effects of installation conditions. The location was the Daly meter and regulator station of the Iroquois Gas Corporation, at the south edge of Buffalo. The Bureau was again asked to assist in the program. The work was continued into the fall, and then suspended until late spring of 1927.

Sometime during the winter period the same two men, who at Atlantic City in 1922 had said they wanted the Bureau to stay out of the gas measurement field, went to the Director of the Bureau and asked if Mr. Bean, as a member of the Bureau staff, could supervise their test program. The Director agreed.

3.4 Measurement of Compressible Fluids with the Orifice

During the years since Bureau men first went to inspect town border meters the pressures in gas pipe lines had been increasing. Many of the orifice meter stations were now operating under these higher pressures. Some of us realized that using the simple Boyle's law relation in the computations could lead to appreciable differences in the measurements at two stations operating under different pressures, even if there were no leakage between them. It was decided to make some tests that would show the need for taking account of the true compressibility of fuel gas. Following a design suggested by Dr. Buckingham, an apparatus for determining the compressibility of a gas was constructed, and in the summer of 1928 a few tests were made at the Daly station. However, the maximum line pressure available there was relatively low, possibly a little over 100 psig. So a part of the test line was moved to Hastings, W. Va. where pressures of 200 to 250 psig were available.

Having heard of a gas field in California that was reported to be almost pure methane, I wrote to Mr. Wm. Moller, then Chief Engineer of Southern California Gas Company, to ask if some tests could be arranged in that field. He thought such might be arranged and I made a trip there to see. I obtained approval from the Bureau to do some winter computing in California, with the understanding the desired tests would be made in the spring. Following a trip to the Buttonwillow field near Taft, California, a test line was assembled and a series of tests made during April and May '29. The gas well from which gas was drawn had a well head pressure of about 1000 psig. A 4-inch orifice meter run was connected to the well head valve. The 4-inch meter discharged through two control valves in series, and then to two parallel 8-inch reference orifice meters. Since there was neither a gas line nor compressor plant in the immediate area, the gas was vented from stacks. In the tests that were run the maximum static pressure in the 4-inch meter was about 600 psig. One reason for not going to a higher pressure was to keep the static pressure in the 8-inch reference meters below 30 and desirably below 15 psig. At the conclusion of the tests an evacuated gas cylinder was charged up to the well head pressure and taken to the Taft laboratory of the Standard Oil of California where determinations were made of the compressibility of the gas from that well.

In reporting the results of the Buttonwillow tests, and showing how the actual compressibility, when applied to the high pressure test meter computations brought the computations into agreement with those of the low pressure reference meters, I used the term "supercompressibility." This was done to emphasize that at the higher pressure the gas volume was less, that it was compressed more than the familiar Boyle's law would indicate. The term served the desired purpose and was used for some time, but of late the "super" part is disappearing slowly.

The Edgewood tests had shown that as the ratio of differential pressure to absolute static pressure was increased, the coefficient decreased or increased depending on whether the inlet or outlet static pressure was used. However those tests were made with air, and there had been a desire to obtain similar data with pipe line fuel gas for comparison. The Aliso Street gas plant of the Los Angeles Gas and Electric Company offered an ideal location for such tests. An adequate supply of gas was available from a medium pressure gas main, and the outlet from a test line could be discharged into a holder or the low pressure distribution mains. Test meters of 4, 8 and 16 inches were used in turn. The outlet from these went to a bank of 6 parallel 10-inch reference meters, any 1 or combination of which could be used. It was possible to keep the ratio of differential to static pressure of the reference meters very low (generally less than 0.05), while with both the 4- and 8-inch test meters we went to ratios over 0.5.

It was from the results of the Los Angeles tests, combined with those from Edgewood and some from Germany with air (reported in a 1911 dissertation by Bachman), that Dr. Buckingham derived the expansion factor equation that is still in use.

The activities mentioned so far were in conjunction with the natural fuel gas industry. Incidentally the Natural Gas Association had become the Natural Gas Department of the American Gas Association in 1927.

4. Formation of Research Committees on Fluid Meters

As Chief Engineer of a power plant in Bridgeport, Conn., Mr. R. J. S. Pigott saw the need for collecting information on fluid meters and sponsoring research thereon. He was successful in persuading the ASME to authorize the formation of a Research Committee on Fluid Meters in 1916. Pigott was of course designated chairman, and a few of the other 18 members of the original committee were: Jacob Spitzglass as secretary, E. G. Bailey, M. M. Borden, Dr. Buckingham, Professor Judd, C. G. Richardson and Thomas Weymouth. The first report of the committee, "Fluid Meters, Their Theory and Application," Part 1, was issued in 1924. A second Edition of Part 1 was issued in 1927, and a Third Edition in 1931. Part 2, "Fluid Meters, Description of Meters" was issued in 1931, and Part 3, "Fluid Meters, Their Selection and Installation" in 1933. Parts 2 and 3 were not issued separately again, Part 2 because it was not practical to keep abreast of changes being made in meters, and Part 3 because the material could be incorporated in Part 1 or other equally suitable ASME publications, e.g. the Power Test Codes Instruments and Apparatus series.

I believe it was in 1929 that Ray Sprenkle became a member of the Fluid Meters Committee; I was asked to be a member in 1930 and Sam Beitler in 1931. For several years I had been a member of the Gas Measurement Committee, Natural Gas Department, A.G.A., also, and Weymouth was chairman of this committee. Thus we were both members of the two committees. Since some of the interests and problems of the two committees were the same, I suggested to Weymouth the desirability of a joint committee for doing research on some of the problems. Weymouth discussed the subject with Pigott who agreed, and they decided the joint committee should consist of 3 members from each of the parent committees, and further, since the initiative came from the Gas Measurement Committee, one of its members should be the chairman. The arrangements for the formation of the Joint AGA-ASME Committee on Orifice Meters took place in Pittsburgh on the 24th and 25th of Sept., 1931, and the first meeting thereof was held during the Annual ASME meeting in Dec. 1931.

4.1 Research Project on Determination of Absolute Values of Orifice Coefficients

Among the several decisions reached at the first meeting was the need for a research project on the determination of the absolute values of orifice coefficients. At that meeting Sam Beitler was sitting next to me (almost the first time we met) so I asked him if he could make such tests at OSU. He replied "yes." So I made a motion to have a program of tests to determine the coefficients of orifices, made at OSU, to which the committee agreed unanimously. Thus the 1932-1933 Columbus Tests were launched.

I do not need to go into any details about those tests since one or more accounts of them have been published. We are still using orifice coefficients derived from those tests and it looks like we will continue to do so for some time to come. This is certainly a tribute to the quality of Sam's work [127].

From time to time there had come to our attention papers on orifice meters, from here and abroad, giving the writer's conclusions, but with no data on which the conclusions were based. Thus we could not compare their test data with ours and draw our own conclusions. So it was decided to collect all of the test data from all the several programs mentioned above, beginning with the Edgewood program and on through the Columbus tests. These were all typed on transparent paper double letter sheet size, and blueprinted. The blueprint sheets, when bound, made a volume about 12 x 18 inches and nearly 3 inches thick, and was dubbed "the big report." There were some 50 copies of the "big report" made up, how many are still in existence I do not know, but a few of the locations are: Joint Engineering Societies Library; National Bureau of Standards; Ohio State University, Dept. of Engineering; The Foxboro Company; and the Lone Star Gas Company in Dallas did have one.

During the middle 1930's the committee sponsored programs on flow nozzles, some being done at the National Bureau of Standards, some at the University of California (Berkeley), and some at the University of Oklahoma, Norman. At Norman the tests were made with oil, and thin plate orifices were used as well as nozzles. The first time I visited the work at Norman, Hilding Beck was the assistant professor supervising the test crew. The next time I went there I found Beck had been lured away by John Diehl of the Metric Metal Company (later absorbed by the American Meter Company), and Ed Ambrosius was supervising the work. Both Beck and Ambrosius are now on the emeritti list of the Fluid Meters Committee. Perhaps the most important result gained from the Norman work is that it showed the necessity for careful measurement and control of the oil temperature, especially when metering oil with nozzles or orifices.

About 1948, after years of inactivity, the committee decided to conduct some additional tests on installation effects, and these were made near Rockville, Md. Probably the most important result from these tests was to show the effects of elbow shape. At Buffalo the elbows used had been welded miter joints. Welded miter elbows similar to those used at Buffalo were assembled and comparison tests made, then sets of the present well-curved elbows were substituted. The effects with the formed elbows were less than half those with welded elbows.

About 1951 some of the measurement men of the gas transmission companies became concerned about using the Columbus data with orifices in 30-inch and larger pipe lines. A suitable location for some comparison tests was offered near Refugio, Texas, where an adequate volume of gas for testing orifices in a 30-inch line, could be drawn from a transmission line, through a 30-inch pipe test loop and back into the transmission line. In the inlet line of the test loop was a 30-inch orifice flange union, then a bank of 8-10-inch reference meters, and in the return line of the loop a 30-inch orifice fitting. From these tests it was decided the coefficients from the Columbus tests could be extrapolated to the larger pipes.

5. Various Personalities in Early Flow Measurement

Now some brief comments about a few of the men who have been members of one or both committees. First, Lee Spink who was a member of both committees. I first met Lee during the tests at Cleveland in 1925. He took part in all of the field work from then through the tests at Hastings, W. Va. in 1928. He made up some of the equipment items for some tests, and contributed to the planning. Occasionally he was the recipient of a practical joke by others of the test group, which he took in good turn.

Another was John Overbeck, who passed on this last spring (1973). He grew up in W. Va. well away from any of the larger towns, and his schooling (high school) was such as was available there, adding to his education as he worked. Tom Kerr, for whom John worked for many years, said that in the early days if he asked John a question he could not answer he might stay up most all night to have an answer the next day. John had an exceptional ability for seeing a way around an obstacle to a piping layout or a test setup. In later years Sam Beitler and I often called on Johnny for advice in such matters. For many years he was a member of the Gas Measurement Committee, and took part in all of the field tests along with Lee Spink.

Ed S. Smith, a member of our Fluid Meters Committee for some 20 years, was nicknamed "Ed-no-dot-Smith" because his given name was simply "Ed." For the 1929 Engineering Conference in Tokyo, Japan, Ed submitted a paper on Quantity-Rate Fluid Meters, and which was printed in ASME Transactions in 1930. The important item in the paper applies to metering compressible fluids with differential pressure meters. Ed proposed the use of the compound ratio of differential pressure/absolute static pressure over the ratio of the specific heats, and to which he gave the name "acoustic ratio." Dr. Buckingham used this ratio in the correlation of the test data and the formulation of the expansion factor equation now used with orifice meters. In one of Buckingham's papers he credits Ed with the original proposal of the acoustic ratio.

Professor W. S. Pardoe was another individualistic member of our Fluid Meters Committee, who on occasion was very vigorously outspoken. The Venturi tube was his particular favorite among fluid meters, and he calibrated many in his laboratory at the University of Pennsylvania, in Philadelphia. However, some of us did not have quite the same degree of confidence in his plots of coefficients as he claimed because his points always fell very close to a nice smooth curve. He always reported his data and comments as well as plotted values on cross section paper, with his name prominently placed on each sheet. This at times was very troublesome to the ASME publications group.

At one of the annual meetings the Fluid Meters Committee had no papers for a technical session, instead most of an afternoon was devoted to a somewhat informal debate. I do not know what plans for it had been made ahead, but probably some. The subject debated was the use and validity of dimensional analysis as a tool in correlating experimental data and the formulating of empirical equations. Dr. Buckingham and Ed Smith were the affirmative speakers while Professor Pardoe and Jacob Spitzglass said no. Of course Pigott was the moderator. At times the discussion was fast and spirited, almost vitriolic. Then the discussion would calm down, and if it became too quiet Pigott would inject a question or remark and start it off again. This provided a most interesting session for all, even the debators.

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

Fluid flow is a diverse field concerned with the motion of a wide variety of fluids encountered both in daily life and in scientific applications. It encompasses movement of weather systems by atmospheric winds, travel and dispersion of air pollutants, flow around aircraft and spacecraft bodies, oil and gas pipeline flow, irrigation and waste water flow, and many others. The types of fluid motions encountered in descriptions of these phenomena include closed-conduit, open channel, supersonic, subsonic, steady, unsteady, laminar, and turbulent flow. Measurements of the properties of these flows are instrumental in the functioning of the nation's industries and the advancement of scientific technology, and impact the lives of every consumer.

This report presents the concept of the National Measurement System for Fluid Flow as it exists today and the activities and mechanisms employed within it to generate and implement measurement data. The system structure is presented, and data and information gathered on the interrelationships between the identifiable parts are reported. To further the study, more than 200 contacts were made with trade associations, government agencies, private companies, universities and laboratories.

This study was conducted over the time span June 1973 to December 1975.

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)*

Aerodynamics; air flow; flow measurement; fluid flow; fluid metering; hydraulics

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