WATER TUNNEL DESIGN AND RELATED INSTRUMENTATION

CONSIDERATIONS AND A SELECTED BIBLIOGRAPHY ON INCOMPRESSIBLE

INTERNAL FLUID FLOW

by

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ABSTRACT

This report presents the results of a state-of-the-art survey on flow-tunnel design and related instrumentation for tunnels using water or liquid nitrogen as the working fluid. The scope of the survey is purposely narrowed by considerations of the proposed tunnel to be designed and built at NASA's George C. Marshall Space Flight Center (MSFC). Initial application of the proposed tunnel will include internal-fluid-flow studies of cryogenic fuel-system components or combinations thereof.

Major considerations applicable to the principal components of the proposed tunnel are presented. Some specific recommendations are also presented for consideration by those who will undertake the actual design and operation of the proposed tunnel.

Literature Cited are listed at the end of the report for further detailed study. Many of these references are, in themselves, design studies for liquid-flow tunnels or flow-tunnel sections.

Also included is a selected bibliography on internal fluid flow, with a brief description of each. The categories included are pressure drop; flow patterns including curved flows, mixing, and flow measurement; visualization including flow modeling, cavitation, and transients; flow of cryogenic fluids; and two-phase flow.

FOREWORD

The purpose of this program is to provide a state-of-the-art literature survey on water-tunnel design and related instrumentation and a selected bibliography on internal fluid flow. Special considerations for the tunnel being contemplated and t..ken into account in this survey include:

1. The tunnel is to have flow conditions of 4500 gallons per minute and 70 feet of H_2O pressure head across the pump to provide a velocity of 50 feet per second through a 6-inch-diameter test section.

2. The tunnel is to be used to study internal-flow phenomena.

3. The fluids of interest include water and liquid nitrogen.

Information for this report was obtained from an open-literature search at the Battelle library; the card-index file in the RSIC library at the Redstone Arsenal; the Technical Abstracts Bulletins published by the Defense Documentation Center; and visits to the Ordnance Research Laboratory at the Pennsylvania State University and the NASA Lewis Research Center.

It is difficult to specify the exact sources covered in the bibliography on internal fluid flow, since the compilation includes many items from personal files. A complete search of American Society of Mechanical Engineers (ASME) literature and the Proceedings of the Cryogenic Engineering Conferences for the past 5 years was made. In addition, other references came from the personal scanning over the last 5 to 10 years, by people working in this area, of the Technical Abstracts Bulletins, Atomic Energy Commission (AEC) literature, and many pertinent journals.

References on internal fluid flow are listed alphabetically within each category by major personal author for books and journal articles, and by corporate source for document and report-type literature. A separate personal-author index (indicating reference numbers) is also included for all references in the bibliography. Although some references apply to more than one category, they have been summarized only in the most pertinent category. Cross references to other sections are listed by reference number at the end of each section.

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Section I. INTRODUCTION

Water tunnels for hydraulic studies date back over 50 years. Even though these early tunnels[1] were used primarily to investigate external flow, tunnel-design technology has continued during this period and also has been improved through tunnel-design studies. Because of the extensive and detailed design studies that have been conducted on tunnels and tunnel components, this report presents the water-tunnel information only briefly, and references the sources for more detailed study. Available information is also presented on cryogenic tunnels and on tunnel instrumentation. The specific tunnel under consideration is required to provide a uniform maximum velocity of 50 feet per second through a 6-inch-diameter test section. Such a tunnel would include a replaceable test section, diffuser, pump, and settling and contraction section, comprising a closed-loop system. Special attention was given to a requirement that the proposed tunnel could utilize liquid nitrogen as an alternative working fluid.

In the general design of the fixed-flow circuit, special attention must be directed toward cavitation inception and prevention, temperature control, and flow geometry as it affects the velocity profile at the test-section entrance. The design of the convergent section is critical in that at least partial corrections in undesirable upstream-flow profiles can be accomplished with proper design. The use of vaned elbows and a conservative diffusion angle is considered important. The use of a centrifugal pump is indicated, and suitable pumps are available from conventional sources which incorporate seals and bearings suitable for cryogenic use. Although the control of working-fluid temperature and heat pickup are important when water is used as the working fluid, this aspect becomes paramount when cryogenic fluids are used. The use of a cryogenic bath appears warranted for the proposed tunnel. Adequate information is available to support the choise of basic construction materials, coatings, and insulation for a cryogenic tunnel.

Instrumentation and techniques are available for measuring pressures, temperatures, etc., as may be required for operation with either water or liquid nitrogen as the working fluid.

These observations have been incorporated into general recommendations to guide the design of the proposed tunnel. If these considerations are adequately handled, the proposed insertion of missile components within the test section appears to be realistic.

The selected bibliography is a compilation of references on internal fluid flow. Rather than being limited strictly to a library literature search, it includes appropriate items taken from personal files and references of a number of people working in this area. In addition to a brief description of each reference, in many cases some evaluation of its usefulness has been given.

In general, only incompressible, turbulent, internal flow has been stressed. However, references are included from outside this area if any parts of the work described have application in this area. The references have been divided into seven categories as follows:

1. Pressure Drop

2. Flow Patterns Including Curved Flows

3. Mixing

4. Flow Measurement and Visualization Including Flow Modeling

5. Cavitation and Transients

6. Flow of Cryogenic Fluids

7. Two-Phase Flow.

Because the main interest in two-phase flow phenomena would be in the area of cavitation, this was made a separate category. The general two-phase flow category is quite brief, listing mainly other survey-type reports that would provide access to the vast amount of literature existing in this area.

Section II. FLOW-TUNNEL CONSIDERATIONS

A large variety of flow tunnels have been constructed for various types of hydraulic investigations.[1] Because this state-of-the-art study is concerned with the collection of information which will assist in the design of a tunnel for investigating internal flow, the study is limited to the available literature on the closed-jet type of tunnel and tunnel components. Based on considerations of the flow rate of the planned tunnel, economy, desired visual capability within the test-section region, and nonautomated instrumentation for the tunnel (at least initially), the study is further limited to information on the design of closed-circuit types of tunnels.

1. Flow Circuit

A number of studies have been performed that have resulted in relatively complete guidelines for the design of closed-circuit water tunnels. Notable among these are the studies done at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota[2] and at the ordnance Research Laboratory of Pennsylvania State University.[3,4,5,6,7] Subsequently, the theory and procedures included in these reports have been used to design tunnel systems.[1,8] Additional references[9,10,11,12,13,14] were later identified as pertinent to water-tunnel design, but most of these were not available to this study. Another source of information on existing water-tunnel facilities is the Proceedings of the ASME Symposium on Cavitation Research and Techniques.[15] Papers presented at this symposium describe tunnel facilities and techniques used for studying cavitation in fluid systems. Because the prevention of cavitation is essential to the economic operation of most fluid systems, much of the information presented during the symposium is pertinent to the design of water-tunnel facilities.

Most of the work reported in the above cited literature was done during the early 1950's. Because of this, advances in materials and material-protection techniques for flow tunnels have outdated some of the design information. However, because structural-design information is a minimum in most of these reports and because fundamental hydrodynamic theories have changed little over the years, the reported information is still very pertinent to water-tunnel design.

Figure 1 presents one possible flow-circuit configuration for a water or liquid-nitrogen tunnel, incorporating good design features based only on a preliminary study of the above references and from discussions with NASA-Lewis Research Center and Pennsylvania State University personnel. These features include:

1. An area-contraction ratio between 9 to 16, with values in the lower portion of this range preferred.

2. A heat exchanger (if needed) located at the minimum fluid-velocity portion of the circuit to reduce flow losses.

3. A maximum of 5 degrees total-diffusion angle throughout the circuit to enhance uniform-flow conditions.

4. Corner-turning vanes to reduce energy losses and minimize disturbances to the tunnel test-section flow.

5. A minimum amount of the flow circuit located outside the liquid-nitrogen cooling bath. The only part of the circuit not in the bath is that part which requires changing to accommodate various missile fuel-system configurations. This part requires the installation of a suitable insulation material.

6. Supports that allow for tunnel contraction and expansion due to large temperature changes on cooldown and warmup when using liquid nitrogen as the test fluid.

The flow circuit in Figure 1 is similar to several existing tunnel configurations.[1,2] This type of recirculating tunnel consists of the high-velocity test section, a diffuser, a variable-speed pump, a settling region and contraction section, a heat exchanger, and elbow sections with turning vanes. A brief discussion follows pertaining to each of the above, with references identified for more detailed study.

a. Test Section

Because the primary purpose for the proposed tunnel is to test circuit components of missile cryogenic-fuel systems, the test section of the proposed tunnel is a replaceable section which can vary throughout the range of possible combined configurations of fuel-system components. The chief requirement placed on the tunnel, therefore, is that it must supply a steady, radially-uniform fluid stream to the entrance of the test section. Ross and McGinley[4] have developed
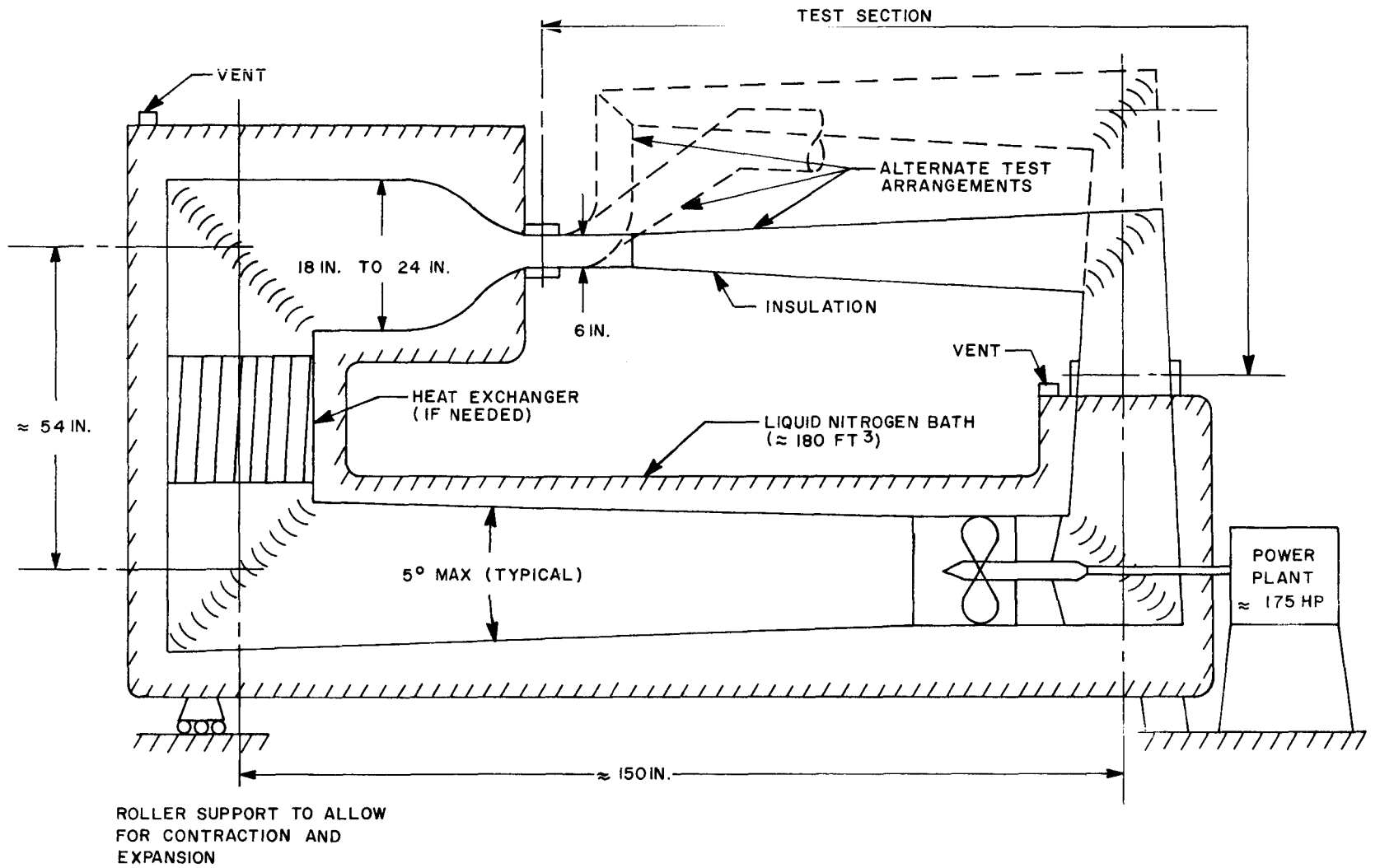
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Figure 1. Possible Flow-Circuit Configuration for Water or Liquid-Nitrogen Tunnel

equations for the growth of the boundary layer in the entrance region
as well as pressure and energy-head losses in working sections.
Theory is compared with experimental data in their studies of
closed-jet working sections.

Olson[14] has conducted studies on closed-jet working sections
with divergent walls where it is desirable to eliminate the static-
pressure gradient or to permit tests to be made at a lower cavitation
index. Ripken[2] has also conducted detailed studies that are appropriate
to the design of the test section of the proposed tunnel.

To achieve realistic results of tests of the fuel-system components,
the components should have inlet-velocity profiles that are representa-
tive of the profiles that exist in the actual system of which the component
is a part. The working-fluid velocity profile can change from a very
uniform shape with a minimum thickness of boundary layer to a shape
in which the majority of the flow cross section is in the boundary layer.
These changes are a function of the turbulence level in the working
fluid and the length of fluid run in a constant cross section cylindrical
section. Therefore, control of the shape of the velocity profile for
realism can best be achieved by varying the length of the cylindrical
portion of the test section just upstream of the test component (within
reason, of course) and by introducing controlled turbulence into the
working fluid.

b.   Contraction Section

The achievement of radial uniformity of fluid velocity
at the entrance to the test section is a function of the configuration
of the contraction section and the velocity distribution of the flow
entering the contraction section.

Ripken points out that a properly-shaped contraction will provide
a strong corrective action to velocity variations in a fluid stream,
providing that a substantially-uniform pressure distribution can
be achieved in the flow sections both preceding and following the con-
traction. Uniform pressure distributions are a result of maintaining
parallel (noneddying) flow in all sections of the flow circuit. Upstream
parallel flow is dependent upon the quality of the recirculating system,
i.e., in the proper design of the turning vanes, in the provision of
flow straighteners as necessary, etc., to provide for the prevention
of separation and the resultant eddying-flow patterns. The selection
of a proper contraction ratio can provide a velocity variation across
the entrance to the test stream of less than 1 percent. Based on
reasonable construction costs and the velocity variation figure of less

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than 1 percent, the contraction ratio usually required is from 9 to 15. The radius of curvature of the contraction boundary must never be great enough to cause the fluid to separate, owing to the centrifugal force of the fluid under curved flow being greater than the pressure forces acting on the fluid. Ripken details a number of different approaches taken to establish the shape of contraction curves that have been employed in American and European water tunnels. After presenting these analyses, he describes experimental studies that include the measurement of velocity distributions, separation-zone pressure distributions, and energy losses.

c. Diffuser Section and Vaned Elbows

The purpose of the diffuser section is to reduce the high-velocity test stream from the working section to a lower value throughout the remainder of the tunnel. This reduction of velocity serves a number of related purposes including a reduction in pumping-power costs owing to reduced frictional-energy losses (power varies as velocity cubed); the minimization of the destruction of the initial uniformity of the fluid motion while returning the test fluid through 360 degrees to the entrance of the working section; and the reduction in temperature rise of the working fluid or the reduction in heat-exchanger requirements with reduced frictional-energy losses. Ross and Robertson[3, 11, 12, 16] have conducted extensive flow studies in water-tunnel diffuser sections. These studies have included the development of an analytical method termed "Superposition Analysis" which yields good theoretical predictions of velocity profiles in diffusers. This method gave results that compared quite favorably with experimental data obtained in a 7.5-degree diffuser. Steele,[7] in summarizing the results of Ross and Robertson's design studies conducted for the 48-inch water tunnel at the Ordnance Research Laboratory of Pennsylvania State University, stated that "the optimum diffuser angle was a function of the total diffuser angle, the effective working section length, and effective working section diameter."

Ripken[2] also describes numerous considerations for the design of diffusers for flow tunnels. He concludes that 5- to 7-degree diffusers may be used, although the 5-degree diffuser is preferable, owing to the decreased likelihood of separation with subsequent cavitation occurring.

In the flow circuit of Figure 1, diffusion continues through the first two vaned elbows. This design approach is taken to provide for a flow tunnel of decreased length to enhance the use of a cryogenic

bath for insulation when using liquid nitrogen as the test fluid. It is pertinent to point out that a careful study of the vaned elbows with such a design is needed. Ripken describes extensive design studies on vaned elbows. Similar studies appear desirable for the proposed tunnel.

d. Pumps

The information on pumps and their application in facilities comparable to the proposed water tunnel is extensive.[17, 18, 19] The fundamentals of this general subject will not be reviewed here. It can be stated, however, that suitable pumps are available for application such as in the proposed water tunnel.

Based on the flow-tunnel requirement of a flow rate up to 4500 gallons per minute, a maximum head of 75- to 100-feet H_2O across the pump, and a maximum shaft speed of 1750 revolutions per minute, the specific speed of the pump can be determined from the relation:

$$N_S = \frac{N\sqrt{Q}}{H^{3/4}} \quad ,$$

where NS is the specific speed, N is the pump speed in revolutions per minute, Q is the pump discharge in gallons per minute, and H is the pump head in feet.

This relation yields a specific speed from 3700 to 4600 for a 75- to 100-foot head, which indicates that a centrifugal pump would be preferred for the proposed tunnel. Sandercock[20] at Lewis Laboratories confirmed the preference for a centribugal pump and also suggested that an inducer stage ahead of the centrifugal pump might be desirable to decrease the likelihood of cavitation with low pump-inlet pressure. Acosta[21] and Montgomery[22] have conducted inducer studies for cryogenic pumps. The inducer is an extension of the main rotor, enabling it to be run at a higher speed than the impeller on a coaxial shaft. The resultant additional head rise enables the main-pump impeller to run cavitation free.

Another pump consideration, in addition to freedom from cavitation, is that the fluid stream from the pump should be constant in flow and free of pulsations. Also, the flow should be free of rotation at all rates of discharge.

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The pumping of cryogenic liquids such as liquid nitrogen introduces a number of special considerations. Jacobs, Martin, Van Wylen, Birmingham, and Hardy[23,24] have conducted experimental studies on pumping liquefied gases and have identified bearings and seals as two of the major problem areas for such pumps. Standard ball bearings fabricated from AISI 52100 steel and Type 440C stainless steel and containing suitable nonmetallic separators as substitutes for metallic separators[25] can provide satisfactory bearing service when submerged in liquid nitrogen. Carbon seals are normally used in liquid-nitrogen pumps at NASA-Lewis Research Center; pump details can be discussed with the pump supplier.

e. Heat Exchanger

Because the energy input of the pump shaft increases the enthalpy of the test fluid, it may be necessary to incorporate a heat exchanger into the proposed tunnel in order to maintain the working fluid at a constant temperature. Steele describes in rather complete detail the steps involved in determining the cooling requirements and heat-exchanger design for a water tunnel. Ripken[2] and Lehman[6] also discuss cooling requirements for water-tunnel design. Procedures identified in these references are straightforward once the tunnel dimensions, materials, and operating parameters are established. Additional requirements for a cryogenic tunnel are discussed in a later section of this report. The use of a bath or immersion system as dictated for cryogenic-fluid handling may suffice for temperature control when using water as the working fluid. In either case, the effects of the temperature-control device on the temperature profiles at the test-section entrance must be considered.

f. Materials

In most of the larger water tunnels,[1,6,7,15] economics have dictated the choice of steel as the major tunnel material with a protective coating applied to prevent corrosion. Steele[7] describes "Lithglow," a phenol-base plastic, and "Durofilm," a vinyl plastic-base paint as examples of protective coatings used in water tunnels.

Materials must obviously be selected carefully for this proposed water tunnel because of the intention of using liquid nitrogen as the working fluid in the future.

Because of expansion and contraction that would occur with liquid nitrogen, carbon steel with a protective coating is undoubtedly unsatisfactory as a tunnel material. Based on properties of the

materials, stainless steel or anodized aluminum appear to be the most promising materials for the proposed tunnel. Campbell[26] and Kaufman[27] have published data that support this statement.

Ruggeri and Gelder[28] have set up a small tunnel at NASA-Lewis Research Center that will handle cryogenic as well as most ordinary liquids. This flow tunnel is fabricated from 6061 T-6 aluminum and has a heavy anodized treatment for surface protection. Double Lucite panels having a 2-inch thickness are used for the windows. A bath surrounding the tunnel is fabricated of 304 stainless steel and is insulated with $\frac{1}{2}$-inch-thick composition corkboard bonded directly to the stainless steel. These materials have proven satisfactory in this tunnel application.

2. Cryogenic Aspects of a Flow Circuit

This state-of-the-art survey on flow-tunnel technology has considered both water and liquid nitrogen as test fluids. One of the most difficult problems to solve in the design of a flow circuit for cryogenic fluids is the control of temperatures to prevent liquid vaporization.

Figure 2 shows the variation of temperature and pressure for vaporization of liquid nitrogen. The stagnation temperature-pressure operating point of the liquid nitrogen must be maintained at such a level that temperature increased due to friction from power input and pressure decreased due to circuit configuration do not cause vaporization. Figure 2 also shows that the control of temperature must be more precise than the control of pressure. Note that a 30-fold increase in pressure (from 1 to 30 atm) at 140°R increases the temperature margin to vaporization by only 83°R. This shows that heat transfer and heat additions to the working fluid about the flow circuit must be held to a minimum regardless of the planned test pressures and, therefore, the choice of insulation surrounding the tunnel is critical.

There are several ways of insulating all or parts of a cryogenic-flow loop. These include immersion in a cryogenic bath, insulation by vacuum, and insulation by a low-conductivity insulating material. The preferred method, according to the personnel at NASA-Lewis Research Center, is immersion of the tunnel in a cryogenic-liquid bath. If this method is used, the total size of the flow circuit should obviously be kept to a minimum so that the quantity of fluid required for the bath does not become excessive. Also, by holding the flow-circuit size to a minimum, the heat input due to fluid friction is held to a minimum as the circuit boundaries are held to a minimum.

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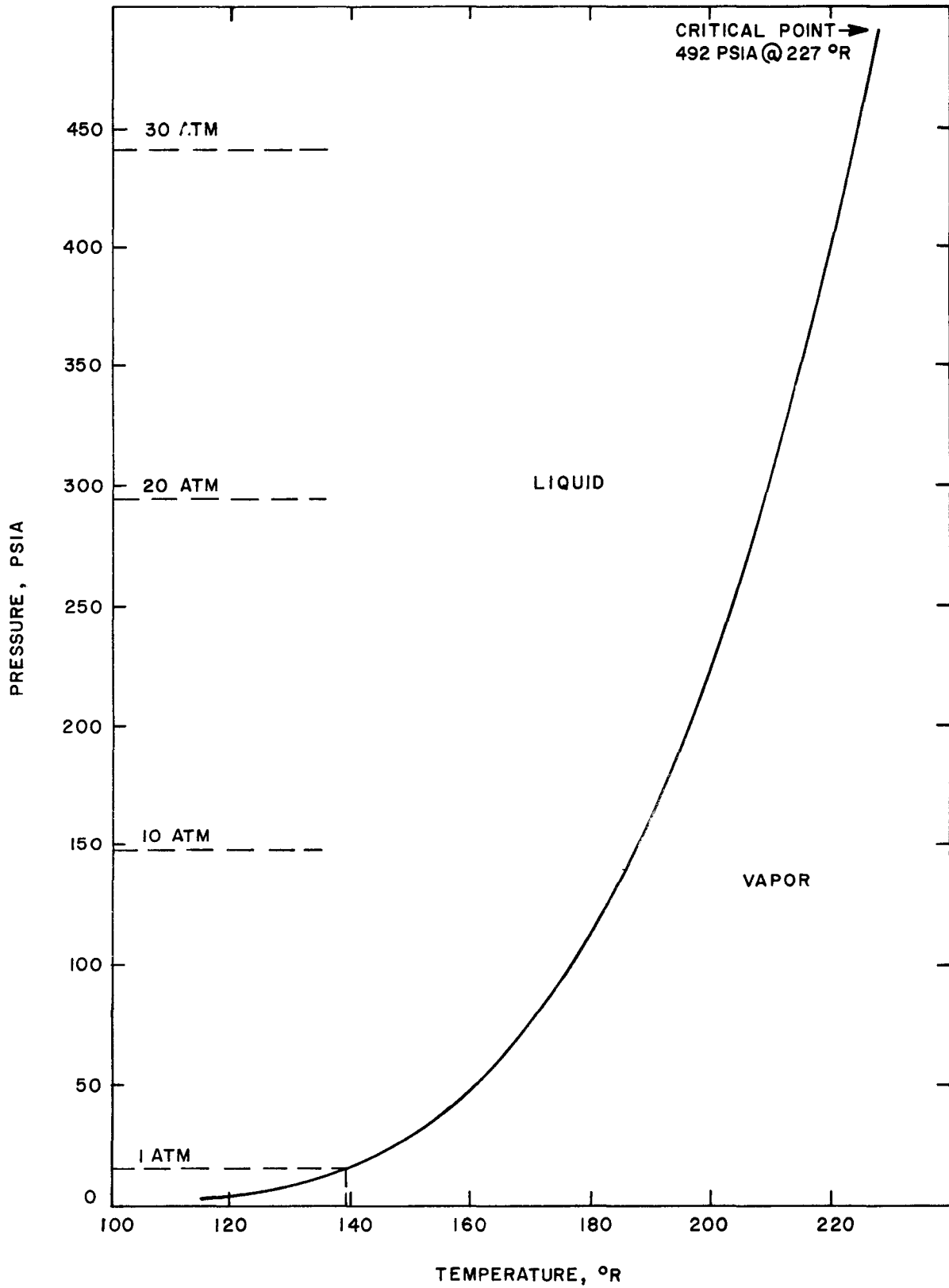
Figure 2. Temperature and Pressure for Vaporization of Nitrogen

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Figure 1 shows a flow-circuit design that makes use of a cryogenic bath around all of the flow circuit except the working section. This arrangement has the advantage of a cryogenic bath, yet the convenience of ready access to the working section. This is particularly desirable if flow visualization during testing is to be utilized. Special insulations of either fibers, foams, or powders can be used on the working section. Moeller, Loser, Snyder, and Hopkins[29] have compiled thermophysical-property data for such insulating materials.

Section III. INSTRUMENTATION

Instrumentation for a liquid-tunnel system may be considered to include two specific areas; direct instrumentation for the measurement and study of phenomena in the tunnel test section, and instrumentation or controls associated with the tunnel operation.

The types of instrumentation may vary from one test-configuration installation to another, depending upon the specific nature of the planned tests. Most tunnels utilize static-pressure taps across the contraction section that are connected to appropriate manometers or other pressure read-out methods and calibrated to measured test-section velocities to facilitate monitoring velocities during tests. Pressures in the working section are measurable by conventional pressure orifices connected to pressure transducers located outside the tunnel. Ruggeri and Gelder[30] describe in considerable detail the instrumentation in the NASA-Lewis Research Center cryogenic tunnel. Copper-constantan thermocouples are used to measure inner and outer-wall temperatures as well as temperatures in the cavitated region. Absolute values of tunnel-liquid temperature are measured upstream of the contraction nozzle to within $\pm 0.05°F$ by means of a calibrated platinum-resistance thermometer. Photographic equipment is utilized to photograph cavitation phenomena through the Lucite test-section windows. Treaster[31] describes in detail the calibration of the NASA Ultra-High-Speed Cavitation Tunnel at Pennsylvania State University, which is the water-tunnel counterpart to the NASA-Lewis Research Center Cryogenic Tunnel. Information is given in that report of procedures followed for determining velocity and pressure distributions across the test-section cross section, the calibration of velocity to the pressure difference across the contaction section, and the determination of the static-pressure distribution on the test-section walls.

The Instrument Society of America has published a Transducer Compendium[32] covering all known sources of transducers complete with their characteristics. It is suggested that this reference be consulted for appropriate transducers to convert pressures to a suitable read-out for input to recording systems.

Pressure-control systems for water tunnels, along with pertinent auxiliary equipment, are described by Steele.[7] Either one form or another of the approaches described is necessary to control the working static pressure. Either the Semiautomatic Control as by Cartesian Manostat or the Fully-Automatic Control systems are preferred to a manual system.

Ruggeri and Gelder[28] discuss instrumentation and static-pressure
control for the cryogenic tunnel at NASA-Lewis Research Center
when using water as the working fluid. This is an excellent report
because, in addition to describing the tunnel facilities and instrumen-
tation, it presents procedures and data-reduction methods for
cavitation studies.

Section IV. RECOMMENDATIONS

Although the purpose of this study was to conduct a state-of-the-art survey of water and cryogenic-tunnel design, several lasting impressions were formed during the study that are pertinent. Because of the nature of these impressions, they are best formulated as recommendations that apply to the design and development of the facility. These recommendations are:

1. Design the flow circuit and its auxiliary equipment for a cryogenic working fluid rather than for water. The most stringent requirements that will be placed on the system will be those due to the pumping, pressure regulating, and measuring functions of the tunnel while using a cryogenic working fluid. Designing the equipment necessary to perform these functions with a cryogenic fluid should result in an adequate water system, but designing for water will not necessarily yield an adequate cryogenic system.

2. Perform detailed experimental studies on critical components of the flow circuit for the purpose of optimizing these components. For example, study the spacing and angular setting of the turning vanes at a circuit corner to develop a configuration that will cause a minimum pressure loss. Perform the study by experimental and not by analytical means, because the exact analytical expressions required for the task are too cumbersome to handle.

3. Consider, during the design and development phases of the tunnel, the need for building and testing a scaled model of the system. Very often, the problems solved by this approach result in ultimate savings exceeding the costs of the model tunnel.

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oscillating flow was observed
at low ratios of total flow to
nozzle flow; and empirical
correlation for predicting the
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74. NASA Lewis Research Center, TN-D-2088, "Cavitation of Nitrogen in a Tunnel Venturi," Ruggeri, R. S., and Gelder, T. F., 33 pp, February 1964.

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75. Numachi, F., Kobayashi, R., and Kamiyama, S., "Effect of Cavitation on the Accuracy of Herschel-Type Venturi Tubes," ASME Transactions, Journal of Basic Engineering, Vol. 84, Ser. D, No. 3, pp 351-362, September 1962.

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Test results on the net positive suction-heat (NPSH) requirement for centrifugal pumps handling water up to 420°F, some hydrocarbons, and Freon-11 are presented. The cavitation process is discussed, and methods of prediction for all liquids are proposed.

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84. Stripling, L. B., and Acosta, A. J., "Cavitation in Turbo-pumps," ASME Transactions, Journal of Basic Engineering, Vol. 84, Ser. D, No. 3, pp 326-350, September 1962.

Cavitation-performance data of several helical inducers for various flow coefficients are correlated with existing theory. A method is developed which employs semiempirical-correlation coefficients to supplement idealized free-streamline solutions.

85. Wood, G. M., Murphy, J. S., and Farquhar, J., "An Experimental Study of Cavitation in a Mixed-Flow Pump Impeller," ASME Transactions, Journal of Basic Engineering, Vol. 82, Ser. D, No. 4, pp 929-940, December 1960.

A mixed-flow impeller design was tested in a closed water loop to study the effects of cavitation on hydraulic perform-ance, and the results are compared with the work of other investigators. Two idealized-flow models for incipient cavitation were derived to illustrate limits of cavitation design.

FLOW OF CRYOGENIC FLUIDS

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A model is developed to predict the cooldown time of cryogenic systems. Although the model does not consider the dynamics of the system, it has been used with success and is apparently the only published method available.

87. Corruccini, R. J., "Tempera-ture Measurements in Cryogenic Engineering," Advances in Cryogenic Engineering, Vol. 8, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1963, pp 315-333.

A summary of temperature-measurement techniques cover-ing the entire cryogenic range is presented. Calibration methods and temperature scales are also discussed. An extensive bibliography is included.

88. Jacobs, R. B., "How Low Temperatures Encountered Affect Design, Installation, and Operation of Cryogenic Piping Systems," Heating, Piping, and Air Conditioning, Vol. 32 (5), pp 143-156, May 1960.

Fluid-flow considerations, pumps, and instrumentation are stressed in this second of a two-part series on design problems unique to cryogenic piping systems.

89. Jacobs, R. B., "What to Consider When Designing Cryogenic Piping Systems," Heating, Piping, and Air Conditioning, Vol. 32 (2), pp 130-140, February 1960.

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Special problems in the design of piping for cryogenic fluids are considered. An economic study of the use of various vacuum insulations is included. Typical connections, other components, and materials of construction are also discussed.

91. National Bureau of Standards, Cryogenic Engineering Laboratory, Boulder, Colorado, Circular 596, "Single-Phase Transfer of Liquefied Gases," Jacobs, R. B., 42 pp, December 1958.

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92. National Bureau of Standards, Cryogenic Engineering Laboratory, Boulder, Colorado, Report No. 3569, "Pumping Cryogenic Liquids," Jacobs, R. B., Martin, K. B., Van Wylen, G. J., and Birmingham, B. W.

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93. National Bureau of Standards, Cryogenic Engineering Laboratory, Boulder, Colorado, NBS Technical Note No. 129, "The Thermodynamic Properties of Nitrogen from 64° to 300°K Between 0.1 and 200 Atmospheres," Strobridge, T. R., January 1962.

This report includes P-V-T as well as enthalpy and entropy-property tables for nitrogen in the ranges listed in the title. A temperature-entropy chart is also available separately.

94. Richards, R. J., Jacobs, R. B., and Pestalozzi, W. J., "Measurement of the Flow of Liquefied Gases with Sharp-Edged Orifices," Advances in Cryogenic Engineering, Vol. 4, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1960, pp 272-285.

This report demonstrates that the sharp-edged orifice can be used with liquefied gases. There are certain limitations, however, and these are discussed.

95. Purcell, J. R., Schmidt, A. F., and Jacobs, R. B., "The Venturi Tube as a Liquefied Gas Flow-Measuring Device," Advances in Cryogenic Engineering, Vol. 5, K. D. Timmerhaus, Editor, Plenum Press, Inc., New York, 1960, pp 282-288.

Tests on a venturi tube used for liquid-hydrogen metering are reported. Experimental accuracies are listed and discussed to the extent that they influence the test results. The usefulness as well as the limitations of the venturi as a low-temperature fluid meter are indicated.

96. Scott, R. B., Cryogenic Engineering, D. Van Nostrand Co., Inc., Princeton, New Jersey, 1959.

This book is the standard reference in the field of cryogenic engineering. It consolidates in a single text information from numerous sources and presents it in easily understandable terms.

97. Surdi, V. L., and Romaine, D., "Fundamentals of Low-Temperature Piping Design," Hydrocarbon Processing and Petroleum Refiner, Vol. 43 (6), pp 116-124, June 1964.

A general discussion of low-temperature piping is presented. Particular emphasis is placed on piping materials, gasket materials, and insulation.

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TWO-PHASE FLOW

98. Argonne National Laboratory, Report No. ANL-6734, "Two-Phase (Gas-Liquid) System: Heat Transfer and Hydraulics. An Annotated Bibliography," Kipple, R. R., and Tung, T. V., 428 pp, July 1963.

A very extensive bibliography is presented covering the areas of heat transfer and hydraulics in gas-liquid systems. Abstracts are given for nearly all references.

99. Hatch, M. R., and Jacobs, R. B., "Prediction of Pressure Drop in Two-Phase Single-Component Fluid Flow," American Institute of Chemical Engineering Journal, Vol. 8 (1), pp 18-25, March 1962.

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This report presents the results of a state-of-the-art survey on flow-tunnel design and related instrumentation for tunnels using water or liquid nitrogen as the working fluid. The scope of the survey is purposely narrowed by considerations of the proposed tunnel to be designed and built at the NASA Marshall Space Flight Center. Initial application of the proposed tunnel will include internal-fluid-flow studies of cryogenic fuel-system components or combinations thereof.

Major considerations applicable to the principal components of the proposed tunnel are presented. Some specific recommendations are also presented for consideration by those who will undertake the actual design and operation of the proposed tunnel.

Literature cited is listed at the end of the report for further detailed study. Many of these references are, in themselves, design studies for liquid flow tunnels or flow-tunnel sections.

Also included is a compilation of references on internal fluid flow with a brief description of each. The categories included are pressure drop, flow patterns including curved flows, mixing, flow measurement and visualization including flow modeling, cavitation and transients, flow of cryogenic fluids, and two-phase flow.

14. KEY WORDS	LINK A		LINK B		LINK C	
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