https://ntrs.nasa.gov/search.jsp?R=19750016691 2020-03-22T21:59:21+00:00Z

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

(NASA-CR-142955) MATERIALS AND CONSTRUCTION TECHNIQUES FOR CRYOGENIC WIND TUNNEL FACILITIES FOR INSTRUCTION/RESEARCH USE (Rose-Hulman Inst., Terra Haute, Ind.) 72 p HC $4.25 CSCL 14B G3/09

N75-24763

Unclas 25327

JUL 1975
RECEIVED
NASA STI FACILITY
INPUT BRANCH

DEPARTMENT OF MECHANICAL AND CIVIL ENGINEERING

ROSE-HULMAN INSTITUTE OF TECHNOLOGY

REPORT ME 75-1-SFM/ATR

Materials and Construction Techniques For Cryogenic Wind Tunnel Facilities For Instruction/Research Use

Stephen Fredrick Morse
Alan Thomas Roper

Study supported by the National
Aeronautics and Space Administration
Under NASA Grant: NSG 1154

Terre Haute, Indiana

June 1975

Acknowledgments

Many people have made contributions to the study which is the subject of this thesis. I would like to express my thanks to: The staff at the NASA Langley Research Center who, by their continuing interest in education and research, made possible a first-hand look at the development of the cryogenic wind tunnel; my Technical Advisor and co-workers in the Advanced Experimental Methods Section of the Subsonic-Transonic Aerodynamics Branch who have contributed greatly to my understanding of the unique capabilities and challenges of the cryogenic tunnel. In particular, acknowledgment is made to Dr. Robert A. Kilgore for his patient explanations concerning the design and operation of the Langley 1/3-meter Transonic Cryogenic Tunnel; my academic advisor, Dr. Alan T. Roper and the Dean of Graduate Studies, Dr. Noel E. Moore. They have been a constant source of inspiration, help, and encouragement.

ABSTRACT

The results of the cryogenic wind tunnel program conducted at NASA Langley Research Center are complete and presented to provide a starting point for the design of an instructional/research wind tunnel facility. The advantages of the cryogenic concept are discussed and operating envelopes for a representative facility are presented to indicate the range and mode of operation possible. Special attention is given to the design, construction and materials problems peculiar to cryogenic wind tunnels. The control system for operation of a cryogenic tunnel is considered and a portion of a linearized mathematical model is developed to assist in determining the tunnel dynamic characteristics.

SUMMARY

A cryogenic wind tunnel has been designed, constructed, and is being operated at the NASA Langley Research Center as a research facility. The experience gained during this project has demonstrated that the cryogenic tunnel offers an attractive solution to the problem of high Reynolds number flow simulation at levels of complexity with direct and operating costs acceptal to educational institutions currently operating instructional/ research wind tunnel facilities. In this report, the results of the NASA cryogenic wind tunnel project are compiled and presented in such a fashion as to provide a starting point for the design of such a facility.

The inherent advantages of the cryogenic concept are discussed and operating envelopes are presented which indicate the range and mode of operation which is possible with such a facility.

Experience has demonstrated that cooling to cryogenic temperatures by spraying liquid nitrogen directly into the tunnel circuit imposes some restrictions on the materials and construction techniques employed. Special attention is therefore given to design, construction and materials problems peculiar to cryogenic tunnels. The shell of the Langley 1/3-meter Transonic Cryogenic Tunnel is constructed of 6061-T6 aluminum plate which has performed well in service. A literature search indicates that certain other aluminum alloys will provide cost-effective facilities with no increase in difficulty of construction while reducing the required tunnel shell thickness. Reports have also been studied

which indicate that satisfactory results can be achieved using fiberglass-reinforced epoxy resins for structural components with due regard to the safety of operating personnel although burst tests will be required for such a structure.

The control system for the operation of a cryogenic wind tunnel is considered and a portion of a linearized mathematical model has been developed to assist in determining the dynamic characteristics of the wind tunnel circuit. The control system resulting from these linear approximations is adequate for maintaining tunnel operating conditions. Nonlinearities and interactions of the control loops, however, are important where large changes in tunnel operating parameters are involved such as initially setting conditions at the start of a test run.

INTRODUCTION

High Reynolds Number Requirements

Aerodynamic development in the United States and elsewhere has been strongly influenced by advances in the state of the art of flow simulation, particularly wind tunnel testing. The increased sophistication of aerodynamic design and the attendant requirements for high Reynolds number flows for adequate simulation have driven the cost of wind tunnel construction and operation to a nearly prohibitive level for many smaller industrial organizations and most educational institutions.

Additional considerations associated with modern concepts of total energy consumption (including stored and operating

energy) and minimization of negative environmental impact (e.g. sound pressure levels, exhaust gas composition) have further complicated the problem. The performance characteristics of most existing or proposed wind tunnel facilities are compromised to some degree by one or more of the considerations outlined above.

Recognition of the need for increased testing capability within the existing framework of constraints has resulted in a consensus in the United States and Europe that there is an urgent need for wind tunnel facilities with improved Reynolds number capability and little or no increase in total energy consumption requirements.

The possibility of simulating high values of Reynolds number in existing wind tunnels has not been overlooked and many devices for causing boundary layer transition are in use in the various aeronautical laboratories. Fixing the location of boundary layer transition, however, is in itself seldom sufficient to duplicate the flow associated with full-scale Reynolds number.[1*]

Defining the level of Reynolds number which is required for valid extrapolation to full-scale conditions is a fundamental difficulty. Pope and Harper[2] conclude that for a 23012 airfoil, a test Reynolds number of 1.5×10^6 to 2.5×10^6 would be needed if extrapolation of wind tunnel drag data is intended. Agreement on $C_{L,max}$ within $\pm$ 0.1 was obtained when data from a Reynolds number of 1.5×10^6 were extrapolated to 26×10^6 by the method

* Superscripts refer to references listed at the close of this report.

of reference 4. The static longitudinal stability of airplanes having airfoils with forward thickness (such as the 23012, etc.) seems to change little from typical wind tunnel Reynolds numbers of around $1x10^6$ up to flight values of around $20x10^6$, but the extrapolation of pitching moment data when the airfoil thickness is well rearward (e.g. 65 to 66 series airfoils) is far more difficult. In the latter case trippers are of little value and satisfactory tests can be accomplished only at high Reynolds numbers. A similar situation exists for these airfoils, when the effect of Reynolds number on dynamic stability is examined.[1] Current research with two-dimensional airfoils indicate a need for Reynolds numbers of the order of 10^7 for accurate determination of section characteristics.

A review of the performance characteristics of several existing subsonic facilities and the foregoing evidence seems to support a recommendation that proposed new facilities for instruction be capable of providing a Reynolds number at subsonic speeds of at least $1.5x10^6$ based on the mean chord of a typical light airplane, and even higher Reynolds numbers for two-dimensional testing. Although there is incomplete agreement as to the exact level of Reynolds number which must be realized for valid testing, there is complete agreement that use of full-scale Reynolds number is preferable to extrapolation. The agreement as to the desirability of achieving full-scale Reynolds number contrasts sharply with the lack of agreement as how best to meet that need.

SYMBOLS

A	test-section area, m
a	speed of sound, m/s
C	any aerodynamic coefficient
C_D	drag coefficient, $\frac{\text{Drag}}{qS}$
C_L	lift coefficient, $\frac{\text{Lift}}{qS}$
c	heat capacity, J/kg-°K
$\bar{c}$	mean geometric chord, m
ER_t	tunnel energy ratio
GN_2	gaseous nitrogen
h	specific total enthalpy, J/kg
LN_2	liquid nitrogen
l	linear dimension of model or test section, m
M	Mach number
m	molecular weight
$\dot{m}$	mass flow rate, kg/s
P	drive power, W
p	pressure, atm (1 atm=101.3 kN/m^2)
q	free-stream dynamic pressure, N/m^2
R	Reynolds number
S	reference wing area, m^2
s	Laplace transformation variable
T	temperature, K(K=°C+273.15)
t	time
u	specific internal energy, J/kg
V	velocity, m/s
v	volume, m^3

Z	compressibility factor
2-D	two-dimensional
α	$\left.\frac{\partial \rho_v}{\partial T_t}\right\|_s$
β	$\left.\frac{\partial u_v}{\partial T_t}\right\|_s$
γ	ratio of specific heats
δ	$\left.\frac{\partial h_d}{\partial T_d}\right\|_s$
η	tunnel power factor
η'	efficiency of drive motor
μ	viscosity, N-s/m^2
ρ	density, kg/m^2
σ	mass of liquid nitrogen required to cool unit mass of material through given temperature range
χ	$\left.\frac{\partial h_l}{\partial T_l}\right\|_s$

Subscripts:

a	air
$\bar{c}$	mean geometric chord
d	discharge gas
F	Freon-12
f	fan
l	liquid
max	maximum
min	minimum
p	supply pipe

s	steady state value
t	stagnation conditions
v	vapor
w	tunnel wall
2-D	two-dimensional
∞	free stream conditions

Superscript:

'	deviation variable

METHODS FOR INCREASING TEST REYNOLDS NUMBER

The functional performance of a wind tunnel is defined primarily in terms of the run-time, Mach number range, and the maximum Reynolds number that can be achieved - always with the proviso that uncertainties due to wall constraints, sting effects, aeroelastic distortions, etc., are kept within acceptable bounds. The designer of any wind tunnel must find the most economic and effective manner to achieve the performance desired.

At a given Mach number, the Reynolds number may be increased by using a heavy test gas rather than air, by increasing the size of the tunnel and model, by increasing the operating pressure of the tunnel, or by reducing the test temperature. The method chosen to increase Reynolds number will, in general, also affect dynamic pressure, mass flow rate, and the power consumption of the tunnel as well as its initial and operating costs.

Increased Gas Density

The use of a heavy gas is a well-known method of achieving high Reynolds number. Freon-12 is one of the most suitable of the heavy gases for use in a wind tunnel, because it is stable and chemically inert, inexpensive, and readily available.[5] The relations developed in reference 6 may be used to assess the changes in R, q, $\dot{m}$, and P when Freon-12 rather than air is used as the test gas. The relevant properties of Freon-12 compared with those of air are as follows:

Molecular weight,

$$m_F = 4.17\ m_a$$

Ratio of specific heats,

$$\gamma_F = 0.81\ \gamma_a$$

Viscosity, $\mu_F = 0.69\ \mu_a$

If tunnel size, stagnation pressure, and stagnation temperature are assumed constant, these properties give the following comparative tunnel performance parameters[6]:

$$R_F = 2.66\ R_a$$

$$q_F = 0.81\ q_a$$

$$\dot{m}_F = 1.84\ \dot{m}_a$$

$$P_F = 0.36\ P_a$$

Thus, the use of Freon-12 as a test gas can result in significant increases in test Reynolds number coupled with reductions in both dynamic pressure and drive power. While the ratio of specific heats for Freon-12 is considerably different from that for air, the consequences of this are small in subsonic flow, and where

effects do exist, there are correction techniques.

Increases Size or Operating Pressure

The cost of engineering structures of a given complexity and standard of manufacture is usually proportional to their weight while the constant of proportionality is a function of the properties of the material(s) used in their manufacture. Since the weight, in turn, will vary with the pressure and linear scale, tunnel cost varies with pressure approximately according to a power law. For example, consider a family of designs of the same basic type. The thickness of the walls of pressure vessels vary with the pressure. For a simple pressure vessel the wall thickness and hence the weight is proportional to the difference between the internal pressure and external pressure. For more complex structures such as the tunnel shell, a different law will apply, but there will still be a definite relationship between pressure and cost. Similarly, the weight of the tunnel shell varies as the cube of its linear scale whereas the cost of the drive system varies approximately with the square of the tunnel size.

As a first approximation, therefore, we can take the capital cost as being governed by a relationship of the form:

$$\text{cost} \propto p^m l^n$$

where p is the pressure differential between the inside and the outside of the tunnel shell, and l a linear dimension. The indices <u>m</u> and <u>n</u> lie between 0.5 and 1.0 and between 2.0 and 3.0 respectively.[9]

Reduced Test Temperature

A third method of increasing Reynolds number is to decrease the temperature of the test gas. As the temperature is decreased, the density, ρ , increases and the viscosity, μ decreases. Both of these changes result in increased Reynolds number. With decreasing temperature, the speed of sound, a, decreases. For a given Mach number, this reduction results in a reduced velocity V which, while offsetting to some extent the increase in Reynolds number due to the changes in ρ and μ , provides advantages with respect to reduced dynamic pre sure, drive power, and energy consumption.

The effects of a reduction in temperature on the gas properties, test conditions, and drive power are illustrated in figure 1. For comparison purposes, a stagnation temperature of 300K for normal tunnels is assumed as a datum. It can be seen that an increase in Reynolds number by a factor of from one to more than six is obtained with no increase in dynamic pressure and with a large reduction in the required drive power.

The operational limits set by saturation and other real-gas effects have been studied by Kilgore, Goodyer, Adcock, and Davenport.[6] Further unpublished studies on saturation effects are being conducted by Hall and Adcock at Langley Research Center.

Research and Development Program of the Cryogenic Tunnel

Following a theoretical investigation initiated in October 1971 at the Langley Research Center aimed at extending the analysis of Smelt[8], an experimental program was conducted by Kilgore, et al, to verify theoretical predictions and to investigate problems associated with the design, construction and operation of a cryogenic wind tunnel. The experimental program consisted of building and operating two fan-driven cryogenic wind tunnels. The first was a low-speed atmospheric tunnel, the second a pressurized transonic tunnel.

As a result of the programs undertaken thus far, the cryogenic concept has been proven to be a practical means of attaining high Reynolds number flows without the increases in tunnel size, drive power, or cost attendant to other solutions. Further studies have been initiated to incorporate recent advances in cryogenic and materials engineering in the design and construction of cryogenic wind tunnels.

This report contains the major results of the theoretical studies of the cryogenic concept applied to wind tunnels for instructional use. Based on these results, anticipated design features and operational characteristics of cryogenic tunnels capable of achieving useful Reynolds number for instruction/research purposes in the low subsonic speed range are presented.

THEORETICAL PERFORMANCE AND OPERATING CHARACTERISTICS

The scale effect on various aerodynamic characteristics was discussed in the introduction where evidence was presented indicating a Reynolds capability of at least 1.5×10^6 to 2.5×10^6 based on mean aerodynamic chord to be desirable even at low Mach numbers. Because of the high cost associated with large wind tunnels, economic forces have dictated the use of relatively small tunnels for many applications such as instructional use. Therefore, in this section, performance charts, anticipated design features, and anticipated operational characteristics are presented for continuous-flow fan-driven closed-circuit pressure tunnels capable of low subsonic operation at cryogenic temperatures. Although the information was produced specifically for low speed fan-driven tunnels, similar material is available[9] for transonic fan-driven tunnels. Much of the material is general in nature and is therefore applicable to both supersonic cryogenic fan-driven and non-fan-driven tunnels.

Performance Chart: Basic Assumptions

A performance chart for continuous-flow cryogenic tunnels using nitrogen as the test gas has been prepared and is presented for a free-stream Mach number of 0.35, as figure 2 of this report. Detailed examples are included to illustrate the use of the chart and highlight the reduction in size and drive power made possible by operation at cryogenic temperatures.

REYNOLDS NUMBER: The Reynolds number calculations were based on the real-gas properties of the test gas. Simplifying assumptions were made, however, so that the majority of the calculations could be made on a relatively small digital computer. Some of the assumptions had to do with the way in which the properties of nitrogen were calculated at cryogenic temperatures. For example, very precise values of the compressibility factor, Z, can be obtained over the temperature range from 65 to 2000 K at pressures up to 10,000 atmospheres from a National Bureau of Standards computer program by Mr. R. D. McCarty. The equation which covers these wide ranges of temperature and pressure, however, has many more terms than are required to cover the limited range of temperature and pressure of interest in the study of a cryogenic wind tunnel. Therefore, a less complicated equation has been fitted to allow its use in a small digital computer. The same situation is true in the case of both the ratio of specific heats, γ, and the viscosity of nitrogen, μ, where relatively simple equations are used to cover only the limited ranges of temperature and pressure of interest. No particular effort was made to optimize the form of the equations. In general the forms are those which tend to linearize and therefore reduce the number of terms required to provide an adequate fit. These equations were taken from reference 9 without modification since they are relatively simple as presented. The errors introduced by the simplifying assumptions were generally less than two-tenths of one percent and are believed to be entirely negligible.

MINIMUM STAGNATION TEMPERATURE: The values of minimum stagnation temperatures are dictated by the necessity of avoiding liquefaction of the test gas under the most adverse conditions encountered in the test action. Condensation is most likely to begin in the localized low-pressure regions adjacent to the model. The local pressures in turn depend on the shape and attitude of the model, as well as the test Mach number and stagnation pressure. To compute likely conditions in these regions, a variation of maximum local Mach number with free-stream Mach number must be assumed. Initially, very conservative estimates of this variation were assumed to conservatively bias the benefits derived from cryogenic operation. Recent studies, however, have indicated that several degrees of local supersaturation can occur without adverse effects on the test results. Indeed, it appears that no adverse effects are exhibited at any operating point above free-stream saturation. Accordingly, the minimum stagnation temperature was assumed to be dictated by free-stream saturation only.

DRIVE POWER: Drive power was calculated from the equation

$$P = qVA\eta$$

where q is the test section dynamic pressure, V is the test section velocity, A is the cross-sectional area of the test section, and η is the tunnel power factor defined as

$$\eta = \frac{1}{(ER_t)\eta'}$$

η' is the efficiency of the drive motor, and ER_t is the energy ratio of the tunnel. For a given tunnel geometry, the energy

ratio is a function of Reynolds number and Mach number. The value of η used for these calculations was 0.25 which is a typical value based on transonic tunnels at the NASA Langley Research Center operating at low subsonic speeds.

A well-designed tunnel with the drive motor properly matched to the tunnel operating conditions should achieve a much higher tunnel power factor with a resultant decrease in the amount of drive power required. Methods for calculating the energy ratio are available in reference 2. It must, however, be emphasized that accurate determination of power losses for a particular tunnel configuration must be performed empirically.

OTHER FACTORS: Tabulated values of minimum stagnation temperature and other conditions relating to the performance chart are given in Table I.

Use of Performance Chart: Examples

THREE-DIMENSIONAL TESTING ($M_\infty = 0.35$): As previously discussed, operation at a test Reynolds number of 1.5×10^6 to 2.5×10^6 is taken as adequate for three-dimensional subsonic wind tunnel instruction and research. For the purpose of this example, it was assumed that a Reynolds number of 2.0×10^6 based on the mean geometric chord of the model $\bar{c}$, equal to one-tenth of the square root of the test section area is desired in a 20-cm x 40-cm rectangular test section. The mean geometric chord of the model is therefore 3.34-cm. A test Reynolds number of 2.0×10^6 requires a unit Reynolds number of 6×10^7/m. In figure 2, a 1120 cm^2(1.21 ft^2) test

section and a unit Reynolds number of $6x10^7$/m implies operation at a stagnation pressure of approximately 1.26 atmospheres for a drive power of 17.3 kW (23.2 horsepower). At these test conditions, Table I indicates the stagnation temperature of the nitrogen test gas to be about 80.5K (-315°F). By way of comparison, a conventional tunnel operating at 300K (+80°F), the same stagnation pressure, and the same Reynolds number would require a 4.63 m^2 (49.80 Ft^2) test section with a drive power of approximately 1417.4 kW (1900 horsepower). Alternatively, a conventional tunnel operating at 300K with the same size test section (1120 cm^2,1.21 Ft^2) and the same Reynolds number would require a stagnation pressure of 8.14 atmospheres and a drive power of approximately 223.8 kW (300 horsepower).

TWO-DIMENSIONAL TESTING (M_∞ = 0.35): For the purpose of this example it was assumed that a Reynolds number of $10x10^6$ based on $\bar{c}$,2-D is desired in a 50-cm by 20-cm (1.08 Ft^2) test section. Note, however, that the definition of $\bar{c}$ must be modified for two-dimensional testing since the models customarily used in two-dimensional tunnels are larger in proportion to jet size than others. A general rule is that the model chord should not exceed one-fourth of the test section height to avoid excessive error due to wall effects. Thus a test Reynolds number of $10x10^6$ requires a unit Reynolds number of $8x10^7$/m. In figure 2, a 1000 cm^2 (1.08 Ft^2) test section and a unit Reynolds number of $8x10^7$/m implies operation at a stagnation pressure of approximately 1.78 atmospheres for a drive power of 22.2 kW (29.8 horsepower). At these test conditions

Table I indicates the stagnation temperature of the nitrogen test gas to be approximately 83.8K (-309°F).

By way of comparison, a conventional tunnel operating at 300K (+80°F), the same stagnation pressure, and Reynolds number, would require a 1.21-m x 3.03-m (3.98 Ft x 9.95 Ft) test section with a drive power of about 1600 kW (2145 horsepower). Alternatively, with a stagnation temperature of 300K and a 20-cm x 50-cm test section, a test Reynolds number of 10×10^6 would require a stagnation pressure of about 10.94 atmospheres and a drive power of about 266.3 kW (357 horsepower).

From the foregoing examples, it is apparent that operation at cryogenic temperature can significantly increase the Reynolds number capability of continuous-flow fan driven tunnels with no increase in operating pressure while actually decreasing drive power requirements. A comparison of the performance of several existing university-owned subsonic wind tunnels and the theoretical performance characteristics of cryogenic wind tunnels operating under similar conditions except for test gas temperature is presented in figure 3. The test section area is plotted against the maximum test Reynolds number based on $\bar{c}$, equal to one-tenth of the square root of the test section area. The amount of drive power available is listed for each facility.[10] All tunnels operate in the same Mach number range from 0 to approximately 0.30. Note that these are all atmospheric pressure tunnels. Combining the benefits of increased operating pressure and reduced test temperature will provide even greater Reynolds number capability. It is important to note that figures 2 and 3 indicate that for

any given Reynolds number power required decreases with temperature reaching a minimum at free stream saturation temperature. Consequently the tunnel power requirement will be fixed by the minimum acceptable Reynolds number for operation of the tunnel under ambient conditions.

OPERATING ENVELOPES

In addition to the advantages of reduced drive-power requirements, the cryogenic tunnel concept offers some unique operating envelopes. For a body of given orientation and shape which is in motion through a fluid, any aerodynamic coefficient, C, is a function of Reynolds number, R, and Mach number, M. The shape of the model is itself influenced by the dynamic pressure, q. Decreasing the dynamic pressure would decrease the bending stresses in the model and also the aft fuselage distortion necessary to accommodate a sting capable of maintaining the desired model orientation. Reductions in dynamic pressure would also allow reduced balance stresses, increased test lift coefficient capability, reduced sting interference, and an increased stress margin for aeroelastic matching.

The cryogenic tunnel provides the investigator the opportunity to vary temperature in addition to the usual operational variables, velocity and pressure. Consequently, it is possible to alter any of the test parameters, Reynolds number, Mach number, and dynamic pressure independently. It is possible, therefore, to determine the effect of each parameter in turn upon the areodynamic characteristics of the model.

Expressed in terms of partial derivatives, this testing ability, which is unique to the pressurized cryogenic tunnel, allows the independent determination of the partial derivatives,

$$\frac{\partial C}{\partial R}, \frac{\partial C}{\partial q}, \text{ and } \frac{\partial C}{\partial M}$$

In order to illustrate how this is accomplished, envelopes for several modes of operation are presented for a cryogenic low-speed pressure tunnel having a 26.67-cm x 38.1-cm (10.5-in x 15-in) test section. These envelopes are intended to illustrate various possible modes of operation. The size of the tunnel as well as the ranges of temperature, pressure, and Mach number have been selected with some care in order to represent the anticipated characteristics of a typical high Reynolds number tunnel designed for instructional use.

CONSTANT MACH NUMBER MODE: A typical operating envelope showing the ranges of q and R available for subsonic testing is presented in figure 4. The envelope is bounded by the maximum temperature boundary (taken in this example to be 300 K), the minimum temperature boundary (chosen to avoid free-stream saturation), the maximum pressure boundary (2.0 atm), the minimum pressure boundary (1.0 atm), and a boundary determined by an assumed maximum available fan drive power of 37.3 kW (50 horsepower). Typical paths which might be used in determining $\frac{\partial C}{\partial R}$ and $\frac{\partial C}{\partial q}$ are indicated by arrows. With such an operating capability, it is possible, for example, to determine the effect of Reynolds number on the aerodynamic characteristics of the model, $\frac{\partial C}{\partial R}$, at a fixed Mach number, without the influence of altered model shape due to changing dynamic pressure. As indicated by the envelope, pure aeroelastic

studies using purposely "flimsy" models can be made and various combinations of R and q can be established to accurately represent the variations in flight of aeroelastic deformation and changes of Reynolds number with altitude.

CONSTANT REYNOLDS NUMBER MODE: A typical operating envelope is presented in figure 5 which shows the ranges of q and M which are available when testing at a constant Reynolds number of 2.0×10^6. The same temperature, pressure, and fan drive power limits have been assumed as before. Typical paths which might be used to determine $\frac{\partial C}{\partial q}$ and $\frac{\partial C}{\partial M}$ are indicated by arrows. The derivative $\frac{\partial C}{\partial q}$ has been discussed previously. The unique operational capability, associated with the cryogenic tunnel, allows Mach number effects to be obtained by eliminating the problems introduced by changes of Reynolds number or aeroelastic effects. Thus the effects of the high local Mach numbers which can be encountered at large angles of attack even at relatively low free stream speeds can be investigated.

CONSTANT DYNAMIC PRESSURE MODE: Although the three derivatives were illustrated by the above envelopes, an additional form of the envelope is presented in figure 6 which shows the range of R and M obtainable at a constant dynamic pressure of 10 kN/m^2 (208.85 lb/ft^2). Typical paths which might be used in determining $\frac{\partial C}{\partial R}$ and $\frac{\partial C}{\partial M}$ are once again illustrated by arrows. It is therefore possible to determine, for example, drag rise with Mach number, $\frac{\partial C}{\partial M}$, without the influence of Reynolds number or aeroelastic effects.

DESIGN AND CONSTRUCTION CONSIDERATIONS

Tunnel Shell

Many different aspects must be considered in deciding on the construction material for the shell of a cryogenic tunnel. For example, some common structural materials such as carbon steel undergo a ductile-to-brittle transition at service temperatures in the cryogenic region.[11] This transition, however, does not occur in most low strength face-centered-cubic (FCC) materials. It is anticipated, therefore, that cryogenic tunnel circuits will be fabricated from materials such as 9-percent nickel steel or 5083-0 aluminum alloy that have acceptable structural properties down to the temperature of boiling liquid nitrogen (at 1 atmosphere, 77.4K (-320.4°F)).

The minimum shell plate thickness for pressure vessel construction allowed by the ASME Boiler and Pressure Vessel Code[12] for nonferrous materials is 0.3175 cm (0.125 inch). If the tunnel pressure shell is constructed of 0.3175 cm (0.125 inch) thick plates of 5083-0 aluminum alloy, a tunnel the size of the Langley 1/3-meter Transonic Cryogenic Tunnel would have a design pressure capability of nearly 2.5 atmospheres.

Aluminum expands or contracts more with changes in temperature than do most other common metals. This must be adequatedly provided for in design. The worst case would be operation of the whole of the tunnel pressure vessel at the minimum temperature of the test gas stream. The change of linear dimension for an aluminum alloy cryogenic tunnel being operated over a temperature range from 300K (+80°F) to the minimum temperature of about 77K

(-320°F) would be about five times the change of linear dimension for a conventional carbon steel tunnel subjected to a temperature change from normal operating to a low winter ambient of 255K (0°F). Studies made for the pilot cryogenic tunnel[13] indicate that conventional techniques can be used in dealing with the increased thermal expansion. In support of this view, it is noted that no problems due to thermal expansion have been encountered with the Langley 1/3-meter Transonic Cryogenic Tunnel[9]. This tunnel, which is a nominal 10 m (33 feet) long, changes length by about 4.0 cm (1.57 inches) when the temperature of the tunnel is changed from 334K (+152°F) to 86K (-305°F).

The flanges used to join the various sections of a 5083-0 aluminum alloy tunnel shell should be machined from plates of the same material to eliminate local stress concentrations which would result from materials of different coefficients of thermal expansion. Studs of 2024-T4 aluminum may be used for bolting because their coefficient of linear expansion is compatible with the 5083-0 aluminum flanges. This material exhibits high yield strength at cryogenic temperatures, it is readily available, and it is simple to machine. The nuts secured on each end of the studs should be 304 stainless steel to eliminate galling and galvanic corrosion.

Preliminary studies[13] indicated that all flange joints could be sealed with a flat gasket made from a mixture of teflon resin and pulverized glass fiber known as Fluorogreen E-609. This material was selected as the best seal overall because of its reusability. Experience has shown that flat gaskets are unsatis-

factory due to cold flow. Some of the Fluorogreen gaskets in the Langley 1/3-meter Transonic Cryogenic Tunnel have been replaced by ribbon seals made of Gortex. Another attractive alternative being studied is teflon-coated U-shaped spring steel seals.

It should be noted that there is no fundamental reason for using metal for the tunnel pressure shell. The use of an aluminum alloy was chosen to conform to the existing requirements of the ASME Pressure Vessel Code[12]. Recent developments in composite materials[14,15] have made possible significant advances in the use of glass fiber reinforced epoxy resins for cryogenic pressure vessels. With the exception of the restriction placed on the lower temperature limit by Section X of the ASME Pressure Vessel Code, it is entirely possible to design a cryogenic wind tunnel using special composites that meet the Code standards. Due to the lack of experimental data available and the nature of composite materials, design would have to be based upon burst tests performed on sample pressure vessels constructed of the particular resin/fiber combination selected. For the relatively low pressures involved, E-glass fibers in a modified epoxy resin should prove to be satisfactory. Although hand laid-up fiberglass-reinforced pressure vessels are not covered by the Code, there is no reason to believe that a vessel could not be constructed by manually laying mats or strips of preimpregnated fiberglass tape into a mold and curing them by the application of heat and pressure. Quality control is, however, of the utmost importance in the construction of fiberglass-reinforced pressure vessels and hand fabrication should not be attempted by inexperienced personnel. The

principal advantages to the use of fiberglass are the simplicity of repair and the ease with which complex shapes may be formed. The high cost of materials and the difficulty of bonding components together present difficulties as does the relatively low modulus of elasticity which results in structures with very little stiffness. External stiffening rings may be required for thin sections thereby negating some of the inherent material savings of such sections. Reinforcement of the tunnel shell would certainly be necessary at the tunnel support points to prevent buckling.

Whereas composite structures offer many intriguing advantages, the necessity of conducting materials tests will greatly increase the time required between planning and construction of the tunnel.

Tunnel Insulation and Flow Liner

Of the many types of insulation which might be used for a cryogenic tunnel, the expanded foams are perhaps best suited. They are low in initial cost, can be either foamed in place or applied in pre-cut shapes, and they require no rigid vacuum jacket. Although expanded foams have a higher thermal conductivity than some other insulations, the use of more effective and costly types of insulation may not be worth the extra trouble and expense required to incorporate them in the tunnel design.

The optimum type and location of thermal insulation will vary with tunnel size and usage. A 12.7 cm (5 inches) thickness of urethane foam blown on the outside of the tunnel structure with

an exterior fiberglass reinforced polyesther vapor barrier, however, will reduce the heat conduction losses of a relatively small tunnel to an acceptable level. In addition to its ease of application, a major advantage of external insulation is that no flow liner is required to prevent damage to the insulation and subsequent damage to the fan or other parts of the tunnel caused by insulation breaking away from the tunnel wall.

Several manufacturers supply pre-cut polystyrene foam in various shapes and sizes which will also provide adequate thermal insulation and which can be installed and maintained with a minimum of effort. A thin vapor barrier of polyethylene film or some similar material is a necessity to prevent water vapor and air diffusion into the cells of the foam, if the low thermal conductivity of the insulation is to be maintained.

One of the serious disadvantages of rigid foam insulations is their large coefficient of thermal expansion. The insulation should not be bonded directly to the aluminum tunnel wall but rather should be separated from the wall by a shear layer consisting of two thicknesses of fiberglass cloth. This allows the differential expansion between the aluminum and foam insulation to take place without causing the foam to fracture. An additional shear surface between layers of the insulation is advisable to allow differential expansion to take place within the foam without fracture. This method of tunnel insulation has proved completely satisfactory on the Langley 1/3-meter Transonic Cryogenic Tunnel under all operating conditions including periods of high humidity.

Insulation techniques for tunnel shells other than aluminum are identical to those outlined above. Use of pre-cut foam insulation in such facilities would have the added advantage of easy removal for periodic inspection of the tunnel shell. A thin aluminum foil flow liner is recommended to protect the surface of a fiberglass reinforced plastic shell from abrasion. Satisfactory bonding agents have been developed[16] for use at cryogenic temperatures under internal pressure loading. The critical problem involves bonding of metal-to-metal at the longitudinal seams and the number of such joints should be held to a minimum. The pressures involved in testing these liners were on the order of 10 times the maximum operating pressure of five atmospheres used in the Langley 1/3-meter Transonic Cryogenic Tunnel with up to 100 pressure cycles being completed before leakage was detected. At the relatively low pressures involved in a cryogenic wind tunnel, no unusual problems are to be anticipated.

Tunnel Support System

The cryogenic tunnel supports may be constructed in two parts to thermally isolate the support structure from the tunnel shell. The upper portion of each support, which operates at very low temperatures, may be constructed from a 300-series stainless steel for the first 17.8 cm (7 inches) of the support structure. The lower portion, which is not subjected to low temperatures, may be made of more economical A-36 carbon steel. The tunnel shell must be supported in such a manner that the fan hub maintains a fixed position relative to the drive motor. An anchor support is

used to provide a fixed point of reference, with respect to the ground, for the tunnel centerline in the presence of large thermal expansion and contraction. A fork on the tunnel underside at the anchor point (figure 7) may be used to prevent lateral or axial movement of the tunnel at this station. The undersides of all the tunnel support attachments, including those at the anchor point, should be on the horizontal plane through the axis of the tunnel. With symmetrical expansion, the tunnel centerline is held at a fixed height above the ground.

Sliding pads must be provided at each of the tunnel support attachments to allow thermal expansion or contraction of the tunnel walls relative to the centerline. The sliding surfaces should consist of a material with good fabrication qualities, a low coefficient of friction, and strength under compressive and vibrational loads. Vertical and lateral movement at each joint can be constrained by bolts passing through t e tunnel support attachment and structural support insulation into the A-frame. Spherical washers may be used to reduce misalignment of the tunnel support attachment resulting from thermal contraction of the tunnel pressure shell. The support attachments may be slotted in the longitudinal direction to allow free longitudinal expansion or contraction of the tunnel.

Test Section

Cryogenic tunnel test section design problems and their solutions do not differ radically from those of conventional wind tunnels, consequently this section of the report has been limited to one or two considerations of general interest.

For three dimensional testing, Langley Research Center Tunnels of the type described in this report often utilize a rectangular section of 7:10 height to width ratio. This section has been chosen because of its flexibility for general testing purposes, its acceptability with respect to wall effects, and the existence of extensive wall correction charts for the 7:10 configuration.

Conventional test sections are often modified by use of a removable insert to accommodate two dimensional test models. These two-dimensional jet inserts are normally of either the end plate or contraction variety and must be designed with a great deal of care for each individual tunnel. The installation often requires boundary layer control devices to eliminate sidewall boundary layer effects. A study of sidewall boundary layer bleed systems for the Langley 1/3-meter Transonic Cryogenic Tunnel is anticipated in the near future after the installation of a two-dimensional jet insert.

Since direct viewing of the model is always desirable, a word about cryogenic viewing ports is in order. Special optical glass viewing ports have been used in the Langley 1/3-meter Transonic Cryogenic Tunnel. These have been fitted with blast shields in the event of failure while the tunnel is pressurized. The likelihood of glass failure is greatly increased at cryogenic temperatures. For this reason, a more suitable material is being sought. Initial tests of a polycarbonate resin (General Electric "Lexan") indicate that it does not become brittle when submerged in liquid nitrogen. Several sheets of this separated by "air" gaps to prevent frosting over during sustained cryogenic opera-

tion is a possible solution.

Models and Instrumentation

MODEL CONSTRUCTION: The construction of models for use in cryogenic tunnels presents no special problems. Good quality wood models performed in a satisfactory manner in the low speed cryogenic tunnel after being painted to prevent excessive drying of the model. Models for the Langley 1/3-meter Transonic Cryogenic Tunnel have been constructed from Armco 17-4PH stainless steel. All models must be constructed from a single material to avoid changes in model shape with temperature due to different coefficients of thermal expansion. Fasteners used in model construction should also be of stainless steel. Fasteners subjected to the cryogenic environment must be safety-wired to prevent them from working loose as no commercially available locking compound has been found to be effective at cryogenic temperatures.

MODEL MOUNTING: Nearly all modern test facilities employ a sting (three-dimensional testing) or a turntable (two-dimensional testing) mount to support the model and to permit changes in model orientation. Both of these systems have been used in the Langley 1/3-meter Transonic Cryogenic Tunnel and neither has exhibited any unusual problem due to the cryogenic environment.

Magnetic suspension techniques have proved very useful for simulating free-flight conditions in wind tunnels for nearly twenty years. The adaptation of such techniques to high Reynolds number aerodynamic testing has been impeded, however, by the unmanageable design requirements placed on conventional support magnets by the

large sizes and high aerodynamic loads characteristic of such testing. The unique design and operational characteristics of a prototype superconductor magnetic suspension and balance facility are described and discussed in reference 17 from the point of view of scalability to larger sizes. The cryogenic wind tunnel concept offers two main advantages: drastically reduced aerodynamic loads and smaller size models (for a given Reynolds number).

INSTRUMENTATION: In general, it is preferable to calibrate measuring devices at room temperature and to thermally isolate them from the cryogenic environment. In the Langley 1/3-meter Transonic Cryogenic Tunnel pressure measurements are made using multi-channel scannivalves which permit the use of a single transducer for measurement of up to 48 different pressure points. The transducer can be located several feet from the test section. Teflon tubing is now available which does not become brittle at cryogenic temperatures. Strain gage measurement of force and moment data is particularly attractive because of the ease of data reduction through the use of analog-to-digital converters and high-speed computers. Model tests were run utilizing an existing water-jacketed strain-gage balance in the low-speed cryogenic tunnel constructed at NASA Langley Research Center to determine if conventional techniques might be used to make force and moment measurements at cryogenic temperatures.[6] Based on the results of these tests there appear to be no fundamental or practical difficulties in obtaining force and moment data using conventional strain-gage balance techniques. Subsequent tests

have been conducted in the 1/3-meter Transonic Cryogenic Tunnel using electrically heated strain-gage balances. Results of these tests[18] indicate that thermal isolation of the balance from the model and the sting are critical in order to avoid a temperature gradient within the balance itself. Such a temperature gradient will produce a balance zero shift necessitating corrections to the aerodynamic data. Care in the design of the balance should eliminate this problem.

Fan Design

Studies have indicated that aerodynamic matching of the wind tunnel and fan for operation over a range of temperatures into the cryogenic range is no more involved than for a conventional tunnel.[6] Therefore no discussion of fan design will be presented in this report.

Nitrogen Systems

LIQUID NITROGEN INJECTION: Experience with the low-speed and transonic tunnels has demonstrated that simple straightforward liquid nitrogen injection systems work well. Neither the location of the injector nozzles nor their detail design appears to be critical with respect to temperature control or distribution. The two injector locations which have been used, downstream of the test section and downstream of the fan, work equally well. Different types of nozzles have been used with equal success and all have produced satisfactory temperature distributions regardless of the spray pattern at the nozzle.

The liquid nitrogen supply pressure required is dictated by the tunnel operating pressure and the particular injection scheme used. Experience with the Langley 1/3-meter Transonic Cryogenic Tunnel indicates equally good temperature distribution for a particular set of test conditions with either four relatively large nozzles working at a few tenths of an atmosphere differential pressure or twenty small nozzles working at five atmospheres differential pressure.

Large nozzles are less prone to become blocked than smaller nozzles and a low-pressure liquid nitrogen supply system is less expensive than a high-pressure system. Therefore a low-pressure liquid nitrogen supply with a few relatively large nozzles is the preferred injection scheme.

If a tunnel is to be operated over wide ranges of Mach number and pressure, it may be necessary, as was the case with the Langley tunnel, to operate separate banks of nozzles independently. This allows proper control over the wide range of liquid nitrogen flow rates necessary.

Where possible, a recirculating loop liquid nitrogen supply system should be used. Such a system reduces supply pipe cool-down time and simplifies the control of liquid nitrogen flow rate by eliminating boiling in the supply pipe during tunnel operation.

LIQUID NITROGEN REQUIREMENTS: COOL-DOWN. The amount of liquid nitrogen required to cool-down a cryogenic tunnel to its operating condition is a function of the cool-down procedure as well as the insulation and structural characteristics of the tunnel.

Under the idealized assumptions of zero heat conduction through tunnel insulation and zero heat added to the stream by the fan during the cool-down process, the amount of liquid nitrogen required for cooling the tunnel structure is a minimum when the tunnel is cooled slowly and in such a way that the nitrogen gas leaves the tunnel circuit at a temperature equal to that of the warmest part of the structure. With the preceding assumptions and the additional assumption that all of the liquid nitrogen does, in fact, vaporize, the amount of liquid nitrogen required for cool-down is a maximum when only the latent heat of vaporization is used and the nitrogen gas leaves the tunnel circuit at the saturation temperature.

Cool-down experience with the Langley 1/3-meter Transonic Cryogenic Tunnel indicates that the liquid nitrogen required for cool-down is adequately predicted by the analysis suggested in the previous paragraph. That tunnel is made of aluminum alloy with 12.7 cm (5 inches) or urethane foam applied on the outside as thermal insulation. Let σ represent the mass of LN_2 required to cool a unit mass of material through a given temperature range. For aluminum σ_{min} and σ_{max} are 0.44 and 0.74 respectively for cooling from 300 K (+80F) to 110 K (-262°F). The experimental value determined from the total amount of LN_2 used during a 30 minute cool-down of the approximately 3200 kg (7050 lbm) structure of the 1/3-meter tunnel over the same temperature range is $\sigma = 0.62$. Cooling through this large temperature range would not necessarily be a regular occurrence since under some circumstances the tunnel

circuit would be allowed to remain cold between runs. Under these conditions, the heat to be removed before each run would equal the heat gained by the tunnel structure and test gas by conduction through the insulation.

LIQUID NITROGEN REQUIREMENTS: OPERATION. The heat to be removed while the tunnel is running consists of the heat conduction through the walls of the tunnel and the heat energy added to the tunnel circuit by the fan. As previously noted, heat conduction can be made relatively small by using reasonable thicknesses of insulation.

The conditions assumed for the two examples previously given to illustrate the use of the performance chart will now be used to illustrate the amount of liquid nitrogen required to remove the heat added to the tunnel circuit by the fan and by conduction through the tunnel walls.

The following assumptions are made:

1. Thermal conductivity of insulation = 0.0329 W/m^2-K (0.0190 Btu/hr-ft-°F)
2. Insulation thickness = 12.7 cm (5 inches)
3. Tunnel surface area = 620 x test section area*
4. Tunnel inner wall temperature is equal to stagnation temperature
5. Zero temperature gradient in metal pressure shell
6. Temperature of outside surface of insulation = 300 K(+80°F)
7. Cooling capacity of LN_2 equals the latent heat of vaporization plus sensible heat of gaseous nitrogen between saturation temperature and stagnation temperature.

* Assumes a 12 to 1 contraction ratio and a typical divergence angle.

THREE-DIMENSIONAL TESTING ($M_\infty = 0.35$, $R_{\bar{c}} = 2.0 \times 10^6$, $A = 1120\ cm^2$)

The earlier example (page 15) gave a drive power requirement of 17.3 KW (23.2 horsepower) and a value of T_t of 80.5 K (-315°F). Under these conditions, the liquid nitrogen requirement is

To remove heat added by fan - 77.2 g/sec (0.17 lbm/sec)

To remove heat conducted through walls - 19.57 g/sec (0.04 lbm/sec)

For this three-dimensional example, the liquid nitrogen required to remove the heat conducted through the walls amounts to about 20.2 perfent of the total running requirement.

The total nitrogen requirement of 96.77 g/sec (0.21 lbm/sec) would cost about $21/hour based on the 1975 cost of liquid nitrogen in the U.S.A. of $0.06/kg ($55/short ton).

TWO-DIMENSIONAL TESTING ($M_\infty = 0.35$, $R_{\bar{c},2\text{-}D} = 10 \times 10^6$, $A = 1000\ cm^2$)

The earlier example (page 16) gave a power requirement of 22.2 KW (29.8 horsepower) and $T_t = 83.8$ K (-309°F). Under these conditions the liquid nitrogen requirement is:

To remove heat added by fan - 98.0 g/sec (0.216 lbm/sec)

To remove heat conducted through walls - 17.0 g/sec (0.0375 lbm/sec)

For this example, the liquid nitrogen required to remove the heat conducted through the walls amounts to about 14.8 percent of the total running requirement.

The total nitrogen requirement of 115.0 g/sec (0.2536 lbm/sec) would cost about $25/hour based on the 1975 cost of liquid nitrogen in the U.S.A. of $0.06/kg ($55/short ton).

NITROGEN EXHAUST SYSTEM: In order to hold stagnation pressure constant, the excess nitrogen gas, which amounts to about 15 percent of the test section mass flow at the maximum Mach number, must be discharged from the tunnel circuit. If discharged directly from a large tunnel into the atmosphere there would be potential problems associated with fogging, discharge noise, and possible freezing and asphyxiation of personnel and wildlife. Before being discharged, therefore, the excess nitrogen gas should be oxygenated and warmed to a safe level. Based on the results obtained with the Langley 1/3-meter Transonic Cryogenic Tunnel, both oxygenation and warming can be achieved by discharging the nitrogen as the driver gas in an ejector which induces ambient air flow. The resultant mixture should be discharged well above ground level outside the building housing the tunnel. A muffler should be provided to reduce the noise associated with the discharge.

AUTOMATIC CONTROLS

Feedback, one of the most fundamental processes existing in nature, is present in almost all dynamic systems, including those within man, among men, and between men and machines. Feedback concepts have been systematically investigated almost exclusively by engineers. As a result, the theory of feedback control systems has been developed as an engineering discipline for analyzing and designing practical control systems for technological devices. In order to solve a systems problem, the specifications or description of the system configuration and its components must be put into a form amenable to analysis, design, and evaluation.

The object of this chapter is to present a brief look at some of the fundamental problems involved in the automatic control of a cryogenic wind tunnel. It is intended not to present the design of a specific control system but rather to point out general principles involved in the use of controllers in cryogenic tunnels including interactions between various control loops. The Langley 1/3-meter Transonic Cryogenic Tunnel has been utilized as an example of a typical liquid nitrogen system.

Description of the System

The description of this system is taken directly from reference 9. Discussion of the plenum removal system is, however, omitted, since it is peculiar to transonic tunnels and this report is intended to deal primarily with subsonic facilities.

LIQUID NITROGEN SUPPLY SYSTEM: A schematic drawing of the liquid nitrogen system used in the 1/3-meter Transonic Cryogenic Tunnel is shown in figure 8. Liquid nitrogen is stored at atmospheric pressure in vacuum insulated tanks having a total capacity of approximately 30,000 liters (8,000 U.S. gallons). When the tunnel is being operated at less than approximately 2.5 atmospheres absolute pressure, the liquid can be supplied to the tunnel simply by pressurizing the supply tank with the pressurizing coil shown in figure 8. The liquid nitrogen pump must, however, be used whenever the tunnel is operated at higher pressures. When the pump is used, the supply tank is pressurized to about 1.7 atmospheres absolute pressure in order to maintain sufficient net positive suction head at the pump inlet to prevent cavitation. The pump has a capacity of about 500 liters per minute (150 U.S. gal. per minute) with a delivery pressure of 9.3 atmospheres absolute, and is driven by a 22.4 KW (30 horsepower) constant speed electric motor.

During pump operation the liquid nitrogen supply pressure is set and held constant by the pressure control valve, shown in figure 8, which regulates the amount of liquid returned to the storage tank through the pressure-control return line.

The flow rate of liquid nitrogen into the tunnel circuit is regulated by pneumatically operated control valves located outside the tunnel at each of the three injection stations. These valves, which may be used either singly or in combination, can be controlled manually or automatically. A helium filled con-

stant-volume bulb thermometer located in the settling chamber serves as the temperature sensing element when the valves are being controlled automatically.

Since the transonic tunnel operates over wide ranges of pressure and Mach number, it is necessary to allow for a wide range of liquid nitrogen flow rate. This is accomplished by designing the spray bar at each injection station to cover a limited range of flow rate through proper selection of the number as well as size of nozzles. Liquid nitrogen flow rates from 1 to 400 liters per minute (0.25 to 107 U.S. liquid gallons per minute) can be realized by operating various combinations of the three spray bars and by changing the liquid nitrogen supply pressure.

Originally, ten nozzles having small orifice diameters were used on each of the spray bars at injection stations 2 and 3 (figure 8). These nozzles were prone to blockage from foreign matter inevitably left in the liquid nitrogen supply system. The original nozzles were replaced with eight nozzles having larger orifice diameters.

NITROGEN EXHAUST SYSTEM: The system for exhausting gaseous nitrogen from the tunnel is also shown schematically in figure 8. Tunnel total pressure is adjusted by means of pneumatically operated control valves in the exhaust pipes leading to the atmosphere from the low-speed section of the tunnel. To minimize flow disturbance, the exhaust pipes are taken from the low-speed section

at 120° intervals around the circumference of the tunnel shell just ahead of the 3rd set of turning vanes. The valves may be used either singly or in combination to provide fine control over a wide range of exhaust flow rates. A total pressure probe located immediately downstream of the screens provides the reference pressure measurement when tunnel pressure is being controlled automatically.

Control of a Cryogenic Wind Tunnel

The following discussion should be regarded as merely illustrative as a comprehensive study of cryogenic wind tunnel control would require an entire book. Control problems will be discussed in the context of the cryogenic wind tunnel described in the previous section. The goal of the control strategy is to maintain the tunnel at or very near specified steady-state test conditions despite changes in the various independent variables. In practice this goal is directed toward the regulation of test conditions once the operating point has been established in the tunnel.

Specification of a set of independent or input variables for a cryogenic wind tunnel requires careful application of mass and energy balances. For the present purposes, it is assumed that fixed value of fan speed, LN_2 flow rate, and exhaust flow rate imply specific values for stagnation temperature, stagnation

pressure, and Mach number. Hence the following will be considered as input variables:

1. Fan speed (assuming constant fan efficiency)
2. LN_2 flow rate
3. Exhaust flow rate

and the following as output variables:

1. Mach number
2. Stagnation temperature
3. Stagnation pressure

Strictly speaking, a transfer function exists between each of the input and output variables which implies nine transfer functions. For example, a change in exhaust flow rate would cause a change in each of the three output variables. In many cases, however, the major effect will be confined to stagnation pressure and only this transfer function will be considered in the control scheme.

There is usually a control objective of primary importance. For illustrative purposes, assume that it is imperative that the Mach number be maintained. It is also assumed that moderate changes in dynamic pressure due to stagnation pressure changes are tolerable. Clearly other situations can easily be imagined in which only the dynamic pressure, or possibly <u>both</u> dynamic pressure and Mach number, must be carefully controlled.

Before the Mach number can be controlled, however, a means must be provided to measure it. A real time display of

Mach number based on the ratio of total pressure measured downstream of the screens to static pressure measured in the plenum can be provided by a small computer. Thus, if the static pressure is constant, the total pressure of the stream is a simple measure of the Mach number since

$$\frac{p}{p_t} = \left[\frac{2}{2 + (\gamma-1)M^2}\right]^{\frac{\gamma}{\gamma-1}}$$

Assuming the static pressure is maintained constant, a workable strategy is to use measured total pressure as the basis for a Mach number control loop. The total pressure may be controlled by changing the exhaust flow rate. If the exhaust flow rate is increased, the Mach number is decreased and vice versa. In order to be able to increase and decrease the exhaust flow rate, however, there must be a net positive pressure in the tunnel. If the tunnel is operated below atmospheric pressure, an ejector fan must be installed to remove gaseous nitrogen from the tunnel circuit. A variable frequency speed controller on the ejector fan can be used to adjust discharge rate to maintain a constant stagnation pressure in the tunnel circuit.

Total pressure increases (indicating a higher Mach number) are transmitted to a pressure controller which increases the exhaust flow rate. A control loop for this purpose is described by the block diagram of figure 9. While the only load variable indicated in figure 9 is the stagnation temperature, there will of course be other load variables (e.g. LN_2 flow rate). Discussion of these interactions is deferred to a later section.

Selection of a controller for this system is not a simple matter because the transfer functions between exhaust flow rate and total pressure (G_1), and between stagnation temperature and total pressure (G_2) are generally nonlinear. In practice, for loops showing these characteristics, it is often merely assumed that three-mode control (i.e., proportional plus integral plus derivative) is required. The closed-loop system is placed on stream with estimated starting values for the controller constants which are then adjusted for better control as operating experience is acquired. Methods for obtaining initial estimates of controller constants are discussed in reference 19.

It is evident that changes in any of the three input variables will affect the Mach number. Changes in the LN_2 flow rate can be almost entirely eliminated, however, by placing flow controllers on the supply pipes to the injection stations, as shown in figure 8. The function of those controllers will be considered in more detail in a later section.

There is no easy way of preventing changes in the fan speed from affecting the flow. Changes in the fan speed will certainly have an effect on Mach number by changing the static pressure. Thus a feedback type of control scheme for maintaining constant static pressure must be provided. The pressure can be controlled by adjusting the free-stream velocity with the fan. Increasing the free-stream velocity decreases the static pressure and vice versa.

The stagnation temperature can be maintained by adjusting the rate of LN_2 injection. A theoretical analysis of the total temperature control system is presented in the next section. The static pressure control system involves unknown transfer functions with long time constants and thus as in the total pressure control system, design must be achieved by emperical methods.

Theoretical Analysis of a Total Temperature Control System for the Cryogenic Wind Tunnel

In order to investigate theoretically the control of a process, it is necessary to first know the dynamic characteristics of the process which is being controlled. The transfer function relating LN_2 flow and total temperature of the cryogenic wind tunnel and the associated total temperature control system is shown in figure 8. The system, previously described, consists of the tunnel circuit into which LN_2 flows at a variable rate, $\dot{m}_1$. The entering LN_2 is at temperature T_1, which may vary with time. The gaseous nitrogen, GN_2, in the tunnel circuit is well mixed so that it can be assumed to be at uniform temperature T_t and pressure p_t in the area surrounding sensing elements. The temperature of the stream is reduced by the vaporization of LN_2 flowing into the tunnel circuit through the injection nozzles. The temperature of the GN_2 in the tunnel circuit is measured and transmitted to the controller. The output signal from the controller is used to change the stem position of the valves which in turn regulate the flow of LN_2 to the tunnel circuit.

ANALYSIS OF THE TUNNEL CIRCUIT: A major problem is to determine the dynamic characteristics of the tunnel circuit. The tunnel is actually a nonlinear system, and in order to obtain a simplified linear model a number of assumptions are needed. Therefore the following assumptions are made for the tunnel:

1. The heat transfer from the atmosphere is negligible.
2. The volume of GN_2 in the tunnel circuit is constant.
3. The thermal capacity of the insulation, which separates the flow stream from the surroundings, is negligible.
4. The thermal capacity of the tunnel pressure shell, adjacent to the insulation, is finite, and the temperature of this pressure shell is uniform and equal to the stream temperature at any instant.
5. The GN_2 in the tunnel circuit is sufficiently mixed to result in a uniform temperature.
6. The heat capacities of LN_2 and the metal wall are constant.
7. The density of LN_2 is constant.
8. The GN_2 stream in the tunnel circuit is above the saturation limit.
9. Stagnation pressure remains constant despite variations in total temperature.

The assumptions listed here are to some extent arbitrary. For a specific tunnel operating under a particular set of conditions, some of these assumptions may require modification.

The dynamic characteristics of the thermal process can be analyzed by considering the schematic presented in figure 10, in which the thermodynamic system is taken to be the space <u>within the tunnel circuit</u>. Applying the first law to the thermodynamic system outlined in figure 10 yields

$$P_f + \dot{m}_1 h_1 - \dot{m}_d h_d = v \frac{\partial(\rho_v u_v)}{\partial t} + mc_w \frac{dT_t}{dt} \qquad (1)$$

Assumption 4 has been applied in writing to the last term of Eq. (1), which implies that the metal in the tunnel pressure shell is always at the stream temperature.

A mass balance yields

$$\dot{m}_1 - \dot{m}_d = v \frac{\partial \rho_v}{\partial t} \qquad (2)$$

Combining Eqs. (1) and (2) to eliminate $\dot{m}_d$ gives

$$P_f + \dot{m}_1(h_1 - h_d) = (u_v - h_d) v \frac{\partial \rho_v}{\partial t} + mc_w \frac{dT_t}{dt} + \rho_v \, v \frac{\partial u_v}{\partial t} \qquad (3)$$

The variables ρ_v, u_v, h_1, and h_d are functions of the stagnation and discharge temperatures and can be approximated by expansion in Taylor series and linearization as follows:

$$\begin{aligned} \rho_v &= \rho_{vs} + \alpha(T_t - T_{ts}) \\ u_v &= u_{vs} + \beta(T_t - T_{ts}) \\ h_1 &= h_{1s} + \chi(T_1 - T_{1s}) \\ h_d &= h_{ds} + \delta(T_d - T_{ds}) \end{aligned} \qquad (4)$$

where

$$\alpha = \left.\frac{\partial \rho_v}{\partial T_t}\right|_s \qquad \chi = \left.\frac{\partial h_1}{\partial T_1}\right|_s$$

$$\beta = \left.\frac{\partial u_v}{\partial T_t}\right|_s \qquad \delta = \left.\frac{\partial h_d}{\partial T_d}\right|_s$$

The parameters α, β, χ, and δ in these relationships can be obtained from thermodynamic property tables for nitrogen once the operating point is selected.

The first term in Eq. (3) is also nonlinear, since the power is proportional to the square root of the stagnation temperature.[6] In order to obtain a transfer function from Eq. (3), this term must be linearized. By means of a truncated Taylor series expansion, the function $P_f(T_t)$ may be expanded around the steady-state value T_{ts}; thus

$$P_f = P_f(T_{ts}) + \left.\frac{dP_f}{dT_t}\right|_s (T_t - T_{ts}) \tag{5}$$

Since $P_f = kT_t^{1/2}$ where k is a constant, we have

$$P_f = P_{fs} + \frac{1}{R_1}(T_t - T_{ts}) \tag{6}$$

where $P_{fs} = P_f(T_{ts})$ and $(R_1)^{-1} = \frac{1}{2}kT_{ts}^{-1/2}$.

Introducing Eqs. (4) and (6) into (3) gives the following linearized equation:

$$P_{fs} + \frac{1}{R_1}(T_t - T_{ts}) + \dot{m}_1((h_{1s} - h_{vs}) + (\chi(T_1 - T_{1s}) - \delta(T_t - T_{ts}))) = ((u_{vs} - h_{vs}) + 2(\beta - \delta)(T_t - T_{ts}) + \frac{\beta}{\alpha}\rho_{vs} + \frac{mc_w}{\alpha v})\alpha v \frac{dT_t}{dt} \tag{7}$$

where the discharge temperature has been assumed to be equal to the stream temperature.

Some of the terms in Eq. (7) can be neglected. The term

$$\chi(T_1 - T_{1s}) - \delta(T_t - T_{ts})$$

can be dropped because it is negligible compared with $(h_{1s} - h_{vs})$.

For example, for nitrogen at atmospheric pressure, a change of 2°K in both stagnation temperature and LN_2 temperature gives a value of $\chi(T_1-T_{1s}) - \delta(T_t-T_{ts})$ of approximately 160 J/mol while $(h_{1s}-h_{vs})$ is about -5900 J/mol for a stagnation temperature of 80K and a LN_2 temperature of 75K. With some reduction in the accuracy of the representation of the model to the real system, as a first approximation the term $(2\beta - \delta)(T_t-T_{ts})$ can also be neglected. For example, this term is about -50 J/mol for a change in stagnation temperature of 2°K for nitrogen at 1 atm pressure while the term $(u_{vs}-h_{vs})$ is about -640 J/mol under these conditions. Discarding these terms, writing the remaining terms in deviation variables, and transforming yield

$$T_t'(s) = \frac{K_1}{T_1 s-1} \dot{m}_1(s) \tag{8}$$

where

$$T_t' = T_t - T_{ts}$$

$$\dot{m}_1' = \dot{m}_1 - \dot{m}_{1s}$$

$$K_1 = (h_{vs}-h_{1s})R_1$$

$$T_1 = R_1[(u_{vs}-h_{vs})\,\alpha v + mc_w + \beta v \rho_{vs}]$$

Thus Eq. (8) is a linearized first approximation of the transfer function relating LN_2 flow rate and stagnation temperature for constant stagnation pressure. Before completing the analysis of the control system, the effect of valve-stem position on LN_2 flow rate, $\dot{m}_1$, must be considered.

ANALYSIS OF VALVE: The flow of LN_2 through the valve depends upon the variables: LN_2 supply pressure p_p, tunnel stagnation pressure, and the valve-stem position, which shall be assumed to be proportional to the pneumatic valve-top pressure p_a. The tunnel stagnation pressure is, however, assumed to be constant. Thus

$$\dot{m}_1 = f(p_a, p_p) \tag{9}$$

The linearized form of $f(p_a, p_p)$ can be obtained by making some experimental tests on the valve. If the valve-top pressure is fixed at its steady-state (or average) value and $\dot{m}_1$ measured for several values of p_p, a curve such as the one shown in figure 11a can be obtained. If the supply pipe pressure p_p is then held constant and the flow rate is measured at several values of valve-top pressure, a curve such as that shown in figure 11b can be obtained. These curves, referred to as flow curves, can often be obtained from the valve manufacturer in the form of a plot of flow rate vs. valve-top pressure for various pressure differentials. These two curves can now be used to evaluate the partial derivatives in the linear expansion of $f(p_a, p_p)$. It is well to note that these relations are obtained under steady-state conditions and their validity for a dynamic situation will depend upon the accuracy to which a quasi-static assumption can be made.

Expanding $\dot{m}_1$ about the operating point p_{as}, p_{ps} and retaining only linear terms gives

$$\dot{m}_1 \cong \dot{m}_{1s} + \left.\frac{\partial \dot{m}_1}{p_a}\right|_s (p_a - p_{as}) + \left.\frac{\partial \dot{m}_1}{\partial p_p}\right|_s (p_p - p_{ps})$$

This equation can be written in the form

$$\dot{m}_1 = K_2 \, p'_a - \frac{1}{R_2} \, p'_p \tag{10}$$

where

$$\dot{m}'_1 = \dot{m}_1 - \dot{m}_{1s}$$

$$p'_a = p_a - p_{as}$$

$$p'_p = p_p - p_{ps}$$

$$K_2 = \left.\frac{\dot{m}_1}{p_a}\right|_s$$

$$\frac{1}{R_2} = - \left.\frac{\dot{m}_1}{p_p}\right|_s$$

The coefficients K_v and $-\frac{1}{R_2}$ in Eq. (10) are the slopes of the curves of figure 10 at the operating point p_{as}, p_{ps}. This follows from the definition of a partial derivative. Notice that $\frac{1}{R_2}$ has been defined as the negative of the slope so that R_2 is a positive quantity. The experimental approach described here for obtaining a linear form for the flow characteristics of a valve is always possible in principle. However, it must be emphasized that the linear form is useful only for small deviations from the operating point. If the operating point is changed considerably, such as in the initial setting of the test condition, the coefficients K_2 and $\frac{1}{R_2}$ must be reevaluated. Notice that, in writing Eq. (10), the valve is assumed to have no dynamic lag between changes in pneumatic valve-top pressure p_a, and stem position.

This assumption is valid for a system having large time constants, but it is a major deficiency which has arisen from the use of a completely pneumatically activated system for the flow-rate control valves in this thermodynamic system. As a result, the automatic control system described suffers from large oscillations when attempting to attain a given set point. Once the point is reached, however, it works effectively to maintain the operating point.

Interactions in the Control System

When changes in tunnel variables are small (e.g., as in regulation once the test point is set) the control loops may be treated as essentially independent as described in the previous section. When large changes in tunnel variables are necessary (e.g., when initially setting tunnel test conditions), however, the assumption of loop independence is not justified. Even if each of the individual control loops is designed to operate satisfactorily, due to their interdependence, there is no guarantee that when employed simultaneously, the overall tunnel operation will be satisfactory. In fact, it is quite possible for the loops to be individually stable and yet lead to unstable operation of the entire tunnel. This possibility exists since each variable has been assumed to be single-loop despite the fact that there is considerable interaction between the variables. Thus, a more realistic block diagram for the pressure and total temperature control loops might look like figure 12. Process control system design can seldom be based upon such complex diagrams because the

transfer functions are not known. The existence of interactions must be recognized, however, as they may render the scheme inoperative and a new control system which minimizes the effect of the interactions may be required. There are numerous pitfalls in this type of design. In practice these pitfalls may be avoided on the basis of past experience, but it is well to state that the design of a totally automated control system for a cryogenic tunnel is not a trivial task.

CONCLUSIONS

The major conclusions to be drawn from this survey of materials and construction techniques for cryogenic wind tunnel facilities are as follows:

1. Power requirements are acceptable. Both two- and three-dimensional testing is practical at low subsonic speeds with wind tunnels having less than 37.3 KW (50 horsepower) installed drive power. The tunnel power requirement will be fixed by the minimum acceptable Reynolds number for operation of the tunnel under ambient conditions.
2. Suitable alloys exist for pressure vessel construction at cryogenic temperatures. The pressure capability of the tunnel is in excess of 2 atmospheres with a thickness of about 0.3175 cm of 5083-0 aluminum alloy.
3. A fiberglass-reinforced modified epoxy resin composite material appears to be satisfactory for a cryogenic tunnel shell. Burst tests of prototype vessels are required to determine allowable design pressures.

Adhesives are available for bonding flow liners to the pressure shell. Use of fiberglass will substantially increase the time required between conception and completion of the tunnel due to the additional requirement for materials testing.

4. Satisfactory regulation of tunnel operating conditions is possible with a relatively simple pneumatic control system. Design of a totally automated control system to include set point changes in a cryogenic tunnel is not a trivial task.

REFERENCES

1 Lockwood, V. E., Effect of Reynolds Number and Engine Nacelles on the Stalling Characteristics of a Model of a Twin-Engine Light Airplane. NASA TN D-7109, December 1972.

2 Pope, A., and Harper, J. J., "Low-Speed Wind Tunnel Testing." John Wiley & Sons, Inc., 1966.

3 Hills, R., Use of Wind Tunnel Model Data in Aerodynamic Design, JRAS, January 1951.

4 Jacobs, E. N., The Variation of Airfoil Section Characteristics with Reynolds Number, TR 586, 1937.

5 Pozniak, O. M., Investigation Into the Use of Freon-12 as a Working Medium in a High-Speed Wind Tunnel. The College of Aeronautics, Cranfield, Note No. 72.

6 Kilgore, R. A., Goodyer, M. J., Adcock, J. B., and Davenport, E. E., The Cryogenic Wind Tunnel Concept for High Reynolds Number Testing, NASA TN D-7762, November 1974.

7 Pugh, P. G., The Design of High-Reynolds-Number Transonic Wind Tunnels: Some General Principles. Large Wind Tunnels: Required Characteristics and the Performance of Various Types of Transonic Facility. AGARD R-615, June 1974, Paper No. 5.

8 Smelt, R., Power Economy in High Speed Wind Tunnels by Choice of Working Fluid and Temperature. Report NO. Aero. 2081, Royal Aircraft Establishment, Farnborough, England, August 1945.

9 Kilgore, R. A., The Cryogenic Wind Tunnel for High Reynolds Number Testing. Ph.D. Thesis, University of Southampton, 1974.

10 Pirrello, C. J., Hardin, R. D., Heckart, M. V., and Brown, K. R., An Inventory of Aeronautical Ground Research Facilities, NASA CR-1374, November 1971.

11 Barron, R., "Cryogenic Systems." McGraw-Hill Book Co., Inc., 1966.

12 ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, "Unfired Pressure Vessels," American Society of Mechanical Engineers, New York, 1974.

13 Wilson, J. F., Ware, G. D., and Ramsey, J. W., Jr., Pilot Cryogenic Tunnel: Attachments, Seals, and Insulation. Paper presented at

the ASCE National Structural Engineering Meeting, (Cincinnati, Ohio), April 22-26, 1974.

[14] Soffer, L. M., and Molho, R., Cryogenic Resins for Glass Filament-Wound Composites. NASA CR-72114, January 1967.

[15] Lewis, A., and Bush, G. E., Improved Cryogenic Resin/Glass Filament-Wound Composites. NASA CR-72163, April 1967.

[16] Toth, J. M., and Soltysiak, D. J., Investigation of Smooth-Bonded Metal Liners for Glass Fiber Filament-Wound Pressure Vessels. NASA CR-72165, May 1967.

[17] Zapata, R. N., Development of a Superconductor Magnetic Suspension and Balance Prototype Facility for Studying the Feasibility of Applying this Technique to Large Scale Aerodynamic Testing. Report No. ESS 4009-102-75, University of Virginia, January 1975.

[18] Kilgore, R. A., and Davenport, E. E., Static Force Tests of Sharp and Rounded Leading Edge 74° Swept Delta-Wing Models at Ambient and Cryogenic Temperatures. Proposed High-Number TMX, April 1975.

[19] Coughanowr, D. R., and Koppel, L. B., "Process Systems Analysis and Control." McGraw-Hill Book Company, Inc., 1965.

TABLE I - Assumed operating conditions related to a cryogenic nitrogen tunnel at a free-stream Mach number of .35

Maximum Local Mach Number = 0.35

Stagnation pressure p_t, Atm.	Minimum stagnation temperature T_t, min. K	Reynolds number per meter, millions	Reynolds number factor (A)	Dynamic pressure, q kN/M^2	Free-stream static pressure, p, Atm.	Free-stream static temperature T, K	Compressibility factor under free-stream conditions, Z	Ratio of specific heats under free-stream conditions,
1.00	78.5	49.3	6.5	8.0	.92	76.6	.958	1.452
1.25	80.5	59.4	6.5	10.0	1.15	78.6	.951	1.462
1.50	82.2	69.2	6.2	12.0	1.38	80.2	.944	1.472
1.75	83.6	78.7	6.2	14.0	1.61	81.6	.938	1.481
2.00	85.0	87.8	6.0	16.0	1.84	83.0	.932	1.490

(A) Reynolds number obtained at minimum stagnation temperature divided by Reynolds number obtained at typical stagnation temperature of 300 K (+80 F).

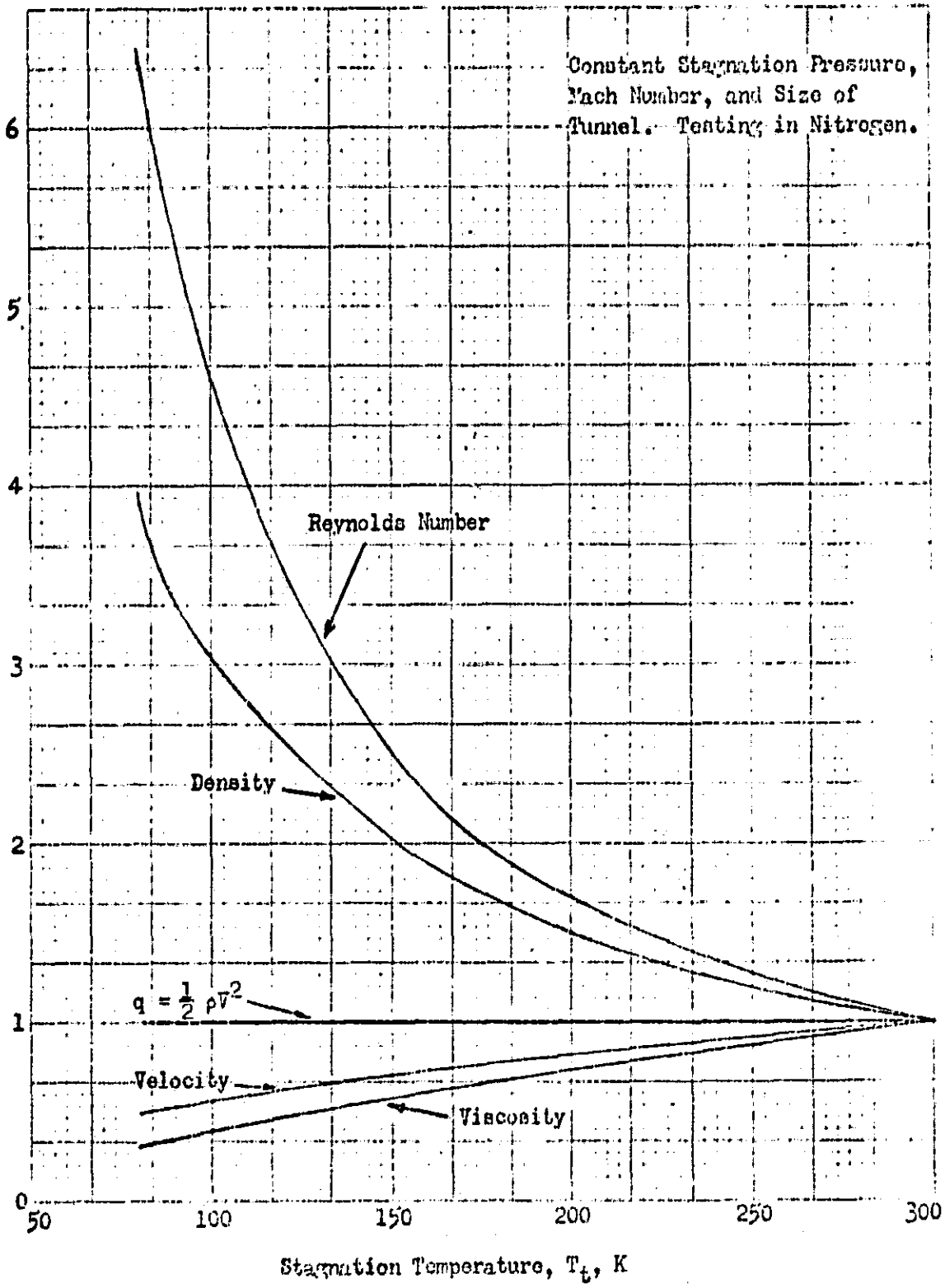


Fig. 1 Variation of test section flow parameters with temperature.

ORIGINAL PAGE IS
OF POOR QUALITY

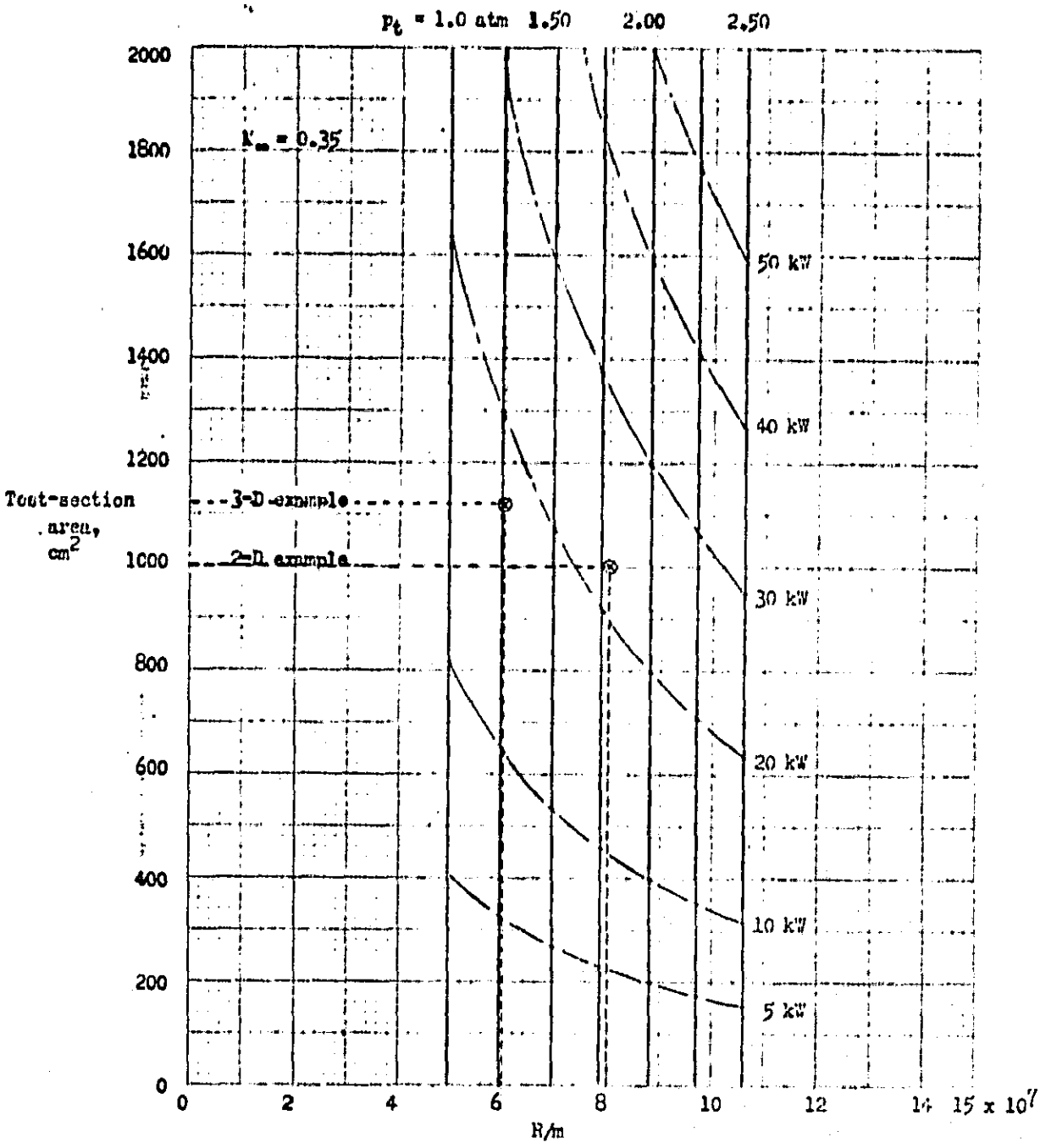


Fig. 2 Performance chart for cryogenic nitrogen tunnel showing relationship between tunnrl size, stagnation pressure, drive power, and Reynolds number for a free-stream Mach number of 0.35.

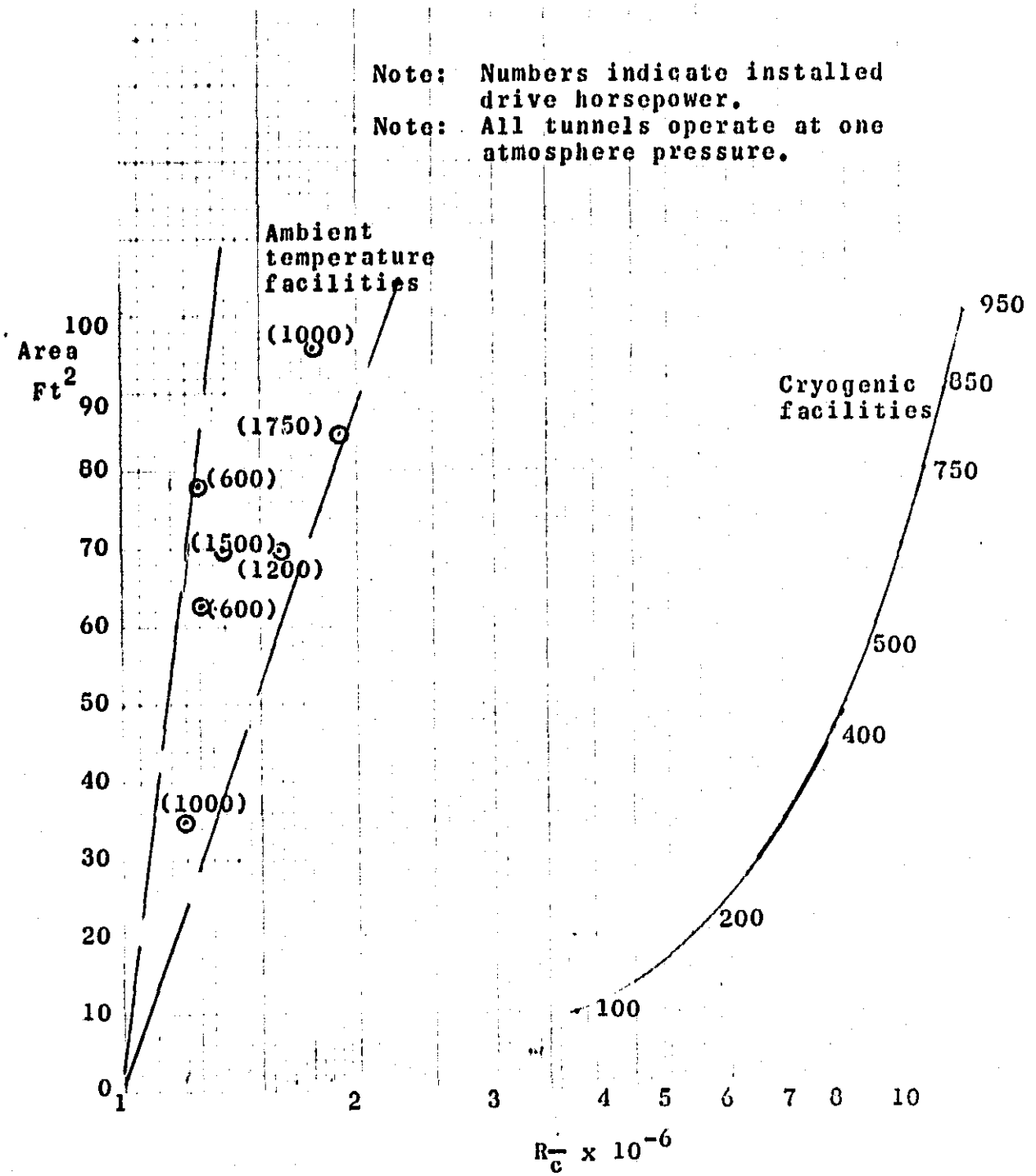


Fig. 3 Comparison of capabilities of existing subsonic ambient temperature facilities with the theoretical capabilities of cryogenic facilities.

ORIGINAL PAGE IS
OF POOR QUALITY

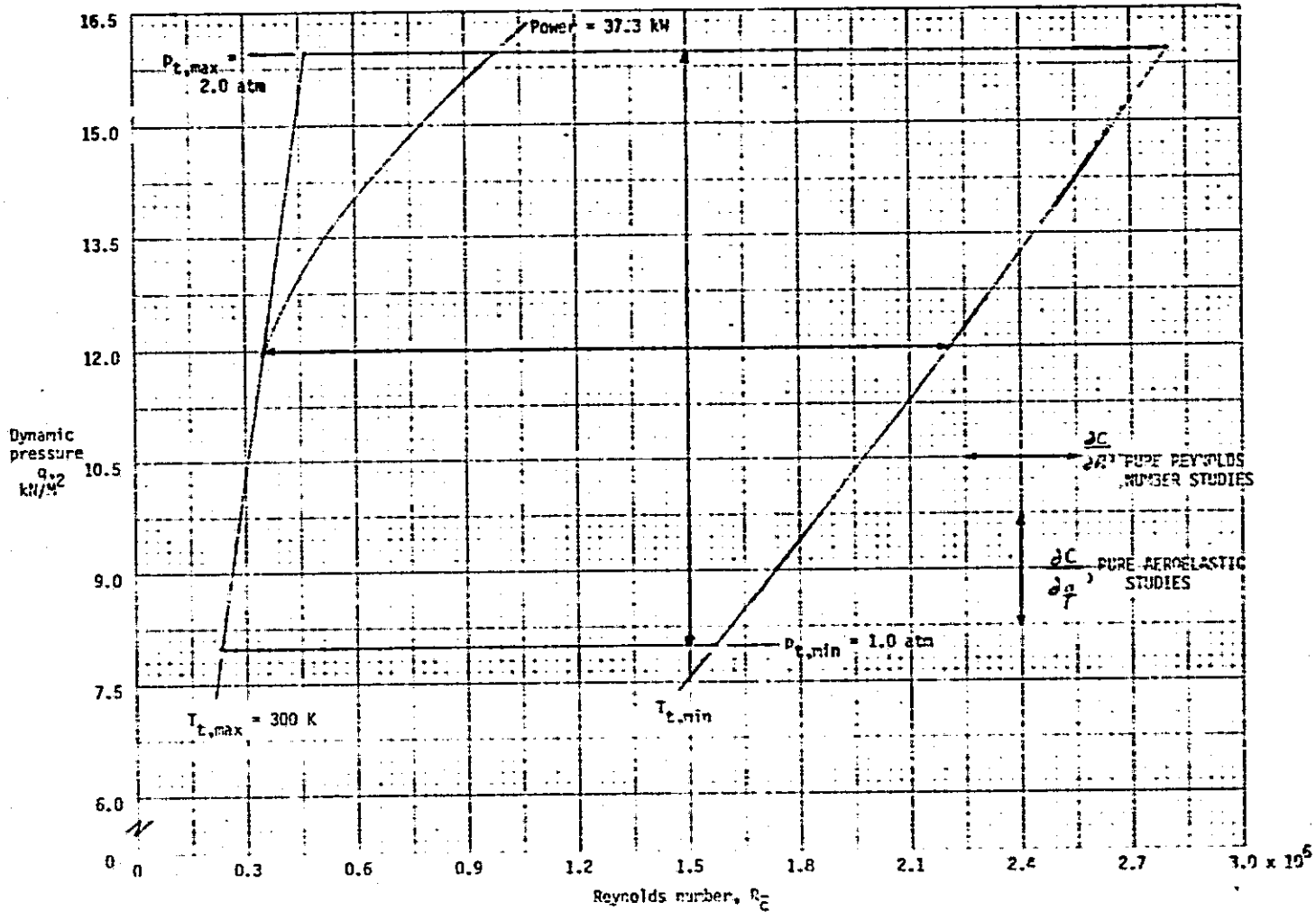


Fig. 4 Constant Mach number operating envelope for a cryogenic nitrogen tunnel having a 26.67 cm x 38.1 cm test section. $M_\infty = 0.35$.

"Page missing from available version"

ORIGINAL PAGE IS
OF POOR QUALITY

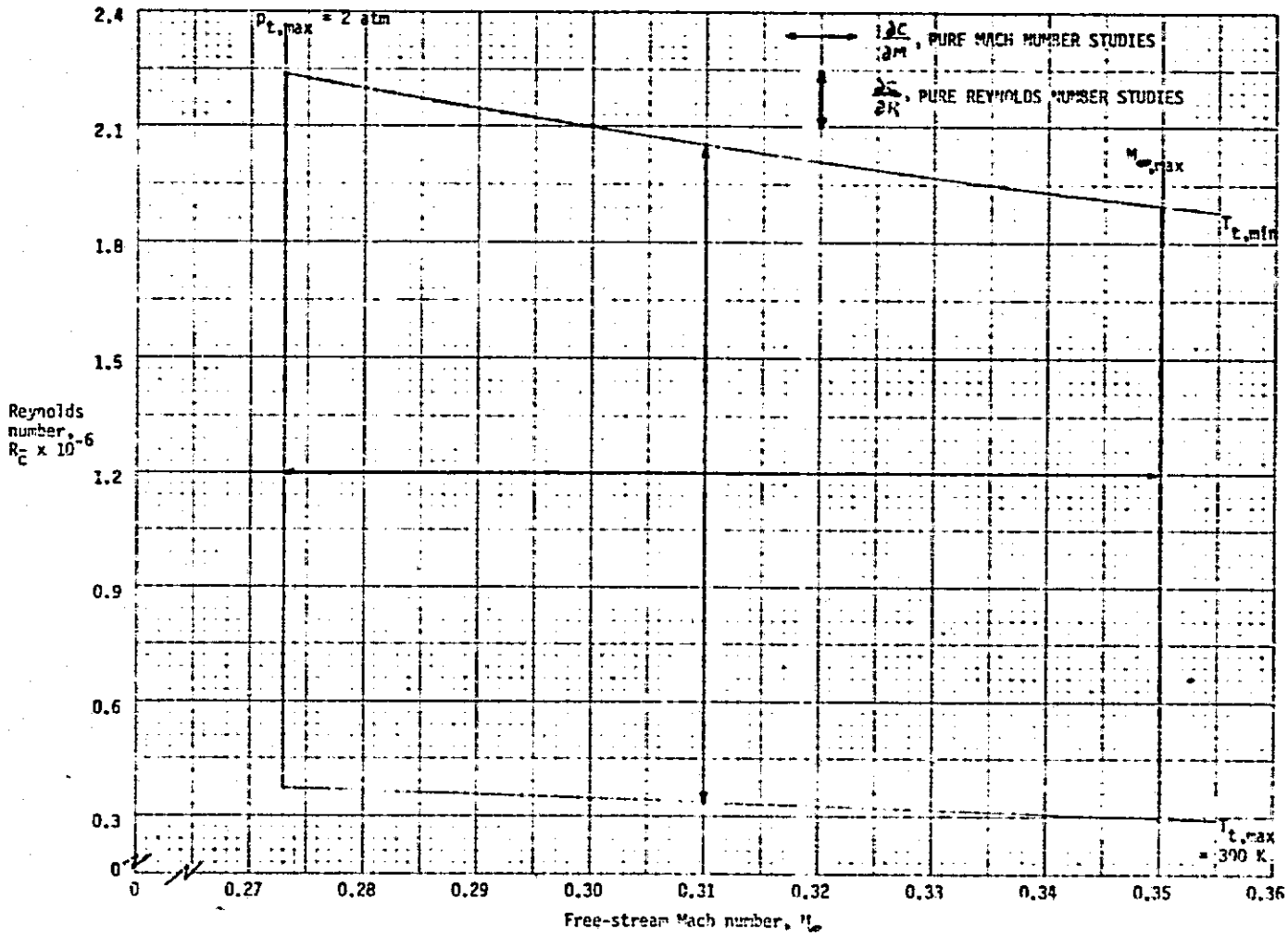


Fig. 6 Constant dynamic pressure operating envelope for a cryogenic nitrogen tunnel having a 26.67-cm x 38.1-cm test section. $q = 10\ kN/M^2$.

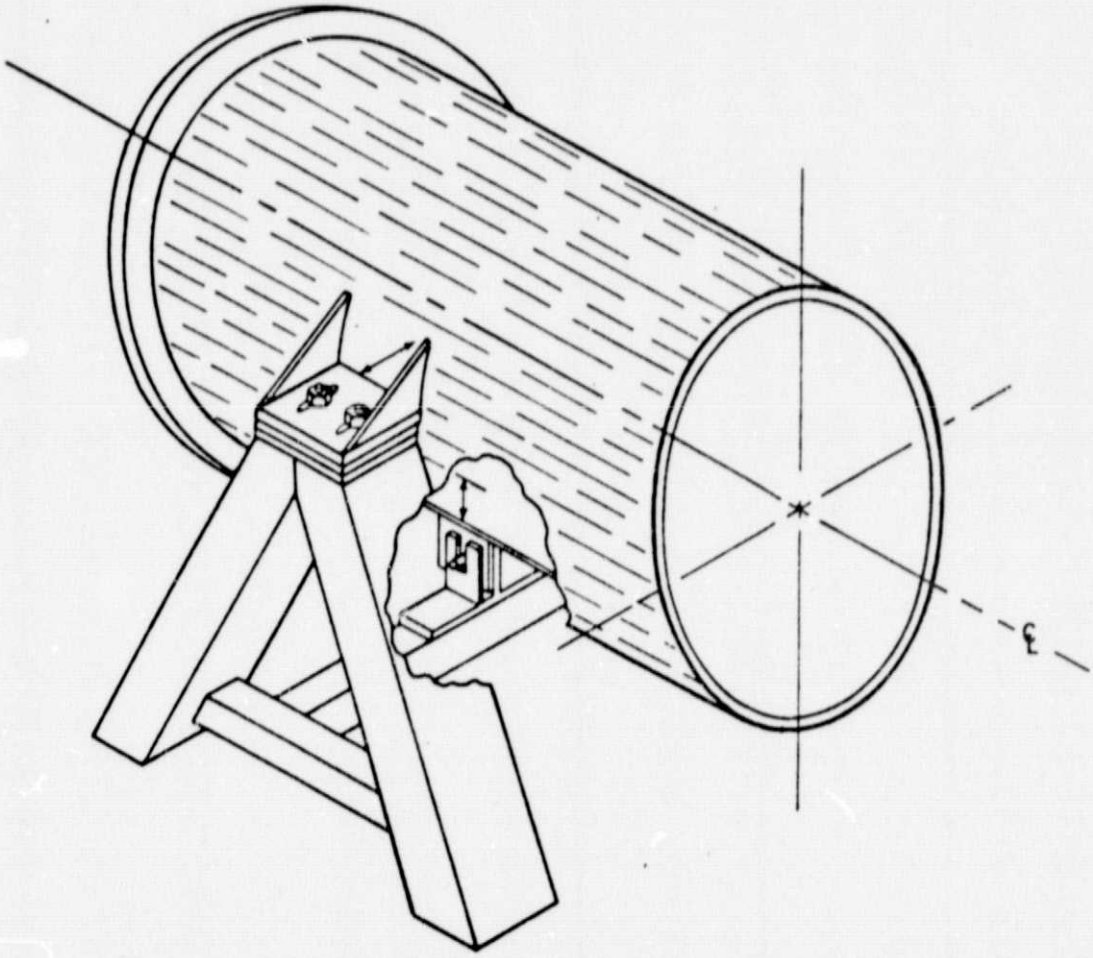


Fig. 7 Cryogenic tunnel anchor support.

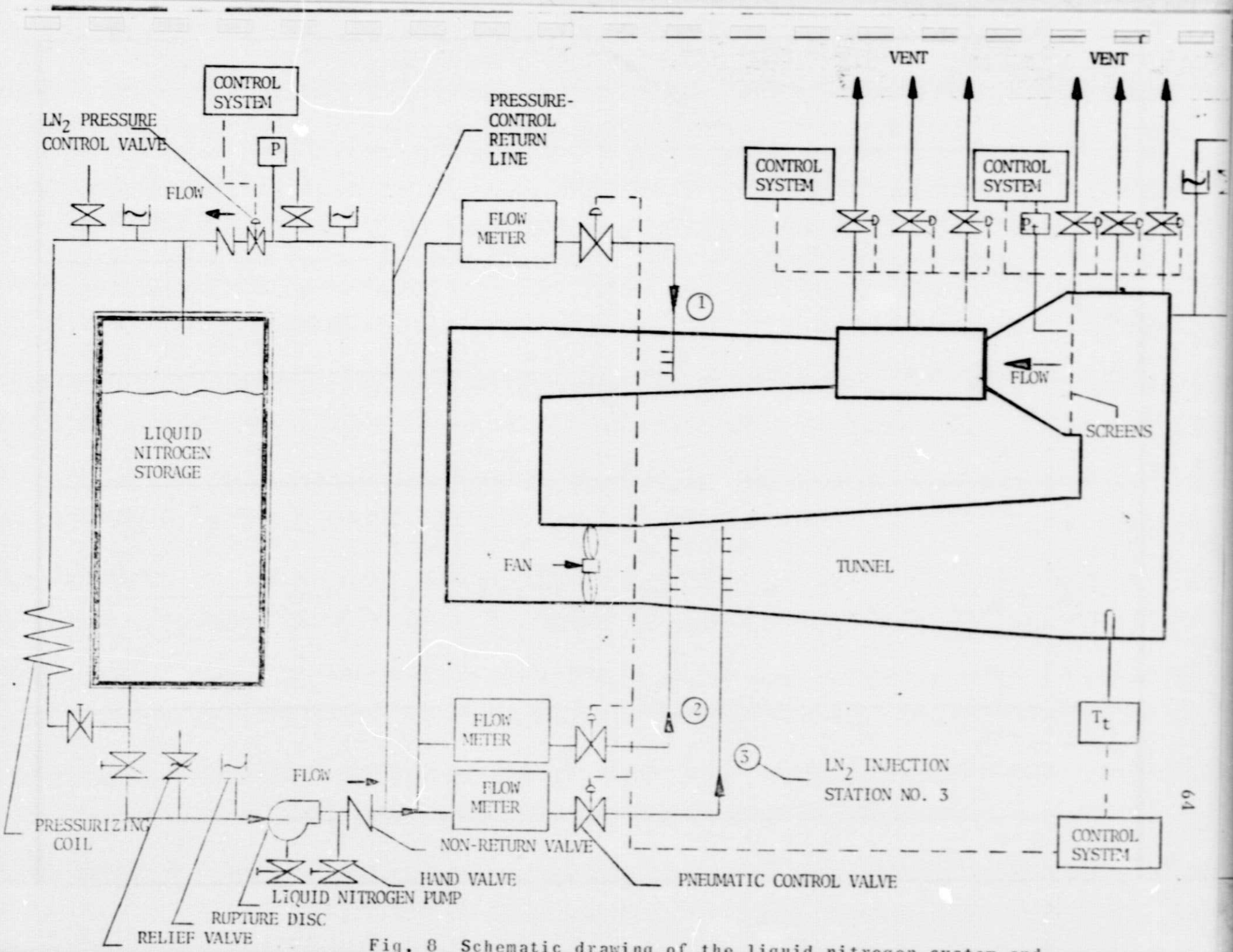


Fig. 8 Schematic drawing of the liquid nitrogen system and nitrogen exhaust system.

ORIGINAL PAGE IS
OF POOR QUALITY

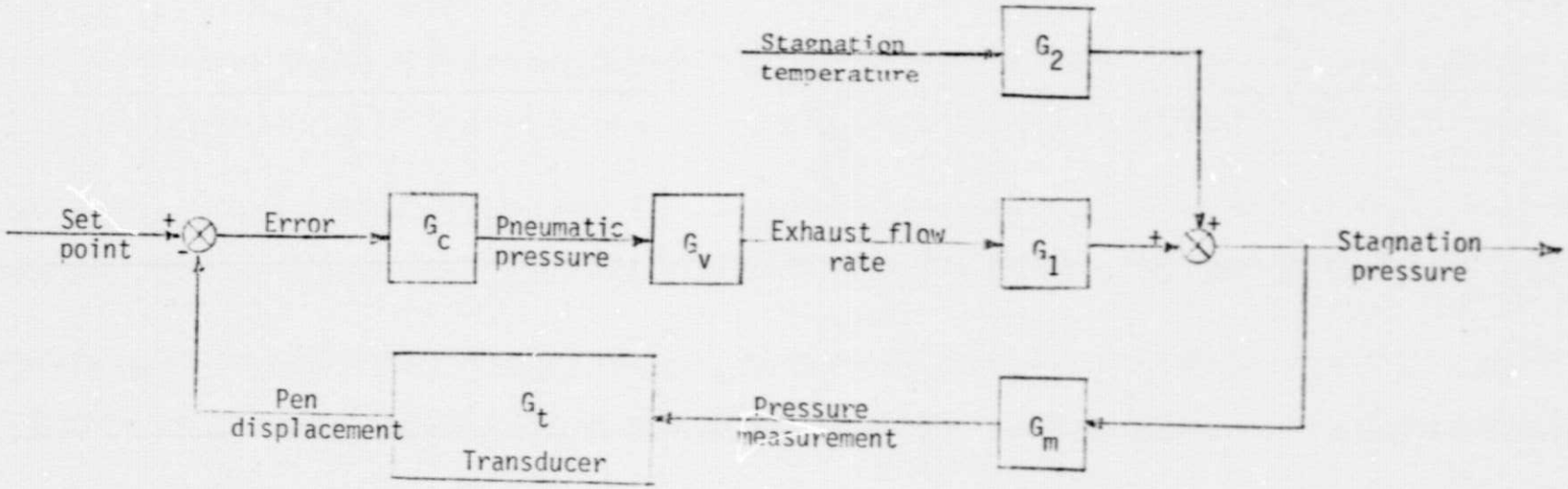


Fig. 9 Control of stagnation pressure.

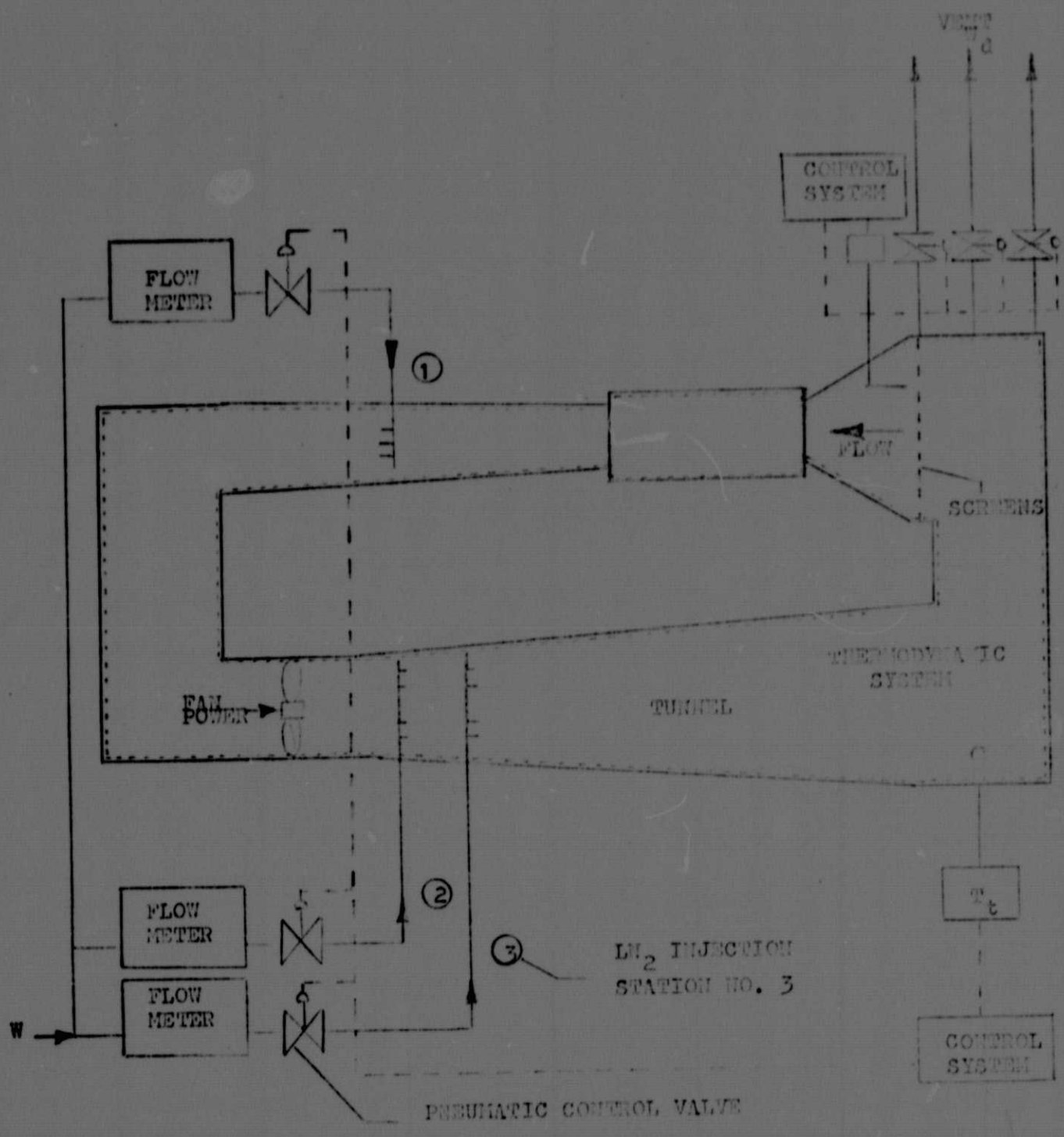
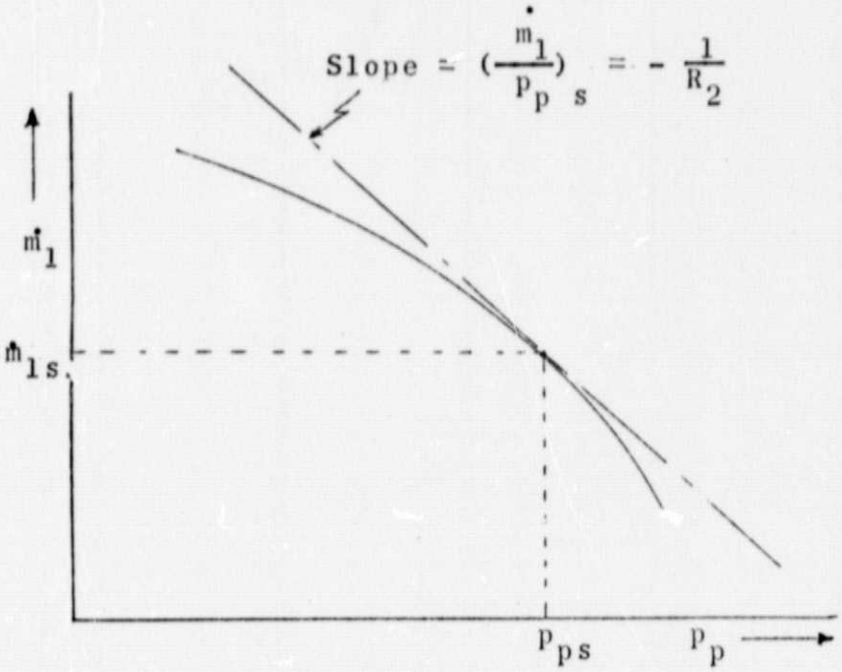
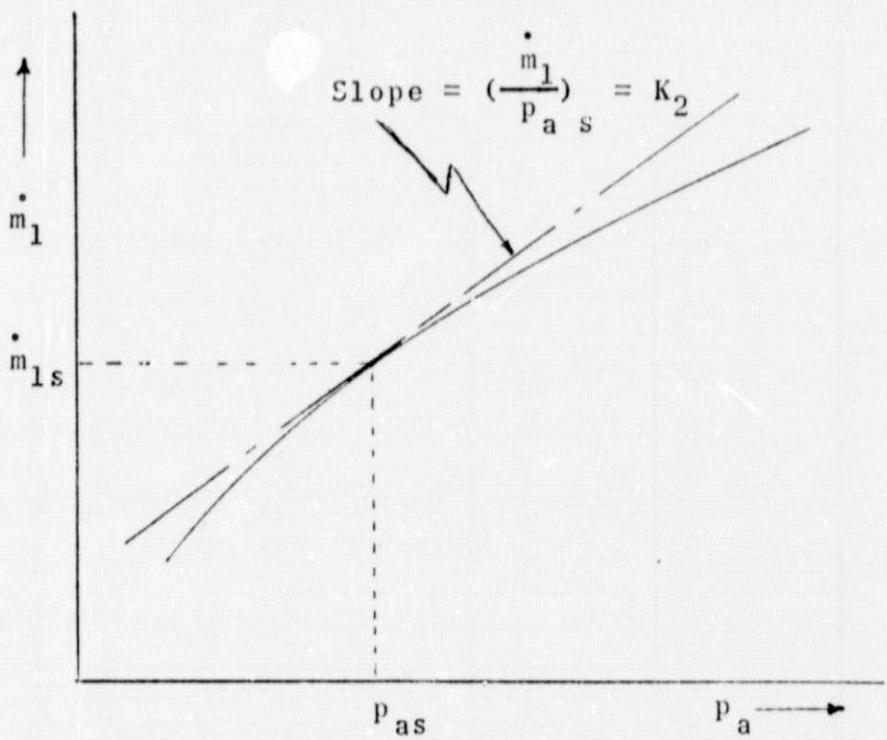


Fig. 10 Thermodynamic system considered in total temperature control system analysis. The system consists of the space <u>within</u> the tunnel circuit.



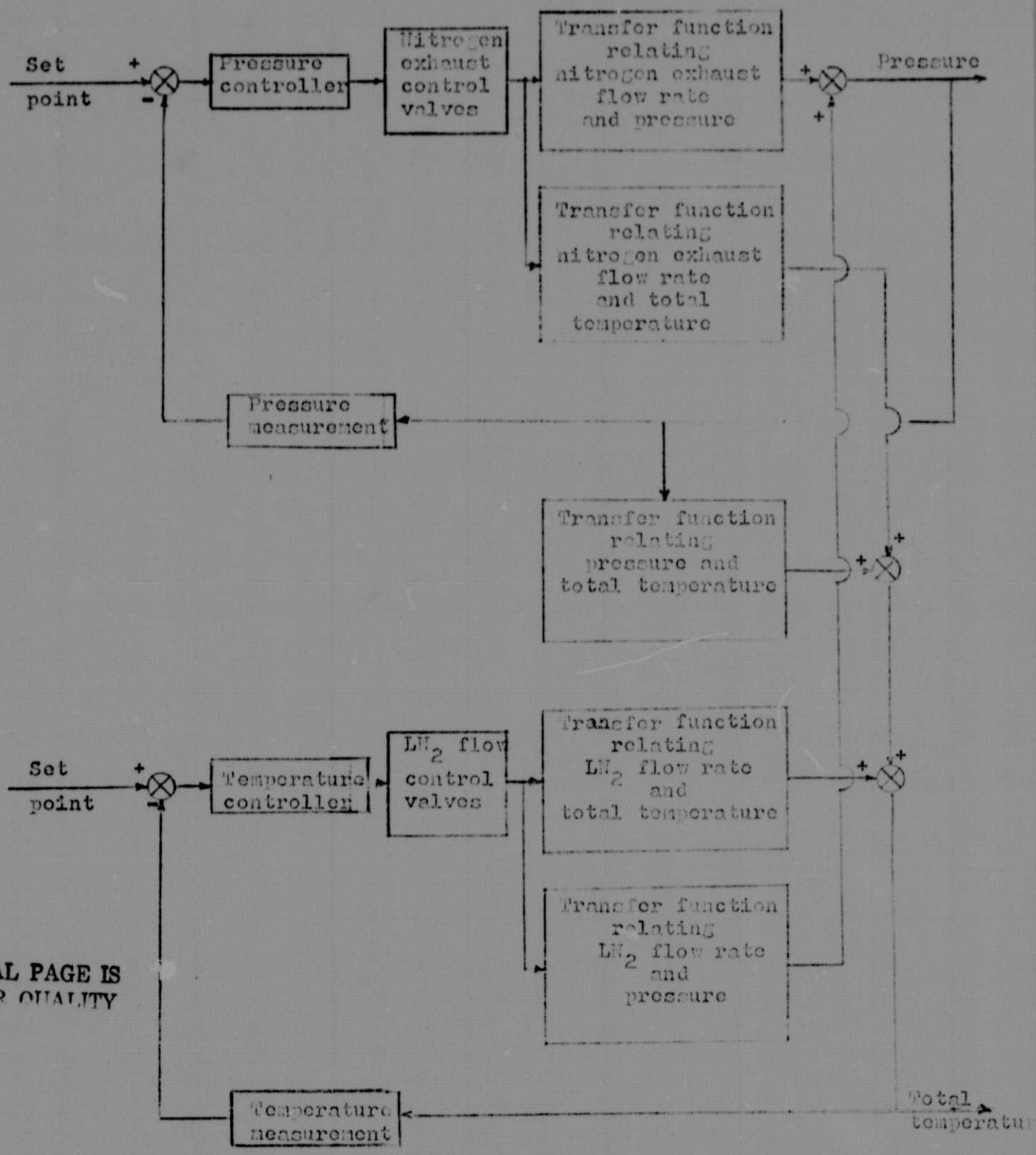
(a) $p_a = p_{as}$



(b) $p_p = p_{ps}$

ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 11 Linearization of valve characteristics from experimental tests.



ORIGINAL PAGE IS
OF POOR QUALITY

Fig. 12 Block diagram for wind tunnel control illustrating interactions between control loops.