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Computer Program for Calculating Flow Parameters and Power Requirements for Cryogenic Wind Tunnels

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Acknowledgments

Summary

A computer program has been written that performs the flow parameter calculations for cryogenic wind tunnels which use nitrogen as a test gas. The flow parameters calculated include static pressure, static temperature, compressibility factor, ratio of specific heats, dynamic viscosity, total and static density, velocity, dynamic pressure, mass-flow rate, and Reynolds number. Simplifying assumptions have been made so that the calculation of Reynolds number as well as the other flow parameters can be made on relatively small desktop digital computers. The program, which also includes various power calculations, has been developed to the point where it has become a very useful tool for the users and possible future designers of fan-driven continuous-flow cryogenic wind tunnels.

Introduction

Operating a wind tunnel at reduced temperatures, first proposed by Margoulis (refs. 1 and 2) in 1920, offers an attractive means of increasing Reynolds number while avoiding many of the practical problems associated with testing at high Reynolds numbers in conventional ambient temperature pressure tunnels. Personnel at the Langley Research Center have been studying the application of the cryogenic wind tunnel concept to various types of high Reynolds number transonic tunnels since the autumn of 1971. The usefulness of the concept (ref. 3) has been realized at Langley with the successful operation of the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT) (refs. 4 and 5) since August 1973 and with the recent completion of the National Transonic Facility (NTF) at the Langley Research Center (refs. 6 and 7).

In the early days of the application of the cryogenic concept at Langley, a computer program was written that aided in the development of cryogenic wind tunnels which use nitrogen as a test gas. This program performed the many flow parameter calculations necessary for cryogenic wind tunnels with operating temperature ranges from saturation to above ambient ($\approx$78 to 350 K). Simplifying assumptions were made so that the calculation of Reynolds number as well as other flow parameters could be made on small desktop digital computers. The program, which also includes various power calculations, has grown to the point where it has become a very useful tool for the users and possible future designers of cryogenic wind tunnels, especially those that are fan driven. The purpose of this report is to document the current version of the program and demonstrate its use. A disk containing a copy of the program is available upon request. (See page 35.) Appendix A discusses the equations for calculating some of the properties of nitrogen. A listing of the program is included in appendix B.

Symbols

A	area, m^2
a	speed of sound, m/sec
C	any aerodynamic coefficient (fig. 6)
c_p	specific heat at constant pressure, J/mol-K
c_v	specific heat at constant volume, J/mol-K
E_m	energy per unit mass, MW-sec/kg
k	thermal conductivity, W/m-K
ℓ	measure of model or test-section linear dimension, m
M	Mach number
$\mathcal{M}$	molecular weight of nitrogen, kg/mol
$\dot{m}$	mass-flow rate, kg/sec
P	power, W
p	pressure, Pa (1 bar = 0.1 MPa; 1 atm = 0.10133 MPa)
per	test-section perimeter, m

q	dynamic pressure, Pa (1 bar = 0.1 MPa)
R	Reynolds number
$\mathcal{R}$	gas constant for nitrogen, J/kg-K
r	fan pressure ratio, $p_{t,2}/p_{t,1}$
T	temperature, K
t	insulation thickness, m
V	velocity, m/sec
Z	compressibility factor
α	isentropic expansion coefficient
β	specific cooling capacity of liquid nitrogen, kJ/kg
γ	ratio of specific heats
η	efficiency factor
μ	dynamic viscosity, N-sec/m^2
ρ	density, kg/m^3
ω	plenum removal $(A/A^* - 1)$

Subscripts:

c	plenum removal compressor
$\bar{c}$	reference chord, $0.1\sqrt{A_{\text{TS}}}$
con	conduction
f	fan
hd	hydraulic diameter, $4A_{\text{TS}}/\text{per}$
i	insulation surface
L	local condition
LN_2	liquid nitrogen
m	motor
max	maximum
min	minimum
SF	tunnel surface
s	static condition
sat	saturation
TS	test section
t	total condition
tot	total
v	vapor
1	upstream of fan or compressor
2	downstream of fan or compressor
∞	free-stream condition

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Superscript:

*   tunnel throat

Program Highlights

The tunnel flow parameters calculated in the program include static pressure, static temperature, compressibility factor, ratio of specific heats, dynamic viscosity, total and static density, velocity, dynamic pressure, mass-flow rate, and Reynolds number. These parameters are calculated based on user-supplied inputs of test-section area, test-section Mach number, total pressure, and total temperature option. The parameters are valid for any Mach number. The valid range of total pressure is from slightly above 0 to 7 atm, and the valid range of total temperature is from saturation to above ambient ($\approx$78 to 350 K). To use the program outside these ranges, the user should verify that the curve fits used in this program are valid for the ranges being considered.

In addition, the program calculates the drive-fan and plenum-removal compressor powers. For the drive-fan power calculations, the program uses either the fan pressure ratio correlation for the 0.3-m TCT or any fan pressure ratio entered by the user.

The drive-fan power calculation pertains to closed circuit cryogenic transonic tunnels with Mach numbers up to approximately 1.3. Above this Mach number, a fan-driven transonic tunnel, similar in design to the 0.3-m TCT (fig. 1), becomes very inefficient. The plenum-removal compressor power is calculated independently of drive-fan power for Mach numbers greater than 1. Other assumptions made with respect to these calculations are discussed in detail later.

The program also calculates liquid nitrogen information such as the specific cooling capacity, flow rates, and power required for continuous production of LN$_2$ at the rate of consumption required for continuous tunnel operation.

Tunnel Flow Parameter Equations

Static Pressure and Temperature

The program is based on inputs of total values of temperature and pressure. The static-to-total temperature and pressure expressions for isentropic flow of an ideal gas are used to calculate the appropriate static values. In reference 8, Adcock shows the validity of using these ideal-gas ratios with the real-gas nitrogen. The relevant ideal-gas ratios are defined as

$$\frac{T_t}{T_s} = 1 + \frac{\gamma - 1}{2} M^2 \tag{1}$$

and

$$\frac{p_t}{p_s} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)} \tag{2}$$

Compressibility Factor, Ratio of Specific Heats, and Dynamic Viscosity

The values of compressibility factor Z, ratio of specific heats γ, and dynamic viscosity μ are based on simplified curve fits to calculations of the properties of nitrogen from a National Bureau of Standards (NBS) computer program (ref. 9). The NBS program is based on Jacobsen's equation of state (ref. 10). These simplified curve fits are discussed in more detail later.

Density

A simple real-gas approximation is used in solving for the density ρ by using the ideal gas equation of state with the compressibility factor as

$$\rho = \frac{p}{\mathcal{R}TZ} \tag{3}$$

Velocity

Velocity V is defined as

$$V = Ma$$

Another simple real-gas approximation is used for the speed of sound a by multiplying the ideal-gas value by $\sqrt{Z}$ (ref. 11) where

$$a = \sqrt{\gamma \mathcal{R} T Z} \tag{4}$$

so that

$$V = M\sqrt{\gamma \mathcal{R} T Z} \tag{5}$$

Dynamic Pressure

Dynamic pressure q is defined as

$$q = \frac{1}{2}\rho V^2 \tag{6}$$

By using equations (3) and (5), the dynamic pressure can be expressed as

$$q = \frac{1}{2}\gamma p_s M^2 \tag{7}$$

Mass Flow

The mass-flow rate through the test section is given by

$$\dot{m} = \rho V A_{\text{TS}}$$

In terms of dynamic pressure, the mass-flow rate is expressed as

$$\dot{m} = \frac{2A_{\text{TS}}q}{V} \tag{8}$$

For the case where $M \geq 1$, the mass-flow rate can be expressed as

$$\dot{m} = \left(\frac{2}{\gamma+1}\right)^{0.5[(\gamma+1)/(\gamma-1)]} \rho_t a_t A^*$$

This equation (ref. 12) is derived by using the throat as the reference section. The term γ can be replaced with α, the isentropic expansion coefficient. By using $\alpha = 1.4$, the test-section area as the throat area, and equations (3) and (4), this mass-flow rate can be expressed as

$$\dot{m} = \frac{(0.685)p_t A_{\text{TS}}}{\sqrt{\mathcal{R}TZ}} \tag{9}$$

The term α is discussed in detail later.

Reynolds Number

Reynolds number R is defined as

$$R = \frac{\rho V \ell}{\mu} \tag{10}$$

Reynolds number per characteristic length R/ℓ is then expressed as

$$\frac{R}{\ell} = \frac{\rho V}{\mu}$$

Expressing R/ℓ in terms of q gives

$$\frac{R}{\ell} = \frac{2q}{V\mu} \tag{11}$$

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Tunnel Power Equations

Drive-Fan Power

A real-gas approximation for drive-fan power is

$$P_f = \dot{m} \left[\frac{\gamma}{\gamma - 1} \mathcal{R} T_{t,1} (r^{(\gamma-1)/\gamma} - 1) \right] Z \tag{12}$$

This equation (ref. 11) actually calculates that portion of the main-drive fan power that is added to the stream. This equation, which is based on an isentropic compression at the fan, is the ideal-gas power equation multiplied by the compressibility factor. It does not include any efficiency factors for the motor-drive system.

Plenum-Removal Compressor Power

The equation for plenum-removal compressor power is given as

$$P_c = \frac{\omega \dot{m} c_p (T_{t,2} - T_{t,1})}{\mathcal{M} \eta_c} \tag{13}$$

This equation is similar to equation (12) by noting that

$$\frac{c_p}{\mathcal{M}} = \left(\frac{\gamma}{\gamma - 1} \right) \mathcal{R}$$

and

$$T_{t,2} - T_{t,1} = T_{t,1} (r^{(\gamma-1)/\gamma} - 1)$$

It has been modified to include a plenum-removal term ω which determines the amount of mass flow that needs to be removed to achieve a given test section Mach number. The term ω is defined as $(A/A^* - 1)$, where A is the effective area at the model location in the test section and A^* is the throat area. This assumes that you have a transonic tunnel with a ventilated, constant-area test section with the beginning of the test section acting as the throat.

For Mach numbers greater than 1, the Mach number at the throat would be 1 while the flow would expand to the desired Mach number at the model location by use of the ventilated walls and plenum-removal compressor. This simple equation assumes that all the flow through the walls is removed from the plenum, which is at static temperature and pressure, and re-injected at a location in the tunnel at total temperature and pressure conditions. Therefore, for this case,

$$T_{t,1} = T_{s,1}$$

in equation (13). This equation can be useful for the rough sizing of a compressor for plenum suction. However, caution should be exercised when using this part of the program if the actual plenum removal being considered differs in detail from that described above.

Liquid Nitrogen Requirements

The liquid nitrogen flow rate required to offset the heat added to the flow by the drive fan and plenum-removal compressor is calculated by using the following equation (ref. 3):

$$\dot{m}_{\mathrm{LN2},f} = \frac{P_f + P_c}{\beta} \tag{14}$$

The liquid nitrogen flow rate required to offset the heat added to the flow by one-dimensional conduction through the thermal insulation from the air outside the tunnel is calculated by using the following equation:

$$\dot{m}_{\mathrm{LN2,con}} = \frac{k A_{\mathrm{SF}} (T_i - T_t)}{t \beta} \tag{15}$$

The tunnel surface area term A_{SF} is based on the empirical relation, $A_{SF} = 600 A_{TS}$, which is a fairly accurate approximation for tunnels that are of a design similar to the 0.3-m TCT and to the NTF.

The power required for the continuous production of LN$_2$ at the rate of consumption required for tunnel operation is calculated by using the following equation (ref. 3):

$$P_{LN_2} = \left(\dot{m}_{LN_2,tot}\right) E_m \tag{16}$$

The term $\dot{m}_{LN_2,tot}$ is the total LN$_2$ mass flow obtained by adding equations (14) and (15). The term E_m is the energy required to produce 1 kg of LN$_2$. Note that this power has the units of megawatts since E_m is expressed in megawatt-seconds per kilogram.

Properties of Nitrogen at Cryogenic Temperatures

Some of the simplifying assumptions used in the program deal with the way the properties of nitrogen are 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 the NBS computer program (ref. 9). However, the equation which covers these wide ranges of temperature and pressure 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 the NBS nitrogen data to allow its use with small desktop digital computers. The same situation is true for the ratio of specific heats, the dynamic viscosity, and the specific cooling capacity, where relatively simple equations are used to cover only the limited ranges of temperature and pressure of interest. No particular effort has been made to optimize the form of the simplified equations. In general, the forms are those which tend to linearize and therefore reduce the number of terms required to provide an adequate fit.

Compressibility Factor

For the ranges of temperature and pressure of interest, the compressibility factor Z was calculated by using the NBS program and fitted with an equation of the form

$$Z = \frac{p}{\rho \mathcal{R} T} = 1 + Ap + Bp^2 \tag{17}$$

where a discussion of the parameters A and B is given in appendix A and in reference 3.

The values of Z calculated by equation (17) agree with the values calculated by the NBS program generally within 0.05 percent for pressures from slightly above 0 to 7 atm and temperatures from saturation to 350 K.

Ratio of Specific Heats

The real-gas ratios of specific heats were calculated from the tabulated data of reference 10 and fitted with an equation of the form

$$\gamma = \frac{c_p}{c_v} = 1.4 + Cp + Dp^2 \tag{18}$$

where a discussion of the parameters C and D is given in appendix A and in reference 3.

For most purposes, the values of γ calculated from equation (18) are adequate for pressures from slightly above 0 to 7 atm and temperatures from saturation to 350 K. The values calculated from equation (18) agree with the values calculated from the data of reference 10 generally within 0.03 percent over the entire range of temperatures from saturation to 350 K for pressures of 4 atm or less. The greatest differences exist for conditions of high pressure and low temperature. For example, the value calculated from equation (18) is about 0.3 percent less than the value calculated from the data of reference 10 at 7 atm and 110 K.

As is shown in figure 2, the real-gas values of γ vary significantly from the ideal diatomic gas value of 1.4 at the higher pressures and lower temperatures (ref. 8). As was shown by Adcock (ref. 8), the use of these values with the ideal-gas equations gives erroneous results when compared with the real-gas solutions. However, Adcock showed that by considering the isentropic expansion coefficient α in place of the ratio of specific heats γ, one can use the ideal-gas equations with $\alpha = 1.4$ because α remains very close

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to this value over the temperature and pressure range of interest in a cryogenic wind tunnel. Therefore, α replaces γ in the preceding equations in this report. The program uses a constant value of 1.4 for α. For a detailed discussion of the isentropic expansion coefficient, see reference 8.

Dynamic Viscosity

Values of the dynamic viscosity of nitrogen μ were calculated by using the NBS program and fitted with an equation of the form

$$\mu = E + FT + GT^2 \tag{19}$$

where a discussion of the parameters E, F, and G is given in appendix A and in reference 3.

The values of μ calculated from equation (19) agree with the values calculated by using the NBS program generally within 0.2 percent for pressures from slightly above 0 to 20 atm and temperatures from saturation to 350 K.

Specific Cooling Capacity

Values of the specific cooling capacity of nitrogen β were calculated from the NBS program for pressures from 1 to 10 atm and for temperatures from saturation to 350 K. The calculated values of β were fitted with an equation of the form

$$\beta = H_0 T_t + H_1 + H_2 \frac{1}{T_t} \tag{20}$$

where a discussion of the parameters H_0, H_1, and H_2 is given in appendix A. Reference 13 has a more extensive discussion of the specific cooling capacity of liquid nitrogen as it pertains to cryogenic wind tunnels. Note that the units for β are kilojoules per kilogram. The program converts the units to joules per kilogram before using β in equations (14) and (15).

Program Inputs

The following parameters are user inputs to the program: test-section area, test-section Mach number, total pressure, total-temperature option, and fan pressure ratio. These inputs can be entered in either International System of Units (SI) or U.S. Customary Units.

For the total-temperature option, one can enter any desired temperature in the range from saturation to 350 K (option 1) or choose one of three other options. With option 2, the total temperature is calculated based on a curve fit for a typical local maximum Mach number on a model as shown in figure 3 (ref. 3). This curve was constructed from inspections of pressure distributions over typical wing sections. (Airfoils having peaky pressure distributions were not included.) With option 3, the total temperature is calculated based on free-stream saturation. (A detailed discussion of the condensation effects on airfoil testing at this lower limit of operating temperature is given in ref. 14.) Option 4 calculates a total temperature based on local saturation of the flow at any local Mach number that you subsequently enter. For options 2 through 4, the total temperatures are calculated by assuming that the nitrogen expands isentropically as an ideal gas from the tunnel settling chamber through to the Mach number region under consideration. In addition, the calculated static temperatures for options 2 through 4 lie along the saturation boundary as shown in figure 4.

The fan pressure ratio input allows the user to input a value or to use the value calculated for the 0.3-m TCT. The equation for fan pressure ratio for the 0.3-m TCT is

$$r = 0.8205 M^2 R_{\text{hd}}^{-0.096} + 1.001 \tag{21}$$

This equation is taken from reference 15 and was formulated based on data taken in the 0.3-m TCT with the tunnel empty. It is a valid expression for the 0.3-m TCT up to the point where the flow begins to choke. To calculate the hydraulic diameter, an additional input of test-section perimeter is required.

Program Constants

The following is a list of parameters which are given constant values in the program (these can be easily changed by the user by modifying the "Constants" section of the program):

1. Specific heat at constant pressure for nitrogen, $c_p = 29.15$ J/mol-K (this is the value of c_p at 1 atm and 300 K)
2. Energy to produce 1 kg of LN$_2$, $E_m = 2.6$ MW-sec/kg (ref. 16 uses a value of 2.6 MW-sec/kg; this value was verified by checking with the local LN$_2$ plant that supplies the NTF; note that this value is an estimate which can change depending upon factors such as plant efficiency)
3. Thickness of insulation, $t = 0.1016$ m
4. Thermal conductivity of insulation, $k = 0.033$ W/m-K
5. Molecular weight of nitrogen, $\mathcal{M} = 0.0280134$ kg/mol
6. Efficiency of plenum-removal compressor, $\eta_c = 85$ percent
7. Gas constant for nitrogen, $\mathcal{R} = 296.7905$ J/kg-K
8. Isentropic expansion coefficient, $\alpha = 1.4$

Program Operation

Following the input of tunnel-total-temperature option, the program branches to one of four locations depending upon which temperature option has been chosen.

If option 1 is chosen, the user enters any desired total temperature in the range from saturation to 350 K (170°F).

If option 2 is chosen, a typical local Mach number is calculated based on the test-section Mach number by using a curve fit to the data of figure 3. With this local Mach number, the tunnel total pressure, and equation (2), a local static pressure is calculated. By using the logarithm of this local static-pressure value and a curve fit to the data of figure 4, a local static temperature is calculated. This local static temperature and the local Mach number are used along with equation (1) to calculate the tunnel total temperature.

If option 3 is chosen, a test-section static pressure is calculated based on the total pressure and test-section Mach number by using equation (2). By using the logarithm of this static-pressure value and the curve fit to the data of figure 4, a test-section static temperature is calculated. This static temperature and the Mach number are used along with equation (1) to calculate a total temperature based on free-stream saturation.

If option 4 is chosen, the user subsequently inputs an arbitrary value of local Mach number, and the program proceeds as in option 2 following the point in that option where the local Mach number is calculated.

Note that for options 2 through 4, the static pressure is compared to the triple-point value of static pressure for nitrogen. (See fig. 4.) If it is below the triple-point value, the program aborts.

The following is a step-by-step description of the calculations that occur after a total temperature has been calculated:

Step 1: Test-section static temperature and pressure are calculated by equations (1) and (2), respectively. Note that option 3 performed the static-pressure calculation prior to calculating the total temperature. For option 1, this test-section static pressure is compared with the triple-point value of static pressure for nitrogen. If it is below the triple-point value, the program aborts. In addition, option 1 calculates a static temperature by using a curve fit to the saturation line in figure 4. If the test-section static temperature is less than the value on the saturation line, the program aborts.

Step 2: The compressibility factor Z is calculated by using equation (17) based on the total temperature and pressure. It (Z) is also calculated based on the static conditions; however, the value obtained by using the total conditions is used in subsequent calculations (ref. 11).

Step 3: The real-gas value of the ratio of specific heats is calculated by using equation (18) with static values for temperature and pressure. This value is calculated to show its variation over the temperatures and pressures used in a cryogenic wind tunnel.

Step 4: The dynamic viscosity is calculated by using equation (19) with static values of temperature and pressure.

Step 5: The total and static densities are calculated by using equation (3).

Step 6: The velocity, dynamic pressure, and test-section mass-flow rate are calculated by using equations (5), (7), and (8), respectively. If $M \geq 1$, then the mass-flow rate is calculated by using equation (9).

Step 7: Reynolds number per unit length R/ℓ is calculated by using equation (11), and Reynolds number based on a characteristic length is calculated, where ℓ is defined as $0.1\sqrt{A_{\text{TS}}}$.

Step 8: The fan pressure ratio based on the correlation from the 0.3-m TCT is calculated by using equation (21) if this option is chosen. Otherwise, the input fan pressure ratio is utilized. The drive-fan power is then calculated by using equation (12). If $M > 1$, the plenum-removal compressor power is calculated by using equation (13).

Step 9: The specific cooling capacity is calculated by using equation (20).

Step 10: The LN_2 flow rates due to the heat added to the circuit by the fan and conduction are calculated by using equations (14) and (15), respectively. These flow rates are added to get the total LN_2 flow rate which is then expressed as a percent of the tunnel mass-flow rate.

Step 11: The power to produce LN_2 is calculated by using equation (16).

Step 12: The results from equations (12), (13), and (16) are summed to get the total power. Note that the plenum-removal compressor power is 0 if $M \leq 1$.

Step 13: The results are printed in both SI and U.S. Customary Units.

Program Results

Figure 5 shows a sample output from the program. The results are listed in four categories: physical tunnel parameters, tunnel flow parameters, power parameters, and LN_2 flow parameters. For options 2 and 4, there is a fifth category which lists the local conditions.

In addition to using the results in this format, the program can be used in conjunction with a graphics routine to generate plots of various parameters. For example, since a cryogenic wind tunnel has independent control of M, R, and q, operating envelopes in terms of two of these parameters can be generated while holding the third parameter constant. Samples of these plots are shown in figures 6, 7, and 8. In addition, plots involving power parameters can be generated as shown in figures 9 and 10. Also, performance charts, similar to the ones shown in figures 11 and 12, can be made by using this program. The program modifications necessary to generate these plots (figs. 6 through 12) are relatively straightforward and therefore are not described in this report.

Data Comparisons

Figures 11 and 12 contain a few data points from the 0.3-m TCT and the NTF which are used for comparison with the values calculated from the program. These data are tabulated in table I. The drive-motor power data in table I is the amount of power supplied to the motor. To compare this with the drive-fan power calculated in the program, an overall drive-motor system and fan efficiency is assumed. For both tunnels, the overall efficiency is assumed to be 80 percent. The values plotted in figures 11 and 12 include the efficiency. Note that the fan power curves in these figures were generated by using equation (21) which is based on the 0.3-m TCT.

For the 0.3-m TCT data, the comparison is very good. All three values calculated by using the program are within 16 percent of their respective data values. Also, the percent difference decreases as the power level increases.

For the NTF data, the calculated values are within 33 and 9 percent of their respective data values. A more accurate comparison with the NTF data may be obtained if a fan power correlation for the NTF is used. Reference 17 contains such a correlation.

Note that the assumed overall efficiency of 80 percent for the drive-motor system and fan resulted in all five data values for P_f being higher than their respective calculated program values. This trend may imply that an overall efficiency of 80 percent is too high for both tunnels.

Concluding Remarks

A computer program has been written that performs the flow parameter calculations for cryogenic wind tunnels which use nitrogen as a test gas. Simplifying assumptions have been made so that the

calculations of Reynolds number as well as other flow parameters can be made on relatively small desktop digital computers. The program, which also includes various power calculations, has been developed to the point where it has become a very useful tool for the users and possible future designers of fan-driven continuous-flow cryogenic wind tunnels.

The calculations by the program of drive-fan power agree well with the measured data from the 0.3-m TCT. Similar comparisons for the NTF were also good; however, a more accurate comparison with the measured NTF data may be obtained if a fan-power correlation for the NTF is used rather than the correlation for the 0.3-m TCT that is used by the program.

TABLE I. SUMMARY OF TUNNEL DATA PLOTTED IN FIGURES 11 AND 12

Langley 0.3-Meter Transonic Cryogenic Tunnel ($\sqrt{A_{\mathrm{TS}}} = 0.35$ m)

Point	M	p_t, atm	T_t, K	$R_{\bar{c}}$	P_m, kW	P_f,[a] kW
1	0.700	1.36	105	2.66×10^6	212	170
2	0.700	3.06	105	5.98×10^6	400	320
3	0.700	5.85	105	11.52×10^6	685	548

National Transonic Facility (NTF) at the Langley Research Center ($\sqrt{A_{\mathrm{TS}}} = 2.5$ m)

Point	M	p_t, atm	T_t, K	$R_{\bar{c}}$	P_m, MW	P_f,[a] MW
1	0.712	6.46	117	77.00×10^6	49.3	39.4
2	0.972	2.03	113	29.74×10^6	24.3	19.4

[a] P_f is calculated by using P_m and assuming an efficiency of 80 percent.
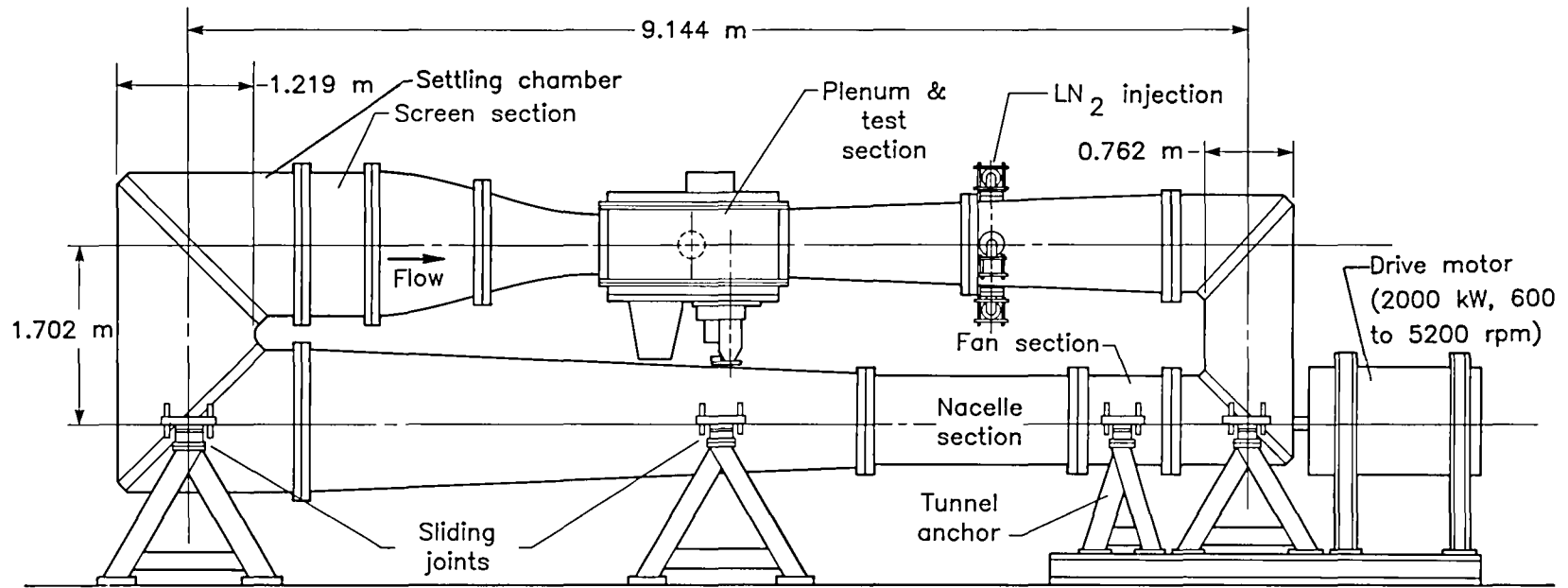
Figure 1. Sketch of Langley 0.3-Meter Transonic Cryogenic Tunnel. (The size of two-dimensional test-section insert shown is 20 by 60 cm.)
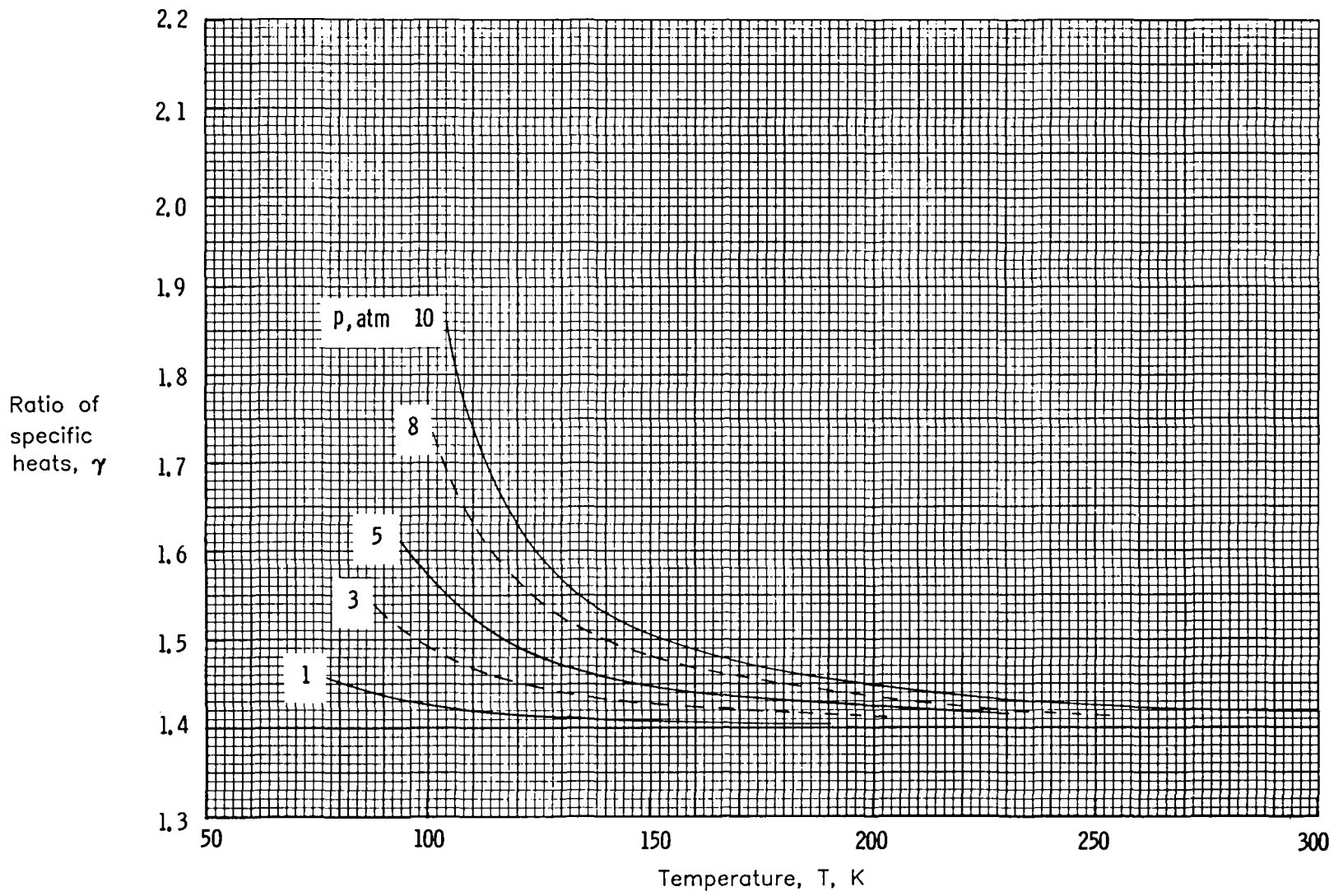
Figure 2. Variation of ratio of specific heats γ with temperature and pressure.
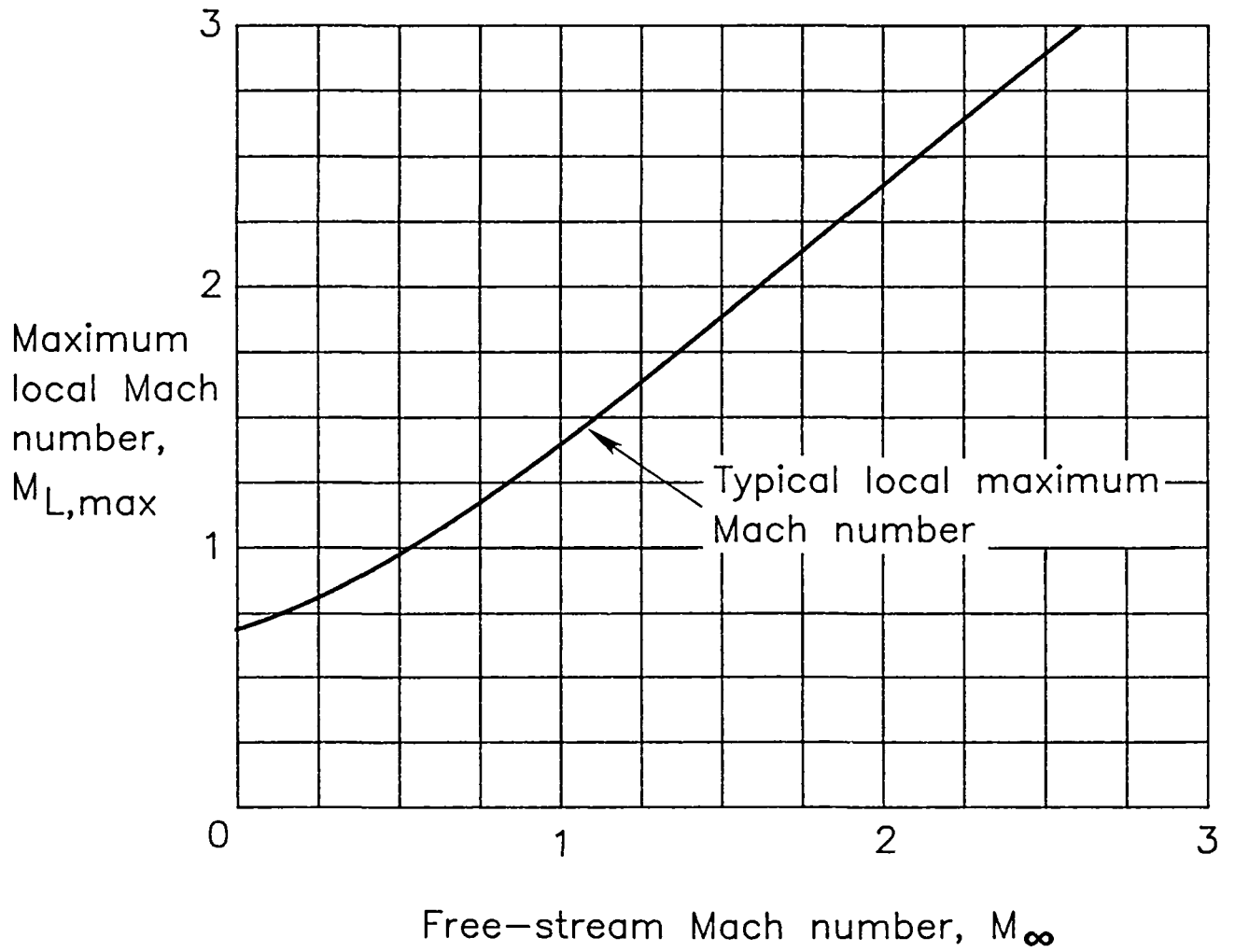
Figure 3. Assumed local Mach number as function of free-stream Mach number.
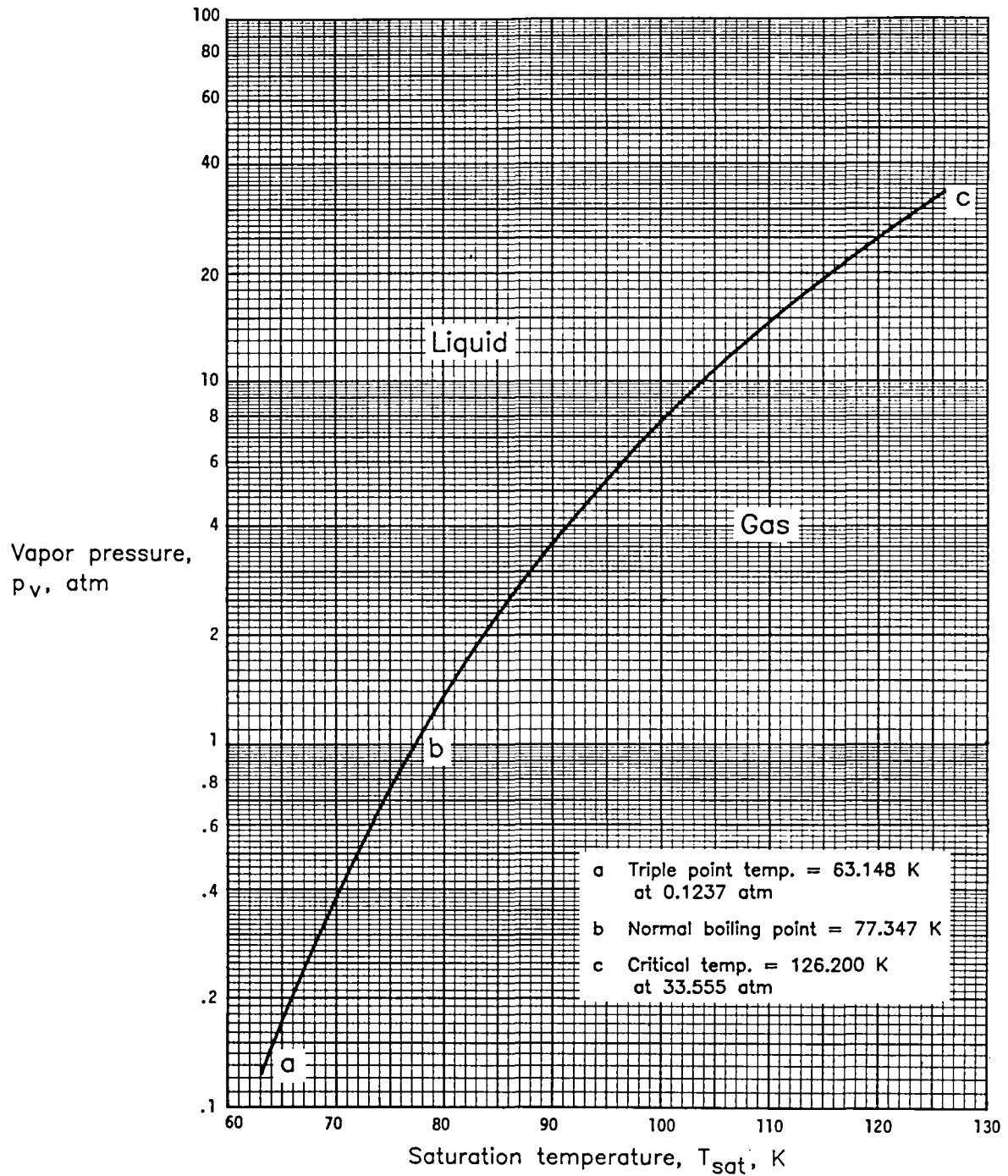
Figure 4. Vapor pressure for nitrogen as function of saturation temperature.

The chart shows vapor pressure p_v, atm (vertical log axis from .1 to 100) versus Saturation temperature, T_{sat}, K (horizontal axis from 60 to 130). Regions labeled Liquid and Gas.

a   Triple point temp. = 63.148 K at 0.1237 atm
b   Normal boiling point = 77.347 K
c   Critical temp. = 126.200 K at 33.555 atm

CRYOGENIC WIND TUNNEL FLOW PARAMETER PROGRAM
UTILIZING NITROGEN AS THE TEST GAS

```
PHYSICAL TUNNEL PARAMETERS                  SI              U.S. CUSTOMARY
  Test section area ....................  6.25 m^2     =    67.27 ft^2
  Test section perimeter ............... 10.00 m       =    32.81 ft
  Reference chord ......................  0.25 m       =     0.82 ft
  Tunnel surface area .............. 3750.00 m^2       =40364.67 ft^2
  Insulation thickness .................  0.10 m       =     0.33 ft

TUNNEL FLOW PARAMETERS
  Total pressure ....................... 7.100 bars    =  102.977 lb/in^2
  Static pressure ...................... 3.751 bars    =   54.401 lb/in^2
  Total temperature .................. 120.000 K       = -243.670 F
  Static temperature ................. 100.000 K       = -279.670 F
  Total density ....................... 21.788 kg/m^3  =    0.0423 slugs/ft^3
  Test section static density ......... 13.812 kg/m^3  =    0.0268 slugs/ft^3
  Compressibility factor based on
    total temperature ................ 0.9150
  Compressibility factor based on
    static temperature ............... 0.9220
  Real gas ratio of specific heats ..... 1.5156
  Viscosity ......................... 7047.E-09 N-s/m^2 = 147.E-09 lb-s/ft^2
  Mach number .......................... 1.000
  Velocity ........................... 194.981 m/s     =  639.702 ft/s
  Test section mass flow ........... 16832.150 kg/s    = 1153.369 slugs/s
  Dynamic pressure ..................... 2.626 bars    = 5483.598 lb/ft^2
  Reynolds number per meter ........... 3.821E+08
  Reynolds number per foot .............................. 1.165E+08
  Reynolds number based on
    reference chord .................. 9.554E+07

POWER PARAMETERS
  Plenum removal ....................... 0.000 %
  Plenum removal compressor
    efficiency ....................... 85.000 %
  Fan pressure ratio ................... 1.1137
  Fan power ........................... 58.175 MW       =    7.798E+04 hp
  Plenum removal compressor power ..... 0.000 MW        =    0.000E+00 hp
  Total drive power ................... 58.175 MW       =    7.798E+04 hp
  Power for continuous
    production of LN2 ............... 645.140 MW        =    8.648E+05 hp
  Total power for
    continuous running ............. 703.314 MW        =    9.428E+05 hp

LN2 FLOW PARAMETERS
  Cooling capacity .................... 235.335 kJ/kg   =  101.244 Btu/lb
  LN2 flow rate for fan heat ......... 247.199 kg/s     =   16.939 slugs/s
  LN2 flow rate for conduction ........ 0.932 kg/s      =    0.064 slugs/s
  Total LN2 flow rate ................ 248.131 kg/s     =   17.002 slugs/s
  Total LN2 flow/test section flow ..... 1.474 %
```

Figure 5. Sample of program output. (Fan power was calculated by using eq. (21).)

$$M_\infty = 1.0, \ 2.5\text{-by } 2.5\text{-m test section}$$
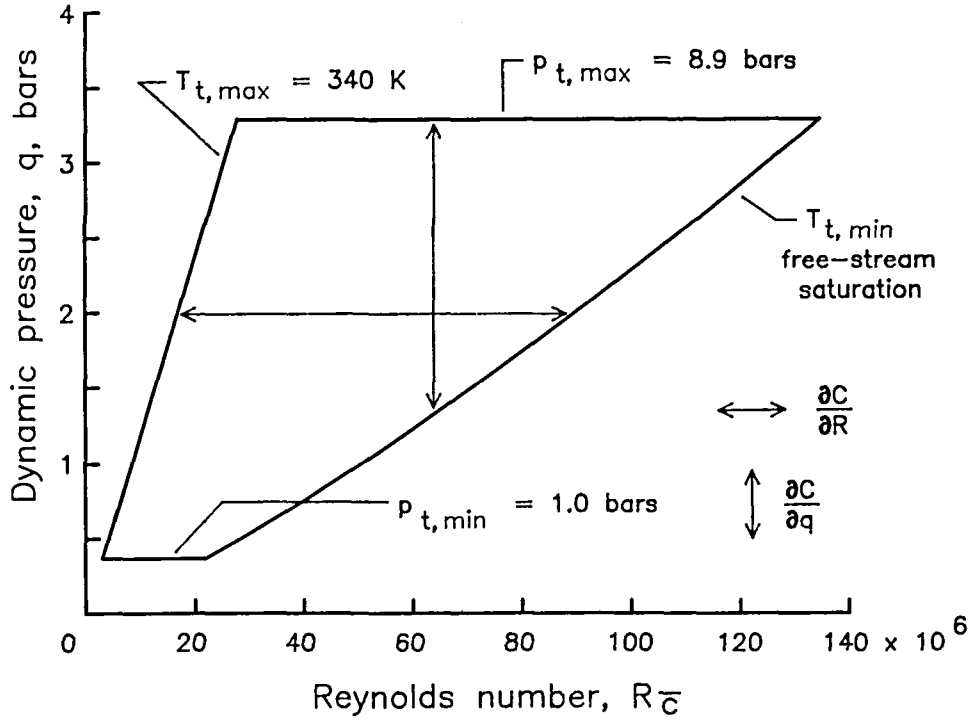
Figure 6. Constant Mach number operating envelope.

$$R_{\bar{c}} = 50 \times 10^6, \ 2.5\text{-by } 2.5\text{-m test section}$$
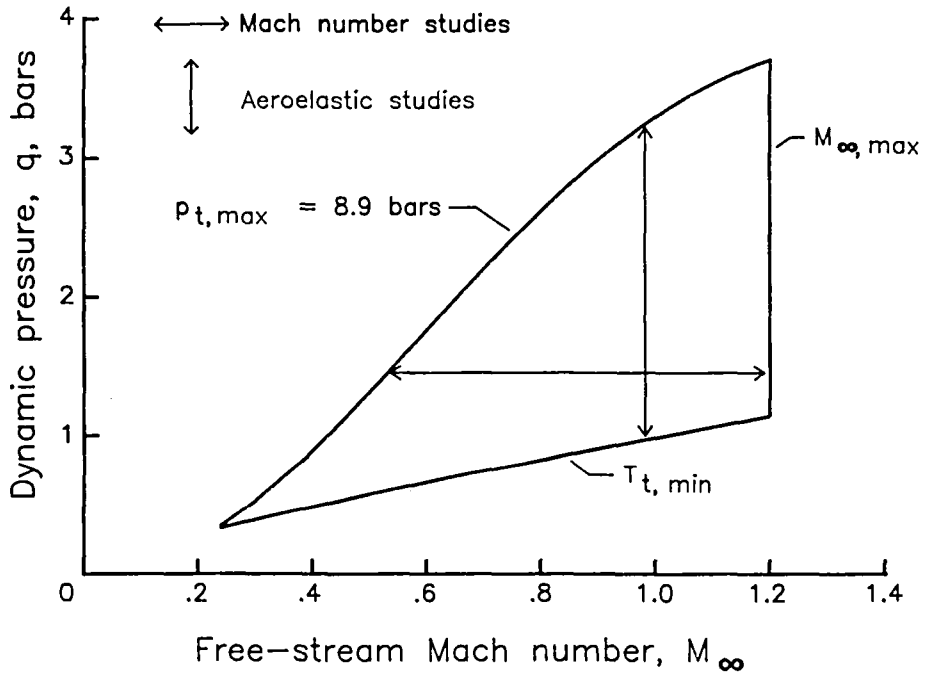
Figure 7. Constant Reynolds number operating envelope.

17
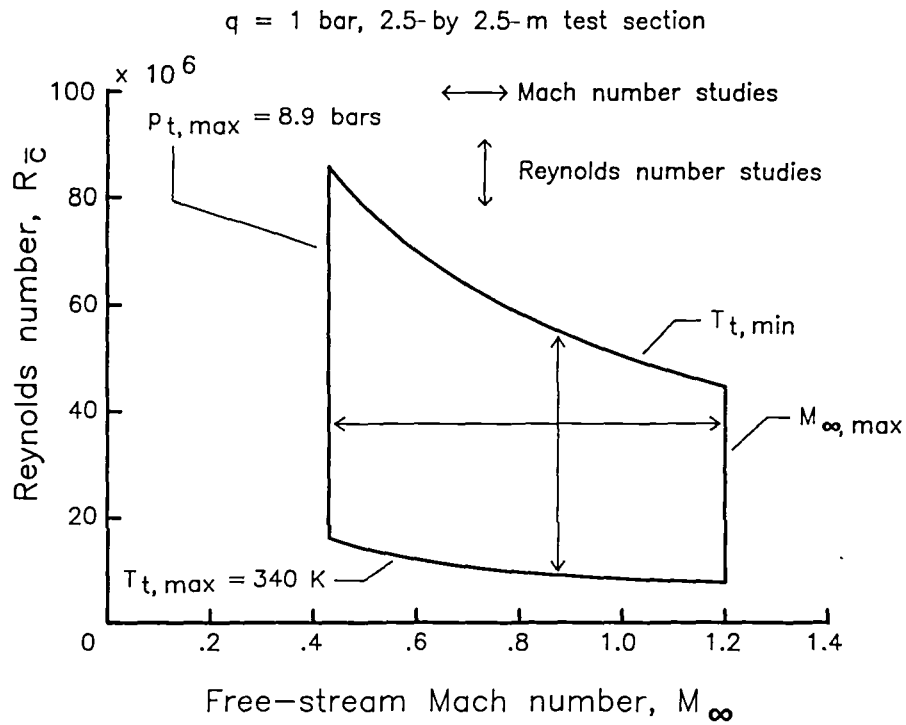
Figure 8. Constant dynamic pressure operating envelope.
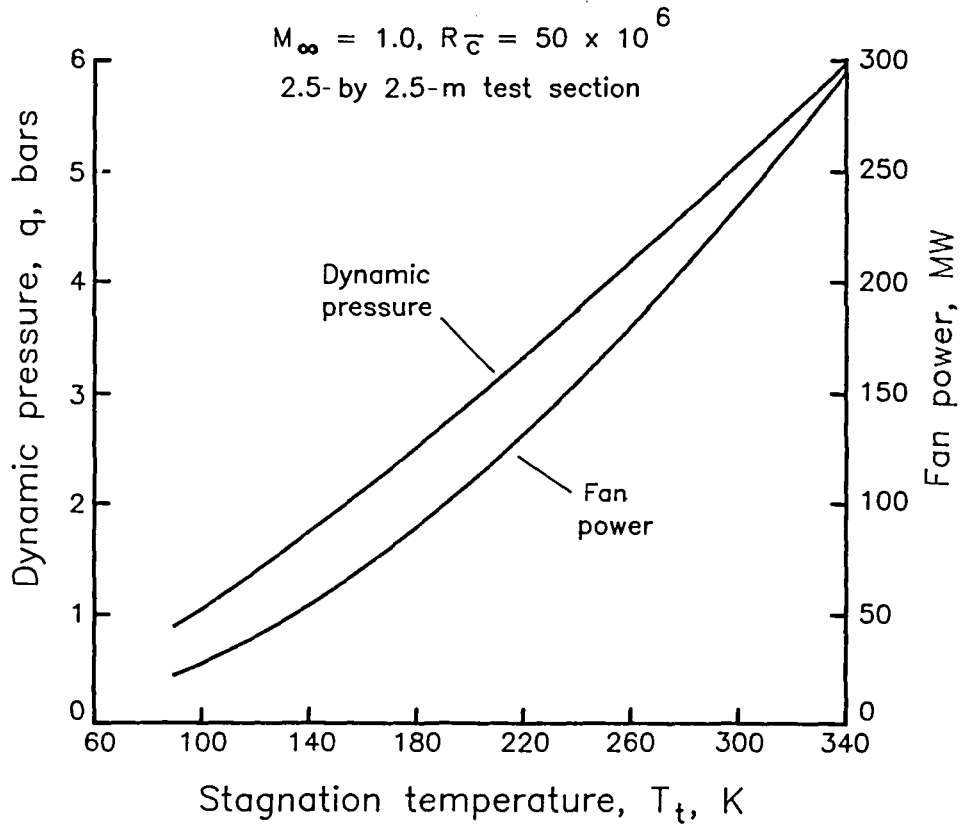
Figure 9. Variation of dynamic pressure and drive power with stagnation temperature. (Note that fan power was calculated by using eq. (21).)
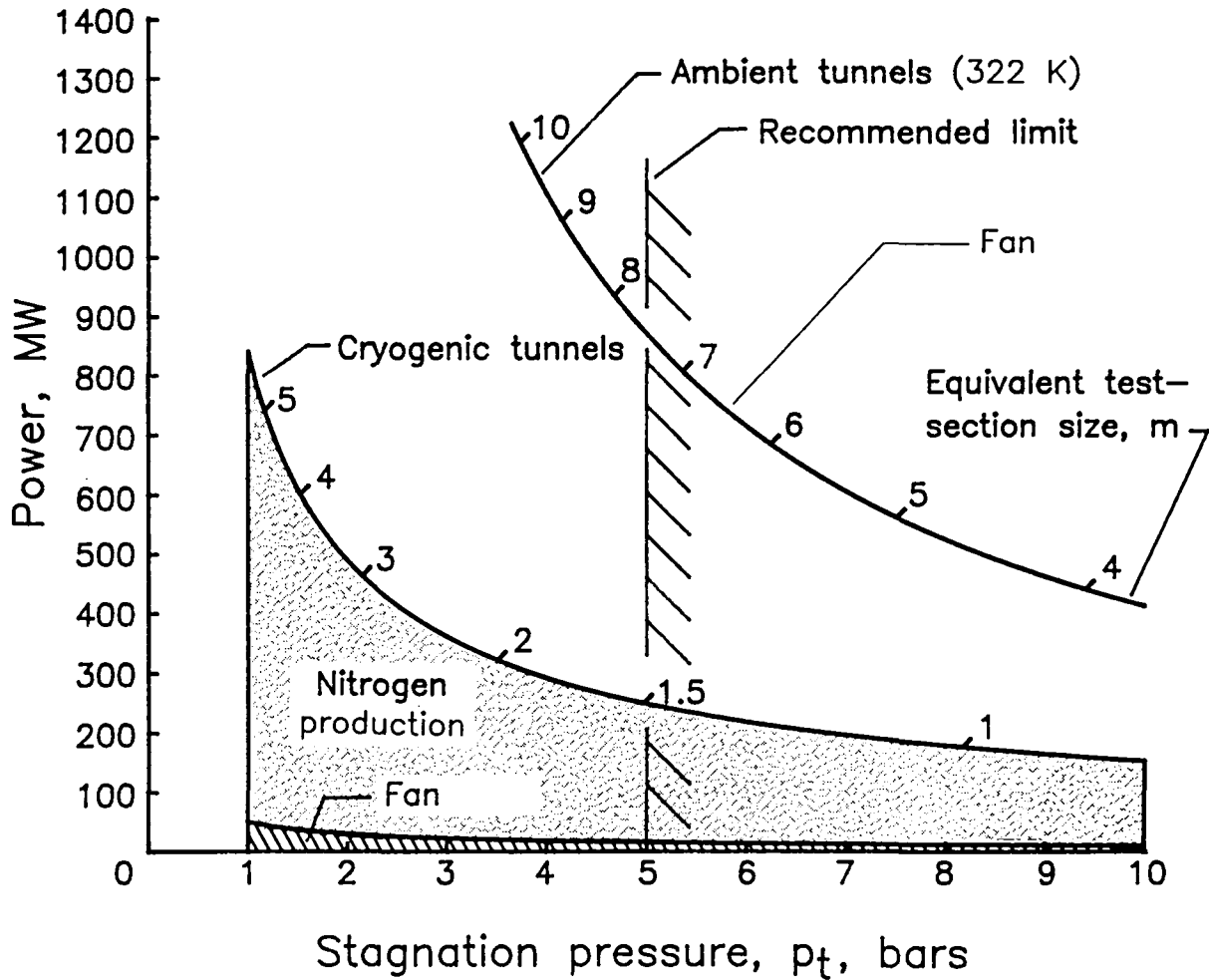
Figure 10. Total power required for continuous running as a function of stagnation pressure for ambient and cryogenic fan-driven tunnels. $M_\infty = 1.0$, $R_{\bar{c}} = 50 \times 10^6$. (Note that fan power portions were calculated by using eq. (21).)
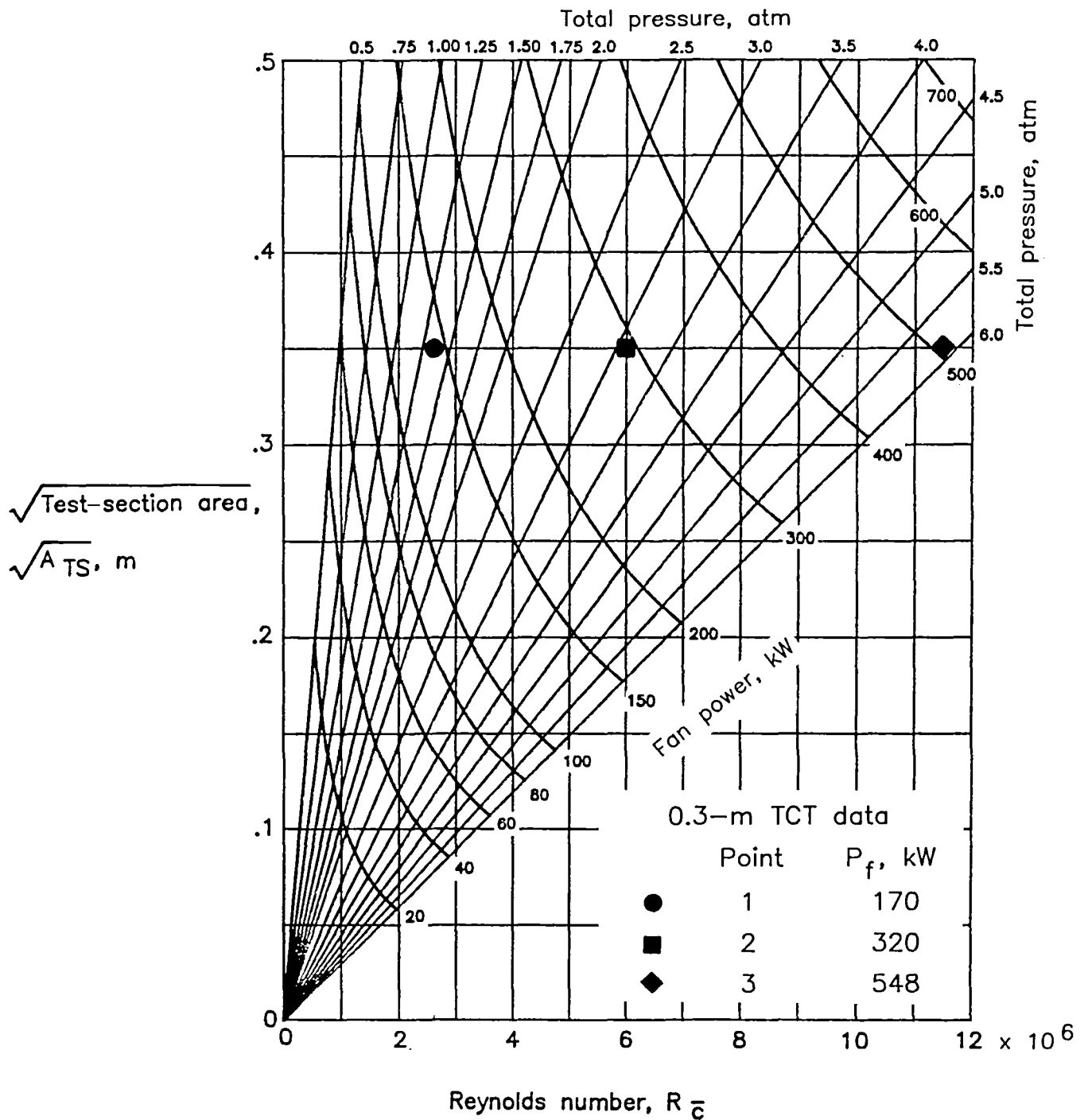
Figure 11. Performance chart for cryogenic nitrogen tunnel showing relationship between tunnel size, stagnation pressure, fan power, and Reynolds number. $M_\infty = 0.70$; $T_t = 105$ K. (Note that fan power was calculated by using eq. (21) and test-section perimeter from 0.3-m TCT.)

(a) $M_\infty = 0.712$; $T_t = 117$ K.

Figure 12. Performance chart for cryogenic nitrogen tunnel showing relationship between tunnel size, stagnation pressure, fan power, and Reynolds number. (Note that fan power was calculated by using eq. (21) and test-section perimeter from NTF.)

(b) $M_\infty = 0.972$; $T_t = 113$ K.

Figure 12. Concluded.

Appendix A

Equation Parameters for Calculating Properties of Nitrogen at Cryogenic Temperatures

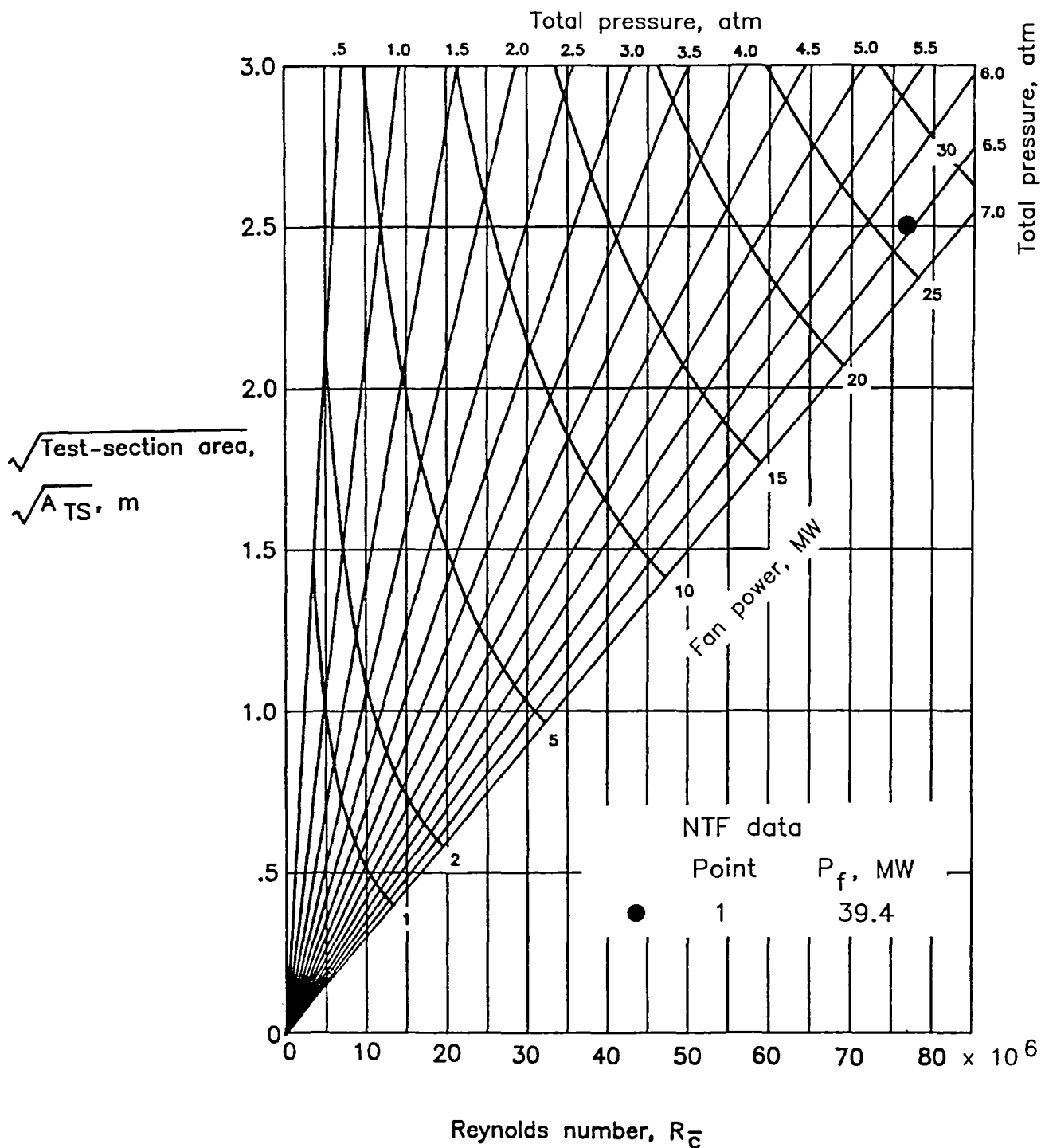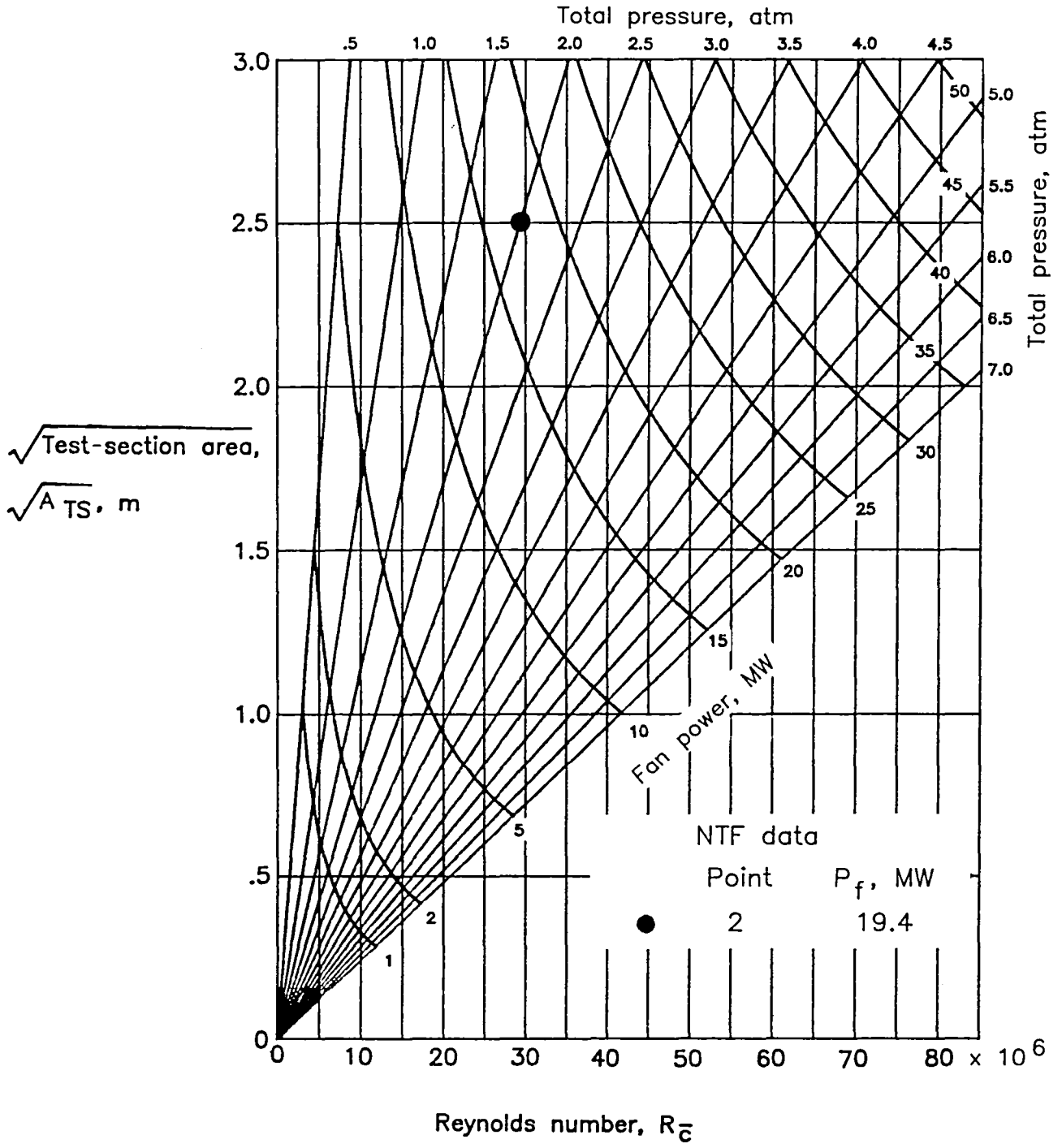Note that the values for pressure used in the equations in this appendix should be in atmospheres.

Compressibility Factor Z

The compressibility factor Z is calculated by using equation (17), which is (ref. 3)

$$Z = \frac{p}{\rho \mathcal{R} T} = 1 + Ap + Bp^2$$

The parameters A and B are given by

$$\ln\, -A = \sum_{i=0}^{4} a_i T^i$$

$$\ln\, -B = \sum_{i=0}^{4} b_i T^i$$

where the values of a_i and b_i are as follows:

$$a_0 = 1.370 \qquad\qquad b_0 = 5.521$$
$$a_1 = -8.773 \times 10^{-2} \qquad\qquad b_1 = -1.986 \times 10^{-1}$$
$$a_2 = 4.703 \times 10^{-4} \qquad\qquad b_2 = 7.817 \times 10^{-4}$$
$$a_3 = -1.386 \times 10^{-6} \qquad\qquad b_3 = -1.258 \times 10^{-6}$$
$$a_4 = 1.462 \times 10^{-9} \qquad\qquad b_4 = 5.333 \times 10^{-10}$$

Ratio of Specific Heats γ

The ratio of specific heats γ is calculated by using equation (18), which is (ref. 3)

$$\gamma = \frac{c_p}{c_v} = 1.4 + Cp + Dp^2$$

The parameters C and D are given by

$$\ln\, C = \sum_{i=0}^{4} c_i T^i$$

$$\ln\, D = \sum_{i=0}^{1} d_i T^i$$

where the values of c_i and d_i are as follows:

$$c_0 = 1.86799 \qquad\qquad d_0 = -1.25126$$
$$c_1 = -9.52187 \times 10^{-2} \qquad\qquad d_1 = -4.96900 \times 10^{-2}$$
$$c_2 = 5.14638 \times 10^{-4}$$
$$c_3 = -1.35950 \times 10^{-6}$$
$$c_4 = 1.31676 \times 10^{-9}$$

Dynamic Viscosity μ

The dynamic viscosity is calculated by using equation (19), which is (ref. 3)

$$\mu = E + FT + GT^2$$

The parameters E, F, and G are given by

$$E = \sum_{i=0}^{2} e_i p^i$$

$$F = \sum_{i=0}^{2} f_i p^i$$

$$G = \sum_{i=0}^{2} g_i p^i$$

where the values e_i, f_i, and g_i are as follows:

$e_0 = -2.86896 \times 10^{-7}$ $f_0 = 7.55226 \times 10^{-8}$ $g_0 = -4.89417 \times 10^{-11}$

$e_1 = 1.23678 \times 10^{-7}$ $f_1 = -6.10964 \times 10^{-10}$ $g_1 = 9.51640 \times 10^{-13}$

$e_2 = 1.29862 \times 10^{-9}$ $f_2 = -1.22089 \times 10^{-11}$ $g_2 = 2.52130 \times 10^{-14}$

Specific Cooling Capacity β

The specific cooling capacity is calculated by using equation (20), which is (ref. 13)

$$\beta = H_0 T_t + H_1 + H_2 \frac{1}{T_t}$$

The parameters H_0, H_1, and H_2 are given by

$$H_0 = 1.0379 - (3.9157 \times 10^{-3}) p_t$$
$$H_1 = (1.2125 \times 10^2) + 2.1577 p_t$$
$$H_2 = 66.585 - (3.9122 \times 10^2) p_t$$

Appendix B

Program Listing

This listing is written in IBM "Advanced Basic" language for the IBM Personal Computers PC/XT/AT.

```
10  .' ***********************************************************************
20  ' ****%*********** THIS PROGRAM CALCULATES FLOW PARAMETERS AND *************
30  ' *************** POWER REQUIREMENTS FOR CRYOGENIC WIND TUNNELS ***********
40  ' *************** UTILIZING NITROGEN AS THE TEST GAS. ********************
50  ' ***********************************************************************
60  ' ***********************************************************************
70  ' *************** NOTE THAT FOR THE POWER CALCULATIONS, THE **************
71  ' *************** PROGRAM IS SET UP FOR TRANSONIC POROUS *****************
80  ' *************** TUNNELS WITH A MACH NUMBER LIMIT OF 1.3. ***************
90  ' *************** HOWEVER, THE VARIOUS FLOW PARAMETER ********************
100 '*************** CALCULATIONS ARE VALID FOR ANY MACH NUMBER. ************
110 ' ***********************************************************************
120 ' ***********************************************************************
130 ' *************** THE PROGRAM INPUTS CAN BE IN EITHER SI OR **************
140 ' *************** U.S. CUSTOMARY UNITS.  ALL CALCULATIONS IN *************
150 ' *************** THE PROGRAM ARE PERFORMED USING SI UNITS. **************
160 ' *************** ALL VALUES ARE SUBSEQUENTLY CONVERTED TO ***************
170 ' *************** U.S. CUSTOMARY UNITS.  VALUES ARE PRINTED **************
180 ' *************** ON RESULTS PAGE IN BOTH SI AND U.S. CUSTOMARY **********
190 ' *************** UNITS. *************************************************
200 ' ***********************************************************************
210 ' ***********************************************************************
220 ' *************** PROGRAM COMMENTS REFER TO THE LINE NUMBER(S) ***********
230 ' *************** FOLLOWING THE COMMENT STATEMENT. **********************
240 ' ***********************************************************************
250 ' ***********************************************************************
260 ' ************************** CONSTANTS *********************************
270 ' ***********************************************************************
280 '
290 ' <------- CP is the specific heat at constant pressure of
                nitrogen in J/mol-K.
300 '
310 CP=29.15
320 '
330 ' <------- EM is the energy required to produce 1 kg of liquid
                nitrogen.
340 '
350 EM=2.6
360 '
370 ' <------- INSUL.THICKNESS is the thickness of the tunnel
                insulation expressed in meters.
380 '
390 INSUL.THICKNESS=.1016
400 '
410 ' <------- K is the thermal conductivity of the insulation
                in W/m-deg C at 295 K.
420 '
430 K=.033
440 '
450 ' <------- M is the molecular weight of nitrogen in kg/mol.
460 '
470 M=.0280134
480 '
530 ' <------- PL.COMP.EFF is the plenum removal compressor
                efficiency in percent.
540 '
550 PL.COMP.EFF=85
560 '
570 ' <------- R is the gas constant for nitrogen expressed
                in J/kg-K.
```

```
580  '
590  R=296.7905
600  '
610  ' <------- ALPHA is the isentropic expansion coefficient.
620  '
630  ALPHA=1.4
640  '
650  ' <------- RATIO1 is a common ratio used frequently throughout
                 this program.
660  '
670  RATIO1=ALPHA/(ALPHA-1)
680  '
690  ' <------- RATIO2 is a common ratio used frequently throughout
                 this program.
700  '
710  RATIO2=(ALPHA-1)/2
720  ' ****************************************************************************
730  ' *************************** INPUTS ****************************************
740  ' ****************************************************************************
750  INPUT "The results can be output to the screen (enter 1) or to the printer (
enter 2).  Enter the appropriate number";OUTPUT
760  IF OUTPUT=1 THEN OPEN "scrn:" FOR OUTPUT AS #1
770  IF OUTPUT=2 THEN OPEN "lpt1:" AS #1
780  INPUT "The input parameters can be entered in either SI units (enter 1) or
             English units (enter 2).  Enter the appropriate number";UNITS
790  COLOR ,1
800  CLS
810  IF UNITS<>1 AND UNITS<>2 THEN 780
820  COLOR 15:LOCATE 2,73:PRINT "page 1"
830  LOCATE 3,17:PRINT "Cryogenic Wind Tunnel Flow Parameter Program"
840  LOCATE 4,22:PRINT "Utilizing Nitrogen as the Test Gas"
850  COLOR 10,0:LOCATE 6,18:PRINT CHR$(213)+STRING$(40,205)+CHR$(184)
860  IF UNITS=1 THEN 890
870  LOCATE 7,18:PRINT CHR$(179)+"      Program Inputs in English Units     "+CHR$(
179)
880  GOTO 900
890  LOCATE 7,18:PRINT CHR$(179)+"        Program Inputs in SI Units        "+CHR$(
179)
900  LOCATE 8,18:PRINT CHR$(212)+STRING$(40,205)+CHR$(190)
910  COLOR 0,10:LOCATE 11,10:PRINT" User Inputs "
920  LOCATE 11,38:PRINT" Acceptable Range "
930  IF UNITS=1 THEN 1230
940  IF UNITS=2 THEN 960
950  ' ******************** INPUTS FOR ENGLISH UNITS ********************
960  COLOR 15,1:LOCATE 13,7:PRINT "Test section area (ft^2)"
970  LOCATE 15,7:PRINT "Mach number"
980  LOCATE 18,7:PRINT "Total pressure (lb/in^2)"
990  COLOR 14:LOCATE 13,40:PRINT "No restriction"
1000 LOCATE 15,40:PRINT "No restriction for"
1010 LOCATE 16,40:PRINT "calculating flow parameters *"
1020 LOCATE 18,40:PRINT "0 < Pt < = 103"
1030 LOCATE 23,5:PRINT "* The power calculations are subject to restrictions.  S
ee documentation."
1040 LOCATE 13,7,1,0,7:INPUT "Test section area (ft^2)";TEST.SECT.AREA2
1050 COLOR 10:LOCATE 13,7:PRINT "Test section area (ft^2)";TEST.SECT.AREA2:COLOR
 15
1060  ' Converting ft^2 to m^2
1070 TEST.SECT.AREA1=TEST.SECT.AREA2*.3048^2
1080 LOCATE 15,7:INPUT "Mach number";MACH.NUMBER
1090 IF MACH.NUMBER<=1.3 THEN 1110
```

```
1100 COLOR 12:LOCATE 15,40:PRINT "Out of range for   ":LOCATE 16,40:PRINT "power
calculations             "
1110 COLOR 10:LOCATE 15,7:PRINT "Mach number";MACH.NUMBER:COLOR 15,1
1120 LOCATE 18,7:INPUT "Total pressure (lb/in^2)";TOTAL.PRESSURE2
1130 IF TOTAL.PRESSURE2>0 AND TOTAL.PRESSURE2<=103 THEN 1150
1140 COLOR 12:LOCATE 18,40:PRINT "0 < Pt < = 103":COLOR 28:LOCATE 18,55:PRINT "
  Out of range! Try again":COLOR 12:LOCATE 18,28:PRINT"             ":GOTO 1120
1150 COLOR 14:LOCATE 18,40:PRINT "0 < Pt < = 103":LOCATE 18,55:PRINT "
         "
1160 COLOR 10:LOCATE 18,7:PRINT "Total pressure (lb/in^2)";TOTAL.PRESSURE2:COLOR
 15,1
1170  ' Converting lb/in^2 to N/m^2
1180 TOTAL.PRESSURE3=TOTAL.PRESSURE2*6894.75715#
1190  ' Converting N/m^2 to bars
1200 TOTAL.PRESSURE1=TOTAL.PRESSURE3/100000!
1210 GOTO 1530
1220  ' *********************** INPUTS FOR SI UNITS ************************

1230 COLOR 15,1:LOCATE 13,7:PRINT "Test section area (m^2)"
1240 LOCATE 15,7:PRINT "Mach number"
1250 LOCATE 18,7:PRINT "Total pressure (bars)"
1260 COLOR 14:LOCATE 13,40:PRINT "No restriction"
1270 LOCATE 15,40:PRINT "No restriction for"
1280 LOCATE 16,40:PRINT "calculating flow parameters *"
1290 LOCATE 18,40:PRINT "0 < Pt < = 7.1"
1300 LOCATE 23,5:PRINT "* The power calculations are subject to restrictions.  S
ee documentation."
1310 LOCATE 13,7,1,0,7:INPUT "Test section area (m^2)";TEST.SECT.AREA1
1320 COLOR 10:LOCATE 13,7:PRINT "Test section area (m^2)";TEST.SECT.AREA1:COLOR
15
1330  ' Converting m^2 to ft^2
1340 TEST.SECT.AREA2=TEST.SECT.AREA1/.3048^2
1350 LOCATE 15,7:INPUT "Mach number";MACH.NUMBER
1360 IF MACH.NUMBER<=1.3 THEN 1380
1370 COLOR 12:LOCATE 15,40:PRINT "Out of range for   ":LOCATE 16,40:PRINT "power
calculations             "
1380 COLOR 10:LOCATE 15,7:PRINT "Mach number";MACH.NUMBER:COLOR 15,1
1390 LOCATE 18,7:INPUT "Total pressure (bars)";TOTAL.PRESSURE1
1400 IF TOTAL.PRESSURE1>0 AND TOTAL.PRESSURE1<=7.1 THEN 1420
1410 COLOR 12:LOCATE 18,40:PRINT "0 < Pt < = 7.1":COLOR 28:LOCATE 18,55:PRINT "
  Out of range! Try again":COLOR 12:LOCATE 18,28:PRINT"             ":GOTO 1390
1420 COLOR 14:LOCATE 18,40:PRINT "0 < Pt < = 7.1":LOCATE 18,55:PRINT "
         "
1430 COLOR 10:LOCATE 18,7:PRINT "Total pressure (bars)";TOTAL.PRESSURE1:COLOR 15
,1
1440  ' Converting bars to N/m^2
1450 TOTAL.PRESSURE3=TOTAL.PRESSURE1*100000!
1460  ' Converting N/m^2 lb/in^2
1470 TOTAL.PRESSURE2=TOTAL.PRESSURE3/6894.75715#
1480  ' Tunnel surface area expressed in meters
1490  ' (Note that using 600 as a multiplication factor gives
1500  '  the approximate external surface area for the 0.3-m TCT.
1510  '  This number may work for other typically designed tunnels
1520  '  or may be changed as required.)
1530 TUN.SURF.AREA1=TEST.SECT.AREA1*600
1540  ' Converting meters to feet
1550 TUN.SURF.AREA2=TUN.SURF.AREA1/.3048^2
1560  ' Converting N/m^2 to atmospheres
1570 TOTAL.PRESSURE4=TOTAL.PRESSURE3/101325!
1580  ' Expressing static pressures in atmospheres
```

```
1590 STATIC.PRESS4=TOTAL.PRESSURE4*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)
1600 CLS
1610 LOCATE 2,73:PRINT "page 2"
1620 PRINT "TOTAL TEMPERATURE OPTIONS"
1630 PRINT
1640 PRINT "  ENTER 1 to run the program based on any desired total temperature"

1650 PRINT "  in the range from saturation to 350 K (170 degrees F)"
1660 PRINT
1670 PRINT "  ENTER 2 to run the program based on local saturation of the flow
            at a typical local maximum Mach number from an assumed plot of"
1680 PRINT "  local Mach number vs. free-stream Mach number."
1690 PRINT
1700 PRINT "  ENTER 3 to run the program based on free-stream saturation of the
            flow"
1710 PRINT
1720 PRINT "  ENTER 4 to run the program based on local saturation of the flow
            at any local Mach number that you desire to enter."
1730 PRINT
1740 INPUT "Enter option number";T.OPTION
1750 IF T.OPTION=1 THEN GOSUB 4290
1760 INPUT"Do you want to use the 0.3-m TCT's fan pressure ratio correlation? Ye
s=1, No=2";FPR
1770 IF FPR=2 THEN INPUT "Input fan pressure ratio";FAN.PRESS.RATIO
1780 IF FPR=2 THEN 1880
1790 IF UNITS=1 THEN 1840
1800 INPUT"Input test section perimeter in feet";PERIMETER2
1810 PERIMETER1=PERIMETER2*.3048
1820 HYDR.DIAMETER2=4*TEST.SECT.AREA2/PERIMETER2
1830 GOTO 1880
1840 INPUT"Input test section perimeter in meters";PERIMETER1
1850 PERIMETER2=PERIMETER1/.3048
1860 HYDR.DIAMETER1=4*TEST.SECT.AREA1/PERIMETER1
1870 HYDR.DIAMETER2=HYDR.DIAMETER1/.3048
1880 IF T.OPTION=4 THEN INPUT "Input local Mach Number";LOCAL.MACH
1890 GOSUB 4200
1900 IF T.OPTION=1 THEN 1960
1910 IF (T.OPTION=2) OR (T.OPTION=4) THEN GOSUB 4410
1920 IF T.OPTION=3 THEN GOSUB 4680
1930  'Converting from Kelvin to Fahrenheit
1940 TOTAL.TEMP2=9/5*TOTAL.TEMP1-459.67
1950  'Expressing static temperature in Kelvin
1960 STATIC.TEMP1=TOTAL.TEMP1*(1+RATIO2*MACH.NUMBER^2)^(-1)
1970  'Converting from Kelvin to Fahrenheit
1980 STATIC.TEMP2=9/5*STATIC.TEMP1-459.67
1990  ' Expressing static pressures in N/m^2
2000 STATIC.PRESS3=TOTAL.PRESSURE3*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)
2010  ' Expressing static pressures in lb/in^2
2020 STATIC.PRESS2=TOTAL.PRESSURE2*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)
2030  ' Expressing static pressure in bars
2040 STATIC.PRESS1=TOTAL.PRESSURE1*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)
2050  ' Expressing static pressure in atmospheres
2060 STATIC.PRESS4=TOTAL.PRESSURE4*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)
2070 IF T.OPTION<>1 THEN 2260
2080  ' Checking static pressure to see if it's below the triple point value of
2090  ' .1237 atmospheres
2100 CHECK1=LOG(STATIC.PRESS4)
2110 IF STATIC.PRESS4>.1237 THEN 2150
2120 ABORT1=1
2130 GOTO 3500
```

```
2140 ·' The next equation is a curve fit to figure 4.
2150 C.STATIC.TEMP1=8.950359E-03*CHECK1^4+.12189951#*CHECK1^3+1.014738*CHECK1^2+
8.465183*CHECK1+77.33925
2160  ' Checking static temperature to see if the nitrogen is in the liquid or
2170  ' gas phase
2180 IF STATIC.TEMP1>=C.STATIC.TEMP1 THEN 2260
2190 ABORT2=1
2200 GOTO 3500
2210  '
2220  ' <------- A and B are coefficients used to calculate the
2230  '          compressibility factor based on total temperature
2240  '          and pressure.
2250  '
2260 A=1.37-.08773*TOTAL.TEMP1+.0004703*TOTAL.TEMP1^2-1.386E-06*TOTAL.TEMP1^3+1.
462E-09*TOTAL.TEMP1^4
2270 B=5.521-.1986*TOTAL.TEMP1+.0007817*TOTAL.TEMP1^2-1.258E-06*TOTAL.TEMP1^3+5.
333E-10*TOTAL.TEMP1^4
2280 COMPRES.FACTOR=1-EXP(A)*TOTAL.PRESSURE4-EXP(B)*TOTAL.PRESSURE4^2
2290  '
2300  ' <------- A1 and B1 are coefficients used to calculate the
2310  '          compressibility factor based on static temperature
2320  '          and pressure.
2330  '
2340 A1=1.37-.08773*STATIC.TEMP1+.0004703*STATIC.TEMP1^2-1.386E-06*STATIC.TEMP1^
3+1.462E-09*STATIC.TEMP1^4
2350 B1=5.521-.1986*STATIC.TEMP1+.0007817*STATIC.TEMP1^2-1.258E-06*STATIC.TEMP1^
3+5.333E-10*STATIC.TEMP1^4
2360 COMPRES.FACTOR1=1-EXP(A1)*STATIC.PRESS4-EXP(B1)*STATIC.PRESS4^2
2370  '
2380  ' <------- C and D are coefficients used to calculate the
2390  '          real gas gamma.
2400  '
2410 C=1.86799-9.521871E-02*STATIC.TEMP1+5.146381E-04*STATIC.TEMP1^2-1.3595E-06*
STATIC.TEMP1^3+1.31676E-09*STATIC.TEMP1^4
2420 D=-1.25126-.04969*STATIC.TEMP1
2430 GAMMA.REAL.GAS=1.4+EXP(C)*STATIC.PRESS4+EXP(D)*STATIC.PRESS4^2
2440  '
2450  ' <------- E, F, and G are coefficients used to calculate
2460  '          the viscosity.
2470  '
2480 E=-2.86896E-07+1.23678E-07*STATIC.PRESS4+1.29862E-09*STATIC.PRESS4^2
2490 F=7.55226E-08-6.10964E-10*STATIC.PRESS4-1.22089E-11*STATIC.PRESS4^2
2500 G=-4.89417E-11+9.5164E-13*STATIC.PRESS4+2.5213E-14*STATIC.PRESS4^2
2510  ' Viscosity in N/m^2
2520 VISCOSITY1=E+F*STATIC.TEMP1+G*STATIC.TEMP1^2
2530  ' Converting viscosity to lb-s/ft^2
2540 VISCOSITY2=VISCOSITY1*.0209
2550  ' Total density in kg/m^3
2560 TOTAL.DENSITY1=TOTAL.PRESSURE3/(COMPRES.FACTOR*R*TOTAL.TEMP1)
2570  ' Total density in slugs/ft^3
2580 TOTAL.DENSITY2=TOTAL.DENSITY1*.00194
2590  ' Static density in kg/m^3
2600 STATIC.DENSITY1=STATIC.PRESS3/(COMPRES.FACTOR*R*STATIC.TEMP1)
2610  ' Static density in slugs/ft^3
2620 STATIC.DENSITY2=STATIC.DENSITY1*.00194
2630  ' Velocity in m/s
2640 VELOCITY1=MACH.NUMBER*(ALPHA*COMPRES.FACTOR*R*STATIC.TEMP1)^.5
2650  ' Converting m/s to ft/s
2660 VELOCITY2=VELOCITY1/.3048
2670  ' Dynamic pressure in N/m^2
```

```
2680 DYNAM.PRESSURE3=ALPHA/2*MACH.NUMBER^2*STATIC.PRESS3
2690  ' Converting N/m^2 to lb/ft^2
2700 DYNAM.PRESSURE2=DYNAM.PRESSURE3/47.880258#
2710  ' Converting N/m^2 to bars
2720 DYNAM.PRESSURE1=DYNAM.PRESSURE3/100000!
2730 IF MACH.NUMBER>1 THEN GOSUB 4870
2740 IF MACH.NUMBER>1 THEN 2790
2750  ' Test section flow in kg/s
2760 TEST.SECT.FLOW1=2*TEST.SECT.AREA1*DYNAM.PRESSURE3/VELOCITY1
2770  ' Converting kg/s to slugs/s
2780 TEST.SECT.FLOW2=TEST.SECT.FLOW1/14.5939029#
2790 RE.NO.PER.METER=2*DYNAM.PRESSURE3/(VISCOSITY1*VELOCITY1)
2800 RE.NO.PER.FOOT=RE.NO.PER.METER*.3048
2810 REY.NO.HYD.DIAM=RE.NO.PER.FOOT*HYDR.DIAMETER2
2820 REF.CHORD=.1*TEST.SECT.AREA1^.5
2830 REYNOLDS.NUMBER=RE.NO.PER.METER*REF.CHORD
2840 IF FPR=2 THEN 2900
2850  '
2860  ' <------- The fan pressure ratio is calculated based
2870  '          on a correlation of data taken in the 0.3-m TCT.
2880  '
2890 FAN.PRESS.RATIO=.8205*MACH.NUMBER^2*REY.NO.HYD.DIAM^(-.096)+1.001
2900 TOTAL.TEMP3=TOTAL.TEMP1/(FAN.PRESS.RATIO^(1/RATIO1))
2910 IF MACH.NUMBER>1 THEN GOSUB 5080
2920 IF MACH.NUMBER>1 THEN 3010
2930  ' Fan power in watts
2940 FAN.POWER1=TEST.SECT.FLOW1*RATIO1*R*TOTAL.TEMP3*((FAN.PRESS.RATIO^(1/RATIO1
))-1)*COMPRES.FACTOR
2950  ' Converting watts to megawatts
2960 FAN.POWER1A=FAN.POWER1/1000000!
2970  ' Converting watts to hp
2980 FAN.POWER2=FAN.POWER1/746
2990 PLENUM.REMOVAL=0
3000 PLENUM.POWER1=PLENUM.POWER1=PLENUM.POWER1A=PLENUM.POWER2=0
3010 TOTAL.D.POWER1A=FAN.POWER1A+PLENUM.POWER1A
3020 TOTAL.D.POWER2=FAN.POWER2+PLENUM.POWER2
3030  '
3040  ' <------- H0, H1, and H2 are coefficients used to
3050  '          calculate the liquid nitrogen cooling capacity.
3060  '
3070 H0=1.0379-.0039157*TOTAL.PRESSURE4
3080 H1=121.25+2.1577*TOTAL.PRESSURE4
3090 H2=66.585-391.22*TOTAL.PRESSURE4
3100  ' Specific cooling capacity of liquid nitrogen in kJ/kg.
3110 COOL.CAPACITY=H0*TOTAL.TEMP1+H1+H2/TOTAL.TEMP1
3120  ' Converting kJ/kg to J/kg
3130 COOL.CAPACITY1=COOL.CAPACITY*1000
3140  ' Converting kJ/kg to Btu/lbm
3150 COOL.CAPACITY2=COOL.CAPACITY*.43021
3160  '
3170  ' <------- DELTA.T is the temperature difference across the
3180  '          insulation with 300 K being the ambient temperature.
3190  '
3200 DELTA.T=300-TOTAL.TEMP1
3210  ' Liquid nitrogen flow rate due to conduction from outside the tunnel
3220  ' in kg/s
3230 LN.FLWRATE.CON1=K*TUN.SURF.AREA1*DELTA.T/(INSUL.THICKNESS*COOL.CAPACITY1)
3240  ' Converting kg/s to slugs/s
3250 LN.FLWRATE.CON2=LN.FLWRATE.CON1/14.5939029#
3260  ' Liquid nitrogen flow rate due to tunnel drive fan in kg/s
```

```
3270 LN.FLWRATE.FAN1=(FAN.POWER1+BL.COMP.POWER1*BL.COMP.EFF/100)/COOL.CAPACITY1
3280  ' Converting kg/s to slugs/s
3290 LN.FLWRATE.FAN2=LN.FLWRATE.FAN1/14.5939029#
3300  ' Total liquid nitrogen flow rate in kg/s
3310 TOTAL.LN.FLOW1=LN.FLWRATE.FAN1+LN.FLWRATE.CON1
3320  ' Total liquid nitrogen flow rate in slugs/s
3330 TOTAL.LN.FLOW2=LN.FLWRATE.FAN2+LN.FLWRATE.CON2
3340  ' Liquid nitrogen flow expressed as a percent of the tunnel mass flow
3350 IF MACH.NUMBER>1 THEN 3380
3360 PERCENT.LN.FLOW=TOTAL.LN.FLOW1/TEST.SECT.FLOW1*100
3370 GOTO 3390
3380 PERCENT.LN.FLOW=TOTAL.LN.FLOW1/T.MASS.FLOW1*100
3390  ' power to produce liquid nitrogen in MW
3400 POWER.PROD.LN1A=TOTAL.LN.FLOW1*EM
3410  ' Converting MW to horsepower
3420 POWER.PROD.LN2=POWER.PROD.LN1A*1340.4826#
3430  ' Total power required in MW
3440 TOTAL.POWER1A=TOTAL.D.POWER1A+POWER.PROD.LN1A
3450  ' Total power required in horsepower
3460 TOTAL.POWER2=TOTAL.D.POWER2+POWER.PROD.LN2
3470  ' ********************************************************************
3480  ' ************************* PRINTING SECTION *************************
3490  ' ********************************************************************
3500 IF T.OPTION=2 OR T.OPTION=4 THEN 3530
3510 PRINT #1,"PHYSICAL TUNNEL PARAMETERS               SI              U.S. C
USTOMARY"
3520 GOTO 3540
3530 PRINT #1,"PHYSICAL TUNNEL PARAMETERS"
3540 PRINT #1,USING " Test section area ................... ##.## m^2        =###
##.## ft^2";TEST.SECT.AREA1,TEST.SECT.AREA2
3541 IF FPR = 2 THEN 3560
3550 PRINT #1,USING " Test section perimeter ............. ##.## m          =###
##.## ft";PERIMETER1,PERIMETER2
3560 PRINT #1,USING " Reference chord ..................... #.## m          =###
##.## ft";REF.CHORD,REF.CHORD/.3048
3570 PRINT #1,USING " Tunnel surface area ............. #####.## m^2        =###
##.## ft^2";TUN.SURF.AREA1,TUN.SURF.AREA2
3580 PRINT #1,USING " Insulation thickness ............... ##.## m          =###
##.## ft";INSUL.THICKNESS,INSUL.THICKNESS/.3048
3590 PRINT #1,""
3600 IF OUTPUT=2 THEN 3630
3610 PRINT "Press any key to continue"
3620 A$=INKEY$: IF A$="" THEN 3620
3630 PRINT #1,"TUNNEL FLOW PARAMETERS"
3640 PRINT #1,USING " Total pressure ...................... #.### bars      =###
##.### lb/in^2";TOTAL.PRESSURE1,TOTAL.PRESSURE2
3650 PRINT #1,USING " Static pressure ..................... #.### bars      =###
##.### lb/in^2";STATIC.PRESS1,STATIC.PRESS2
3660 IF ABORT1=1 THEN PRINT #1,"The static pressure is below or equal to the tri
ple point value of .1253 bars.  The program has aborted."
3670 IF ABORT1=1 THEN 4160
3680 PRINT #1,USING " Total temperature ................. ###.### K         =###
##.### F";TOTAL.TEMP1,TOTAL.TEMP2
3690 PRINT #1,USING " Static temperature ............... ###.### K          =###
##.### F";STATIC.TEMP1,STATIC.TEMP2
3700 IF ABORT2=1 THEN PRINT #1,"The nitrogen is in a liquid state at these condi
tions (See figure 4).         The program has aborted."
3710 IF ABORT2=1 THEN 4160
3720 PRINT #1,USING " Total density ...................... ##.### kg/m^3    =
##.#### slugs/ft^3";TOTAL.DENSITY1,TOTAL.DENSITY2
```

```
3730 PRINT #1,USING " Test section static density ......... ##.### kg/m^3   =
##.#### slugs/ft^3";STATIC.DENSITY1,STATIC.DENSITY2
3740 PRINT #1," Compressibility factor based on"
3750 PRINT #1,USING "  total temperature ................... #.####";COMPRES.FAC
TOR
3760 PRINT #1," Compressibility factor based on"
3770 PRINT #1,USING "  static temperature ................. #.####";COMPRES.FAC
TOR1
3780 PRINT #1,USING " Real gas ratio of specific heats ..... #.####";GAMMA.REAL.
GAS
3790 PRINT #1,USING " Viscosity ........................ #####.^^^^ N-s/m^2 = ##
##.^^^^ lb-s/ft^2";VISCOSITY1,VISCOSITY2
3800 PRINT #1,USING " Mach number ........................... #.###";MACH.NUMBER
3810 PRINT #1,USING " Velocity ........................... ###.### m/s     =###
##.### ft/s";VELOCITY1,VELOCITY2
3820 IF MACH.NUMBER>1 THEN 3850
3830 PRINT #1,USING " Test section mass flow ........... #####.### kg/s     = ##
##.### slugs/s";TEST.SECT.FLOW1,TEST.SECT.FLOW2
3840 GOTO 3860
3850 PRINT #1,USING " Test section mass flow ........... #####.### kg/s     = ##
##.### slugs/s";T.MASS.FLOW1,T.MASS.FLOW2
3860 PRINT #1,USING " Dynamic pressure ..................... #.### bars    = ##
##.### lb/ft^2";DYNAM.PRESSURE1,DYNAM.PRESSURE2
3870 PRINT #1,USING " Reynolds number per meter ........... ##.###^^^^";RE.NO.PE
R.METER
3880 PRINT #1,USING " Reynolds number per foot ...............................
##.###^^^^";RE.NO.PER.FOOT
3890 PRINT #1," Reynolds number based on"
3900 PRINT #1,USING "  reference chord ................... ##.###^^^^";REYNOLDS
.NUMBER
3910 PRINT #1,""
3920 IF OUTPUT=2 THEN 3960
3930 PRINT "Press any key to continue"
3940 A$=INKEY$: IF A$="" THEN 3940
3950 PRINT #1,""
3960 PRINT #1,"POWER PARAMETERS"
3980 PRINT #1,USING " Plenum removal ....................... #.### %";PLENUM.REM
OVAL
3990 PRINT #1," Plenum removal compressor"
4000 PRINT #1,USING "  efficiency ......................... ##.### %";PL.COMP.EF
F
4010 PRINT #1,USING " Fan pressure ratio ................... #.####";FAN.PRESS.R
ATIO
4020 PRINT #1,USING " Fan power ........................... ###.### MW     =
##.###^^^^ hp";FAN.POWER1A,FAN.POWER2
4030 PRINT #1,USING " Plenum removal compressor power ..... ##.### MW     =
##.###^^^^ hp";PLENUM.POWER1A,PLENUM.POWER2
4040 PRINT #1,USING " Total drive power ................... ###.### MW     =
##.###^^^^ hp";TOTAL.D.POWER1A,TOTAL.D.POWER2
4050 PRINT #1," Power for continuous"
4060 PRINT #1,USING "  production of LN2 ................. ####.### MW     =
##.###^^^^ hp";POWER.PROD.LN1A,POWER.PROD.LN2
4070 PRINT #1," Total power for"
4080 PRINT #1,USING "  continuous running .............. ####.### MW     =
##.###^^^^ hp";TOTAL.POWER1A,TOTAL.POWER2
4090 PRINT #1,""
4100 PRINT #1,"LN2 FLOW PARAMETERS"
4110 PRINT #1,USING " Cooling capacity ................... ###.### kJ/kg   = ##
##.### Btu/lb";COOL.CAPACITY,COOL.CAPACITY2
4120 PRINT #1,USING " LN2 flow rate for fan heat ......... ###.### kg/s     = ##
```

```
##.### slugs/s";LN.FLWRATE.FAN1,LN.FLWRATE.FAN2
4130 PRINT #1,USING " LN2 flow rate for conduction ........ #.### kg/s     = ##
##.### slugs/s";LN.FLWRATE.CON1,LN.FLWRATE.CON2
4140 PRINT #1,USING " Total LN2 flow rate ............... ###.### kg/s     = ##
##.### slugs/s";TOTAL.LN.FLOW1,TOTAL.LN.FLOW2
4150 PRINT #1,USING " Total LN2 flow/test section flow ..... #.### %";PERCENT.LN
.FLOW
4160 END
4170 ' ***************************************************************************
4180 ' ************************** TITLE SUBROUTINE ***************************
4190 ' ***************************************************************************
4200 CLS
4210 PRINT #1,"              CRYOGENIC WIND TUNNEL FLOW PARAMETER PROGRAM"
4220 PRINT #1,"                 UTILIZING NITROGEN AS THE TEST GAS"
4230 PRINT #1,""
4240 PRINT #1,""
4250 RETURN
4260 ' ***************************************************************************
4270 ' *********************** OPTION 1 SUBROUTINE ***********************
4280 ' ***************************************************************************
4290 IF UNITS=2 THEN 4340
4300 INPUT"Input tunnel total temperature in Kelvin";TOTAL.TEMP1
4310  'Converting from Kelvin to Fahrenheit
4320 TOTAL.TEMP2=9/5*TOTAL.TEMP1-459.67
4330 GOTO 4370
4340 INPUT"Input tunnel total temperature in Fahrenheit";TOTAL.TEMP2
4350  'Converting from Fahrenheit to Kelvin
4360 TOTAL.TEMP1=5/9*(TOTAL.TEMP2+459.67)
4370 RETURN
4380 ' ***************************************************************************
4390 ' ******************** OPTIONS 2 AND 4 SUBROUTINE ********************
4400 ' ***************************************************************************
4410 IF T.OPTION=4 THEN 4460
4420 '
4430 ' <-------- The next equation is a curve fit to figure 3.
4440 '
4450 LOCAL.MACH=.014236731#*MACH.NUMBER^4-.13340558#*MACH.NUMBER^3+.44529085#*MA
CH.NUMBER^2+.3790048*MACH.NUMBER+.6949
4460 PRINT #1,"LOCAL CONDITIONS                        SI              U.S. CU
STOMARY"
4470 PRINT #1,USING " Mach number ........................ #.###";LOCAL.MACH
4480  ' Local static pressure in bars
4490 L.STATIC.PRESS1=TOTAL.PRESSURE1*(1+RATIO2*LOCAL.MACH^2)^(-RATIO1)
4500  ' Local static pressure in lb/ft^2
4510 L.STATIC.PRESS2=TOTAL.PRESSURE2*(1+RATIO2*LOCAL.MACH^2)^(-RATIO1)
4520  ' Local static pressure in atmospheres
4530 L.STATIC.PRESS4=TOTAL.PRESSURE4*(1+RATIO2*LOCAL.MACH^2)^(-RATIO1)
4540 PRINT #1,USING " Static pressure .................... #.### bars     =###
##.### lb/in^2";L.STATIC.PRESS1,L.STATIC.PRESS2
4550 CHECK1=LOG(L.STATIC.PRESS4)
4560 IF L.STATIC.PRESS4>.1237 THEN 4590
4570 ABORT1=1
4580 GOTO 3660
4590 L.STATIC.TEMP1=8.950359E-03*CHECK1^4+.12189951#*CHECK1^3+1.014738*CHECK1^2+
8.465183*CHECK1+77.33925
4600 L.STATIC.TEMP2=9/5*L.STATIC.TEMP1-459.67
4610 TOTAL.TEMP1=L.STATIC.TEMP1*(1+RATIO2*LOCAL.MACH^2)
4620 PRINT #1,USING " Static temperature ................. ###.### K       =###
##.### F";L.STATIC.TEMP1,L.STATIC.TEMP2
4630 PRINT #1,""
```

```
4640 RETURN
4650 ' *********************************************************************
4660 ' *********************** OPTION 3 SUBROUTINE *********************
4670 ' *********************************************************************
4680 PRINT #1,"FOR RUNNING AT FREE-STREAM SATURATION"
4690 PRINT #1,""
4700 ' Expressing static pressure in bars
4710 STATIC.PRESS1=TOTAL.PRESSURE1*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)
4720 ' Expressing static pressures in lb/in^2
4730 STATIC.PRESS2=TOTAL.PRESSURE2*(1+RATIO2*MACH.NUMBER^2)^(-RATIO1)
4740 CHECK1=LOG(STATIC.PRESS4)
4750 IF STATIC.PRESS4>.1237 THEN 4780
4760 ABORT1=1
4770 GOTO 3500
4780 STATIC.TEMP=8.950359E-03*CHECK1^4+.12189951#*CHECK1^3+1.014738*CHECK1^2+8.4
65183*CHECK1+77.33925
4790 TOTAL.TEMP1=STATIC.TEMP*(1+RATIO2*MACH.NUMBER^2)
4800 RETURN
4810 ' *********************************************************************
4820 ' ******** SUBROUTINE TO CALCULATE MASS FLOW FOR MACH NUMBERS > 1 ******
4830 ' *********************************************************************
4840 ' Note that the mass flow is calculated for the case of M = 1 at the
4850 ' throat.
4860 ' The static pressure in atmospheres for M = 1.
4870 T.STATIC.PRESS4=.5283*TOTAL.PRESSURE4
4880 ' The static pressure in bars for M = 1.
4890 T.STATIC.PRESS1=.5283*TOTAL.PRESSURE1
4900 ' The static pressure in lb/in^2 for M = 1.
4910 T.STATIC.PRESS2=.5283*TOTAL.PRESSURE2
4920 ' The static temperature in Kelvin for M = 1.
4930 T.STATIC.TEMP1=.8333*TOTAL.TEMP1
4940 ' The static temperature in Fahrenheit for M = 1.
4950 T.STATIC.TEMP2=.8333*TOTAL.TEMP2
4960 D2=1.37-.08773*T.STATIC.TEMP1+.0004703*T.STATIC.TEMP1^2-1.386E-06*T.STATIC.
TEMP1^3+1.462E-09*T.STATIC.TEMP1^4
4970 E2=5.521-.1986*T.STATIC.TEMP1+.0007817*T.STATIC.TEMP1^2-1.258E-06*T.STATIC.
TEMP1^3+5.333E-10*T.STATIC.TEMP1^4
4980 T.COMPRES.FACT=1-EXP(D2)*T.STATIC.PRESS4-EXP(E2)*T.STATIC.PRESS4^2
4990 ' The mass flow equation is from reference 12, pg. 139.
5000 ' The mass flow in the throat in kg/s for M = 1.
5010 T.MASS.FLOW1=.685*TOTAL.PRESSURE3*TEST.SECT.AREA1/(R*TOTAL.TEMP1*T.COMPRES.
FACT)^.5
5020 ' Converting kg/s to slugs/s
5030 T.MASS.FLOW2=T.MASS.FLOW1/14.5939029#
5040 RETURN
5050 ' *********************************************************************
5060 ' *************** SUBROUTINE TO CALCULATE POWER FOR M > 1 *************
5070 ' *********************************************************************
5080 ' Fan power in watts
5090 FAN.POWER1=T.MASS.FLOW1*RATIO1*R*TOTAL.TEMP3*(FAN.PRESS.RATIO^(1/RATIO1)-1)
*COMPRES.FACTOR
5100 ' Converting watts to megawatts
5110 FAN.POWER1A=FAN.POWER1/1000000!
5120 ' Converting watts to hp
5130 FAN.POWER2=FAN.POWER1/746
5140 TEMP.DIFF=TOTAL.TEMP1-STATIC.TEMP1
5150 AREA.RATIO=1.728*MACH.NUMBER*(1+.2*MACH.NUMBER^2)^(-3)
5160 PLENUM.REMOVAL=1/AREA.RATIO-1
5170 ' Plenum removal compressor power in watts
5180 PLENUM.POWER1=PLENUM.REMOVAL*(T.MASS.FLOW1*CP/M*TEMP.DIFF/PL.COMP.EFF)
```

```
5190   ' Converting watts to megawatts
5200    PLENUM.POWER1A=PLENUM.POWER1/1000000!
5210   ' Converting watts to hp
5220  PLENUM.POWER2=PLENUM.POWER1/746
5230  RETURN
5240  END
```

A 5¼-inch floppy disk containing a copy of the program in this report is available upon request from

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The program is written in IBM "Advanced Basic" language for the IBM Personal Computers PC/XT/AT.

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15. Supplementary Notes

16. Abstract

A computer program has been written that performs the flow parameter calculations for cryogenic wind tunnels which use nitrogen as a test gas. The flow parameters calculated include static pressure, static temperature, compressibility factor, ratio of specific heats, dynamic viscosity, total and static density, velocity, dynamic pressure, mass-flow rate, and Reynolds number. Simplifying assumptions have been made so that the calculations of Reynolds number as well as the other flow parameters can be made on relatively small desktop digital computers. The program, which also includes various power calculations, has been developed to the point where it has become a very useful tool for the users and possible future designers of fan-driven continuous-flow cryogenic wind tunnels.

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