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POWER CALCULATIONS FOR ISENTROPIC COMPRESSIONS OF CRYOGENIC NITROGEN

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July 1976

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ABSTRACT

A theoretical analysis has been made of the power required for isentropic compressions of cryogenic nitrogen in order to determine the extent that the drive power for cryogenic tunnels might be affected by real-gas effects. The analysis covers temperatures from 80 to 310K, pressures from 1.0 to 8.8 atm and fan pressure ratios from 1.025 to 1.200. The power required to compress cryogenic nitrogen was found to be lower than that required for an ideal diatomic gas by as much as 9.5 percent. Simple corrections to the ideal gas values were found to give accurate estimates of the real gas power values.

SUMMARY

A theoretical analysis has been made of the power required for isentropic compressions of cryogenic nitrogen. This real-gas analysis was made from a cryogenic wind-tunnel perspective, and its purpose was to determine the extent that wind-tunnel drive power might be affected by the real-gas characteristics of nitrogen. The real-gas solutions covered stagnation temperatures from 80K to 310K, stagnation pressures from 1.0 to 8.8 atms, and fan pressure ratios from 1.025 to 1.200. These solutions are compared to the ideal diatomic gas solutions. At cryogenic temperatures, the power that is required to isentropically compress nitrogen is less than that required for the ideal gas by as much as 9.5 percent. Simple corrections to the ideal values of mass flow, energy and power were found to give accurate estimates of the real-gas values.

INTRODUCTION

The cryogenic wind tunnel concept has been developed at the Langley Research Center in order to improve flight simulation in wind tunnels by increasing the test Reynolds number. The major advantages of increasing the Reynolds number by reducing the temperature of the test gas are given in references 1 to 4. For fan-driven tunnels, as the temperature of the test gas is reduced, the required drive power is greatly reduced as is illustrated in figure 1 for 3 different wind tunnel cases. These calculations are based on the assumption of an ideal gas. However, for the cryogenic wind-tunnel concept as developed at Langley, cooling is accomplished with liquid nitrogen and the resulting test gas is cryogenic nitrogen. Nitrogen at these conditions has real-gas imperfections (Ref. 5). Even though the analysis of Ref. 5 indicated that cryogenic nitrogen would be an acceptable test gas in terms of flow simulation, it is possible that the real-gas characteristics could become important in some of the wind-tunnel design considerations such as drive power requirement.

The purpose of this report is to present the results of a study to determine the extent that the wind-tunnel drive power requirements might be affected by the real-gas characteristics of nitrogen. In this study, real-gas solutions for isentropic compressions of nitrogen were made for the range of operating temperatures (saturation to 310K), pressures (1 to 8.8 atm) and tunnel pressure ratios (1.025 to 1.2) anticipated for fan-driven transonic cryogenic wind tunnels. The solutions were compared to those for an ideal diatomic gas and the results are presented relative to the ideal gas values.

SYMBOLS

C_p	Specific heat at constant pressure
C_v	Specific heat at constant volume
E	Energy per unit mass
f	$Z_{t,2}/Z_{t,1}$
h	Specific enthalpy
M	Mach number
$\mathring{m}$	mass flow rate per unit area
P	power
p	pressure
R	Gas constant for nitrogen, 296.791 J/KGM-K
r	pressure ratio, $p_{t,2}/p_{t,1}$
S	entropy
T	temperature
v	specific volume
W	speed of sound
Z	Compressibility factor, pv/RT
ρ	density
γ	specific heat ratio, Cp/C_v

Subscripts

1	upstream of fan
2	downstream of fan
t	stagnation condition
TH	tunnel throat
TS	test section

R real gas or nitrogen value

I ideal gas value

S entropy

BASIC EQUATIONS

The test gas of a closed-circuit fan-driven wind tunnel is forced to flow around the circuit by the energy which is imparted to the gas by the fan. If the steady-flow compression that takes place at the fan is assumed to be a reversible adiabatic process (i.e. isentropic), then the energy per unit time, or power, which must be imparted to the gas is given by the equation:

$$P = \dot{m} \left(h_{t,2} - h_{t,1}\right)_S \qquad (1)$$

This equation holds for any gas and thus will be termed the real gas power equation for isentropic compressions. This equation appears to be simple enough, but the two factors are not easily calculated and a later section will describe the method used in solving this real-gas equation.

The assumption of an ideal gas and the resulting expressions for isentropic flow allow this power equation to be expressed in an easily calculated form. An ideal gas as used herein is one that is both thermally and calorically perfect. The ideal gas characteristics are:

$$pv/RT = 1 \qquad \text{(Equation of State)}$$

$$\int dh = C_p \int dt \qquad \text{(Specific heats independent of T and p)}$$

$$C_p - C_v = R$$

and the expressions that relate the static variables in an isentropic process are:

$$p = \rho^{\gamma}(\text{const}) = T^{\gamma/(\gamma - 1)}(\text{Const.})$$

By using these characteristics and expressions, equation (1) can be put into the following form:

$$P = \dot{m} \left[\frac{\gamma}{\gamma - 1} R T_{t,1} \left(r^{\frac{\gamma - 1}{\gamma}} - 1 \right) \right] \tag{2}$$

This ideal-gas power equation and the real-gas power equation (1) have been arranged to show two distinct factors. The first is the mass flow rate and the second represents the energy per unit mass for each case. The present study analyzes the real-gas effects on the power required for isentropic compressions by examining the manner in which each of these factors is affected.

The mass flow rate of any gas per unit area is given by

$$\dot{m} = \rho V$$

A subsequent section and appendix describe the real-gas solutions for tunnel mass flow rate. For isentropic flow of an ideal gas, this equation can be expressed as a function of the stagnation conditions and Mach number as follows:

$$\dot{m}_I = \sqrt{\frac{\gamma}{R}} \frac{p_t}{\sqrt{T_t}} M \left(1 + \frac{\gamma - 1}{2} M^2\right)^{(\gamma-1)/(2(1-\gamma))} \tag{3}$$

ANALYTICAL MODEL OF TUNNEL

The real gas effects on the power required for isentropic compressions of nitrogen could be analyzed by assuming that the compressions take place in a constant area duct where nitrogen is flowing at various temperatures, pressures, and velocities. However, since the impetus for this study evolved from the consideration of the power required for the operation of transonic cryogenic wind tunnels, the analysis will instead be made from this perspective.

A sketch of the analytical model of the tunnel is shown in figure 2. For this analysis the conditions upstream of the fan, $p_{t,1}$ and $T_{t,1}$, and the pressure ratio across the fan, r, are the same for the real gas and the ideal gas cases. This means that the outlet temperatures, $T_{t,2}$, are different for the two cases. With the assumption of no energy losses between the fan outlet and the tunnel throat (explained later), the stagnation conditions are the same at both locations. As a consequence, the test section or throat temperature, $T_{t,2}$, is not the same for the real and ideal gas cases. It will be shown later that the difference between $(T_{t,2})_R$ and $(T_{t,2})_I$ is insignificant, so that for all practical purposes the real and ideal gas comparisons are made at the same test section conditions.

The tunnel mass flow will be calculated for the throat conditions (i.e. $T_{t,2}$, $p_{t,2}$, M_{TH}). For subsonic speeds, the throat and test section Mach numbers are assumed to be identical. For supersonic speeds, the effective area of the test section has to be larger than that of the throat. In practice, this larger effective area is created by either diverging the walls of the test section or by allowing some of the mass of gas to flow through porous or slotted sections of the wall into the plenum chamber. In this latter case, the mass may be removed from the plenum by auxiliary suction or it may reenter the test section at the diffuser entrance. For the present analytical model, it is assumed that all the mass that passes through the tunnel throat also passes through the fan.

For simplification all of the tunnel energy losses are assumed to occur between the throat of the tunnel and the fan. Data from existing transonic tunnels indicate that most of the losses do occur in this portion of the tunnel due to the higher flow velocities. However, designers who have an estimate of their tunnel's energy loss distribution will be able to utilize the information herein for their specific cases.

With the liquid nitrogen cooling procedure previously described, mass is added to the stream at the cooler. It is anticipated that the cooling system would be placed upstream of the fan rather than downstream because the longer distance to the test section would permit more thorough mixing of the evaporating nitrogen with the main stream. This additional mass flow due to cooling is at most about 2 percent of the tunnel mass flow. A brief analysis where this additional mass flow was considered indicated that while the absolute level of power was up by 2 percent due to this additional mass being compressed, the ratio of the real to the ideal power requirement was insignificantly affected. Thus for simplicity, cooling of this analytical model is assumed to occur without mass addition.

Typical values of the fan pressure ratio which are necessary to achieve a given Mach number in the test section have been assumed for this analytical tunnel:

M_{TS}	r
0.2	1.025
0.6	1.050
1.0	1.100
1.2	1.200

This Mach number-pressure ratio correspondence is further assumed to be invariant with stagnation temperature and pressure.

This analytical model is assumed to have an operating stagnation pressure range of from 1.0 to 8.8 atm. The maximum pressure matches that of the proposed National Transonic Facility that is currently being designed (Ref. 6). The stagnation temperatures cover the range from near ambient temperatures (310K) down to the saturated vapor temperature. Specifically, this lower limit of stagnation temperature at a given stagnation pressure is taken to be that temperature which causes the static temperature and pressure at the tunnel throat to be coincident with a point on the vapor pressure curve.

PROCEDURE FOR ANALYTICAL SOLUTIONS

Figure 3 shows a flow chart of a program that was written in order to calculate the power required for isentropic compressions of nitrogen and an ideal diatomic gas. This program uses a nitrogen properties program written at the National Bureau of Standards (Ref. 7) that is based on Jacobsen's equation of state (Ref. 8). It also makes use of some of the subprograms and procedures that were developed for the isentropic expansion study of Ref. 5.

As shown on the flow chart the program inputs are the test section stagnation pressure, $p_{t,2}$, Mach number M_{TS}, and the fan pressure ratio, r. First, the program sets the test section stagnation temperature for the real gas or nitrogen case to a value near ambient temperatures (310K). Next, the program makes two sets of real-gas calculations. The first of these is the real-gas calculation of the tunnel throat conditions (Block A). After setting the throat Mach number, this routine determines the static flow properties which would result in the desired M_{TH}. When this is completed, the real gas mass flow rate is determined. As these calculations are being made, a check is made to see if the static flow properties have reached the saturated condition. If this occurs, the solutions are terminated. The details of the throat calculations of block A can be found in Appendix A.

The other set of real-gas calculations are related to the fan as indicated by block B. Assuming isentropic compression, this routine takes the downstream stagnation conditions ($p_{t,2}$, $(T_{t,2})_R$) and the fan pressure ratio and computes the upstream stagnation conditions ($p_{t,1}$,$T_{t,1}$). The real-gas energy per unit mass, E_R, is also determined and combined with the mass flow rate from block A to give the real gas power, P_R, for the compression. The details of these fan calculations are given in appendix B.

The next step in the program is the fan calculations for the ideal gas case. The inlet stagnation conditions as determined from the real-gas calculations and the fan pressure ratio are utilized in these calculations. The outlet temperature is determined from the following isentropic relationship

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

The energy per unit mass is given by

$$E_I = \frac{\gamma}{\gamma - 1} R \, T_{t,1} \left(r^{\frac{\gamma - 1}{\gamma}} - 1\right)$$

which is the second factor of basic equation (2).

With the ideal stagnation temperature, $(T_{t,2})_I$, having been determined, the ideal mass flow rate at the throat is determined from basic equation (3). This mass-flow rate is combined with the energy per unit mass, E_I, to give the ideal power required for the compression.

At this point, the program prints out the real and ideal gas parameters associated with the compression and their relative values. With the completion of this solution, the real gas temperature, $T_{t,2}$, is decreased and the solution repeated. This continues until the throat conditions for the real gas case become saturated.

ANALYSIS OF SOLUTIONS

Isentropic power solutions of the type just described have been made for the analytical model of a cryogenic tunnel. The solutions cover a test section Mach number and fan pressure ratio range from 0.2 to 1.2 and 1.025 to 1.200 respectively. Solutions covering these ranges were made at stagnation pressures from 1 to 8.8 atm and at stagnation temperatures from ambient (310K) to saturation temperatures. This analysis will examine the real-gas effects on the power for isentropic compressions by showing the effects on the two factors, mass flow and energy per unit mass, that combine to give the power.

It should be remembered that the real and ideal gas solutions are for the same fan inlet conditions ($p_{t,1}$, $T_{t,1}$) and for a given pressure ratio, r. The outlet pressure ($p_{t,2}$) will be the same but the outlet temperatures are different. This difference is shown in figure 4 for the conditions which produce the maximum difference ($r = 1.2$, $p_{t,2} = 8.8$ atm). Even at the lowest inlet temperature, the real-gas value of downstream temperature differs from the ideal value by less than 0.3 percent. Thus, for all practical purposes the following comparisons of real and ideal solutions are made at identical test section stagnation conditions as well as for identical fan inlet conditions.

Energy for Isentropic Compressions

The real-gas effects of nitrogen on the energy per unit mass for isentropic compressions is shown in figure 5. The relative values (real or nitrogen to ideal) of energy are presented as a function of fan outlet temperature, $T_{t,2}$, and for various values of outlet pressure, $p_{t,2}$. Each curve is for a given fan pressure ratio. The fan outlet conditions ($p_{t,2}$, $T_{t,2}$) were chosen as the independent variables because these are the values for the tunnel throat and test section.

These figures show that the nitrogen values for energy per unit mass are always less than the ideal values. This difference increases as temperature is reduced. At the maximum pressure (Figure 5d), the real energy per unit mass is as much as 17 percent lower than the ideal distomic gas value. These lower values of energy/unit mass for nitrogen could have been anticipated by comparing the enthalpy versus temperature curves at constant entropy (Figure 6). For the ideal gas, enthalpy is only a function of temperature. Along an isentrope, the enthalpy of nitrogen is a function of both temperature and pressure. With the temperature dependence being dominant, however, the slope difference at a given temperature should be an indication of the energy ratio for the two cases. The slope for the nitrogen isentrope is less than that for the ideal gas.

Figure 5 also shows that the value of fan pressure ratio has a very insignificant effect on the shape of the energy ratio-outlet temperature curve.

Figure 7 shows the effect of pressure on the energy ratio at constant temperatures. As can be seen, the energy ratio decreases nearly linearly with increasing pressure.

Real-Gas Effects on Tunnel Mass Flow

The relative values (real or nitrogen to ideal) of the tunnel mass flow are shown in figure 8 as a function of stagnation temperature for various values of stagnation pressure. As mentioned previously (figure 4), the outlet stagnation temperatures were so near the same value for the real and ideal gas cases that these comparisons are at essentially the same throat conditions. Each curve is for a given throat Mach number.

As stagnation temperature is reduced, the mass flow rates for nitrogen become increasingly greater than those for an ideal diatomic gas. At the maximum pressure (figure 8d), the nitrogen mass flow rate for $M_{TH} = 0.20$ and the minimum temperature is about 9.5 percent greater than the ideal-gas mass flow rate. For an $M_{TH} = 1.0$, the real mass flow is only about 7.0 percent greater due to the saturation temperature being higher than for the 0.2 case. The shape of the mass flow-temperature curve is relatively insensitive to the throat Mach number.

Power for Isentropic Compressions

The real-gas effects on the power required for isentropic compressions is shown in figure 9. The relative power values are shown as a function of outlet or throat stagnation temperature for various values of stagnation pressure. These relative values are a combination of the relative energy ratios and the relative mass flow ratios. The power values for the real gas or nitrogen are in general lower than those for the ideal gas. At the maximum pressure (figure 9d) and minimum temperature, this reduction in the power required is about 9.5 percent for $M_{TS} = 0.2$ ($r = 1.025$) and about 7.5 percent for $M_{TS} = 1.2$ ($r = 1.2$). The shape of this power ratio-temperature curve is essentially independent of the pressure ratio and/or Mach number. This is to be expected since the energy ratio curve and the mass flow curve were essentially independent of the pressure ratio and Mach number respectively.

These power reductions due to real-gas effects are, of course, in addition to the large power reductions due to operating at cryogenic temperature (figure 1).

APPROXIMATE METHODS

Energy/Unit Mass

The following two equations are approximations for the energy required to isentropically compress a unit mass of real gas

$$E_R = \frac{\gamma}{\gamma - 1} Z_{t,1} \frac{R\, T_{t,1}}{(r-1)} \left\{ \left[(r)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \left[r - f \right] + \left[\frac{(\gamma-1)(f-1)}{2\gamma-1} \right] \left[(r)^{\frac{2\gamma-1}{\gamma}} - 1 \right] \right\} \quad (4)$$

$$E_R = Z_{t,2}\, E_I = Z_{t,2} \frac{\gamma}{\gamma - 1} R\, T_{t,1} \left[(r)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \quad (5)$$

Equation (4) is the energy per unit mass portion of the power equation given in ref. 9. It is a result of the following considerations

$$E_R = \int v dP$$

$$P = T^{\frac{\gamma}{\gamma - 1}} (\text{Const}) \text{ [Assumed to remain valid for the real gas]}$$

$$Z = (a + bP)_S \text{ [Z varies linearly with pressure along an isentrope]}$$

Equation (5) is derived with the same considerations with the exception that Z is assumed to be constant along an isentrope. The data presented in figure 10 indicate that this is a reasonably good assumption.

Reference 9 indicates the actual values of specific heat ratio, γ, for the conditions prior to compression should be utilized in these equations. However, in ref. 5, the isentropic expansion coefficients for nitrogen were found to remain near to the ideal diatomic gas value of 1.4 and the present authors found that using the ideal value of 1.4 gives more accurate results over the range of conditions considered herein than using the actual value of γ. For equation (5), the use of either $Z_{t,1}$ or $Z_{t,2}$ gives about the same degree of accuracy. For this report, $Z_{t,2}$ is used.

Figure 11 shows a comparison of these approximate equations with the exact real-gas solutions. Both of the approximate solutions are within 0.5 percent of the exact values. While equation (4) gives excellent values for the energy per unit mass, it is unnecessarily complex for the range of conditions considered herein. Simply multiplying the ideal values by the compressibility factor, $Z_{t,2}$, gives results which are just as accurate.

Mass Flow

The mass flow per unit area is $\dot{m} = \rho V$. This equation may be rewritten in the following form:

$$\dot{m} = (\rho/\rho_t)\ \rho_t\ MW$$

The ratio of the real-gas mass flow, $\dot{m}_R$, to the ideal-gas mass flow, $\dot{m}_I$, at a given Mach number would be:

$$\dot{m}_R/\dot{m}_I = \frac{(\rho/\rho_t)_R}{(\rho/\rho_t)_I}\ \frac{1}{Z_t}\ \frac{W_R}{W_I}$$

If $p = \rho^{\alpha}$ (const) is approximately valid for the real gas and α remains near 1.4 (ref. 5), then

$$W_R/W_I \cong \sqrt{Z} \cong \sqrt{Z_t}$$

Also $(\rho/\rho_t)_R/(\rho/\rho_t)_I \cong 1.0$ from ref. 5. With these considerations

$$\dot{m}_R/\dot{m}_I \cong 1/\sqrt{Z_t}.$$

The accuracy of this simple approximation is illustrated in figure 12. For the range of conditions considered in this report this approximation is accurate to about 0.5 percent.

Power

If $E_R/E_I \cong Z_{t,2}$ and $\dot{m}_R/\dot{m}_I \cong 1/\sqrt{Z_{t,2}}$, then $P_R/P_I \cong \sqrt{Z_t}$. Figure 13 illustrates the accuracy of this simple approximation. For the range of conditions considered herein the accuracy is within about 0.5 percent.

When considering the engineering design of systems which utilize nitrogen, it is very convenient that simple corrections to the ideal-gas values of mass flow, compression energy, and compression power give accurate values for the real-gas case.

CONCLUSIONS

In this report, an analysis has been made of the real-gas effects of nitrogen on the power required for isentropic compressions. The compressions are assumed to occur at the fan of a transonic cryogenic wind tunnel. The analytic model tunnel was assumed to operate at stagnation temperatures from 310K to saturation and at stagnation pressures to 8.8 atm. The results of this analysis lead to the following conclusions:

1. The energy to compress a unit mass of nitrogen at cryogenic temperatures is less than that required for the ideal gas. For the maximum pressure-minimum temperature conditions, this reduction in energy is in the order of 14 to 17 percent.
2. Tunnel mass flow at a given Mach number is higher for cryogenic nitrogen than for the ideal gas.
3. The power for isentropic compressions of cryogenic nitrogen is also less than that required for the ideal gas. At the maximum pressure-minimum temperature conditions, this reduction in power is in the

order of 7.5 to 9.5 percent. The power decrease is less than the energy decrease due to the increase in mass flow.

4. Simple compressibility factor corrections to the ideal values of mass flow, energy, and power give very accurate estimates of the real-gas values.

APPENDIX A.

Tunnel Throat Conditions - Real Gas Calculations

Presented in figure 14 is a flow chart of the portion of the program that makes the real-gas calculations of the throat conditions. The variables required for the part of the program are shown at the top of the chart. The following is a step by step description of the calculations that occur at each block of the flow chart.

Step 1. Subroutine PROP from the National Bureau of Standards (NBS) program is used to calculate the stagnation enthalpy, $h_{t,2}$ and entropy, $S_{t,2}$.

Step 2. An initial guess for the static conditions (p,ρ,T) is made by utilizing the appropriate ideal-gas equations.

Step 3. The real gas value of static temperature, T_R, is initialized to the ideal value, T, and T_R is established as the iterative variable in order to force the solutions to coverge on the desired M_{TH}.

Step 4. Function DSFND finds the real gas density, ρ_R, by simultaneously solving the entropy and state equations with T_R and $S_{t,2}$.

Step 5. Subroutine PROP gives values for static pressure, p_R and static enthalpy, h, by using T_R and ρ_R from steps 3 and 4 respectively.

Step 6. If the static temperature, T_R, and pressure, p_R, are coincident with a point on the vapor pressure curve or if they lie in the liquid region, the solution is terminated.

Step 7. Subroutine VSND (NBS program) calculates the velocity of sound, W_R with T_R and ρ_R as inputs.

Step 8. Subroutine MVCAL calculates the velocity and Mach number from these equations:

$$V_R = \sqrt{2(h_{t,2}-h)}$$

$$M_R = V_R/W_R$$

Step 9. The mass flow rate per unit area is now calculated

$$\dot{m}_R = \rho_R V_R$$

Step 10. The calculated Mach number, M, is checked to see if it is within 0.00001 of the desired M_{TH}. If it is, the solution for the throat conditions is complete and the mass flow rate is printed out.

Step 11. If the Mach convergence is not satisfactory, subroutine TCHANG finds the slope of the temperature-Mach curve, $\Delta T_R/\Delta M$, for a constant entropy, $S_{t,2}$. A linear adjustment is made to the static temperature, T_R, as required for Mach convergence.

Step 12. This adjusted T_R is returned to Step 3 for the next iteration and steps 3 through 12 are repeated until the Mach convergence criteria is met at step 10.

APPENDIX B

Fan Calculations.-- Real Gas

Presented in figure 15 is a flow chart of the portion of the program that calculates the fan conditions for the real gas (nitrogen) case. The objectives of this part of the program are to obtain an isentropic solution for the upstream stagnation quantities ($p_{t,1}$, $T_{t,1}$) and then calculate the energy per unit mass, E_R, and the power, P_R, required for the compression. The downstream conditions ($p_{t,2}$, $(T_{t,2})_R$, $S_{t,2}$, $h_{t,2}$), the fan pressure ratio, r, and the tunnel mass flow rate, $(\dot{m})_R$, are required as inputs to this part of the program. The following is a step by step description of the calculations that occur at each block of the flow chart.

Step 1. The fan inlet pressure is calculated directly as shown. Note that $p_{t,1}$ and $p_{t,2}$ have the same values for both the real and ideal gas cases.

Step 2. An initial guess for the fan inlet temperature, $T_{t,1}$, is made using the ideal gas equation.

Step 3. $T_{t,1}$ is set up for iteration in order to force the upstream entropy, $S_{t,1}$, to be the same as the downstream entropy, $S_{t,2}$. (Step 6)

Step 4. Subroutine PROP is called with $p_{t,1}$ and $T_{t,1}$ to give values for the upstream enthalpy, $h_{t,1}$ and entropy, $S_{t,1}$.

Step 5. The upstream temperature is increased by a factor of 1.001 and is used in subroutine PROP with $p_{t,1}$ to give another point on the entropy temperature curve.

Step 6. A comparison of $S_{t,1}$ and $S_{t,2}$ is made to see if these two entropies agree to within 1×10^{-8}.

Step 7. When the two entropies have not converged sufficiently, a temperature-entropy slope is calculated from the information of steps 4 and 5.

Step 8. This temperature-entropy slope is used to adjust $T_{t,1}$ to account for the difference in the inlet and outlet entropies $(S_{t,2}-S_{t,1})$ and this is returned to step 3 for the next iteration.

Step 9. When the convergence criteria of step 6 is finally satisfied the energy and power are calculated.

Step 10. The solution is complete and the fan inlet conditions and power values are stored for utilization in other parts of the program.

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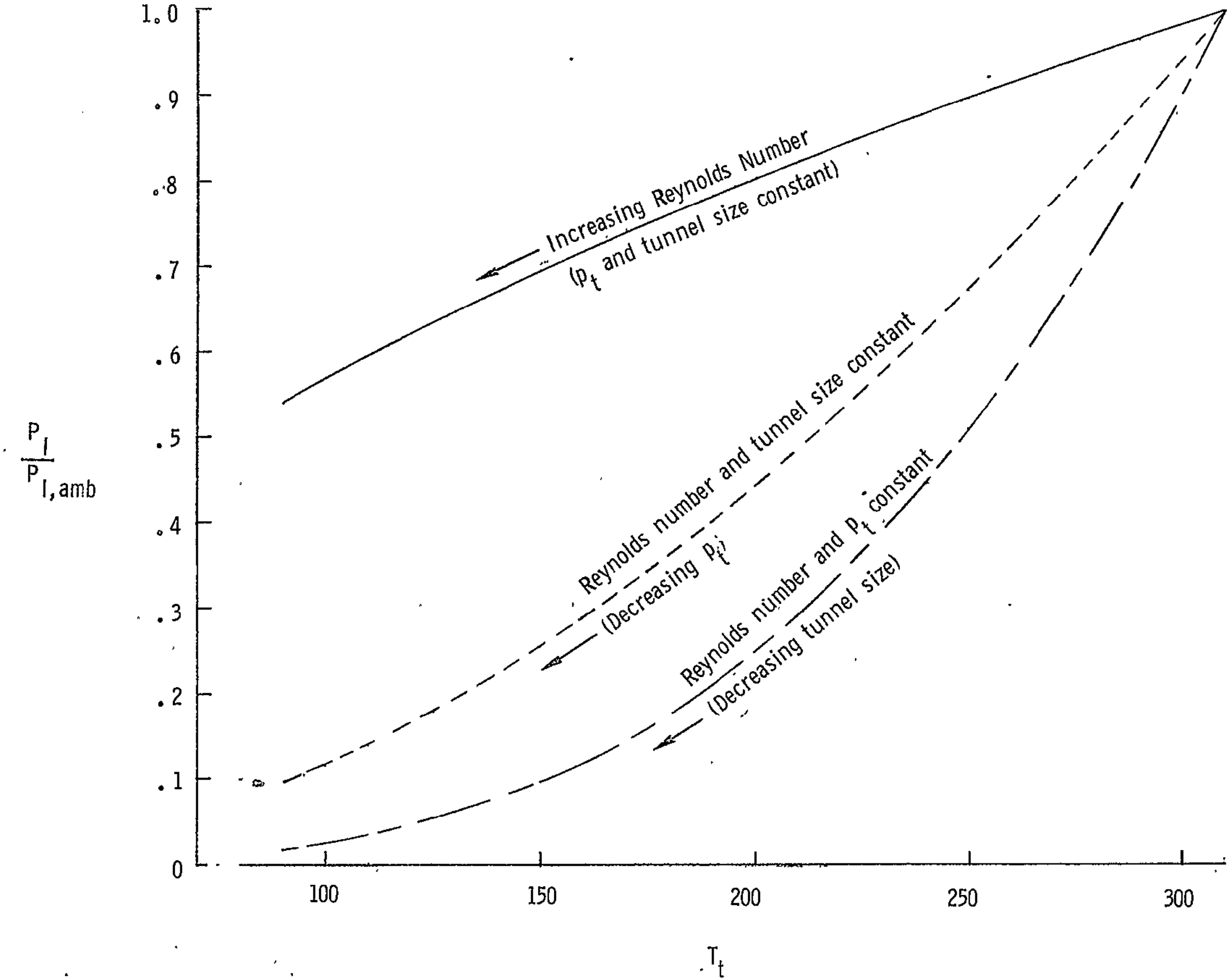


Figure 1. Variation of tunnel drive power with tunnel operating temperature. (M_{TS} = 1.0)

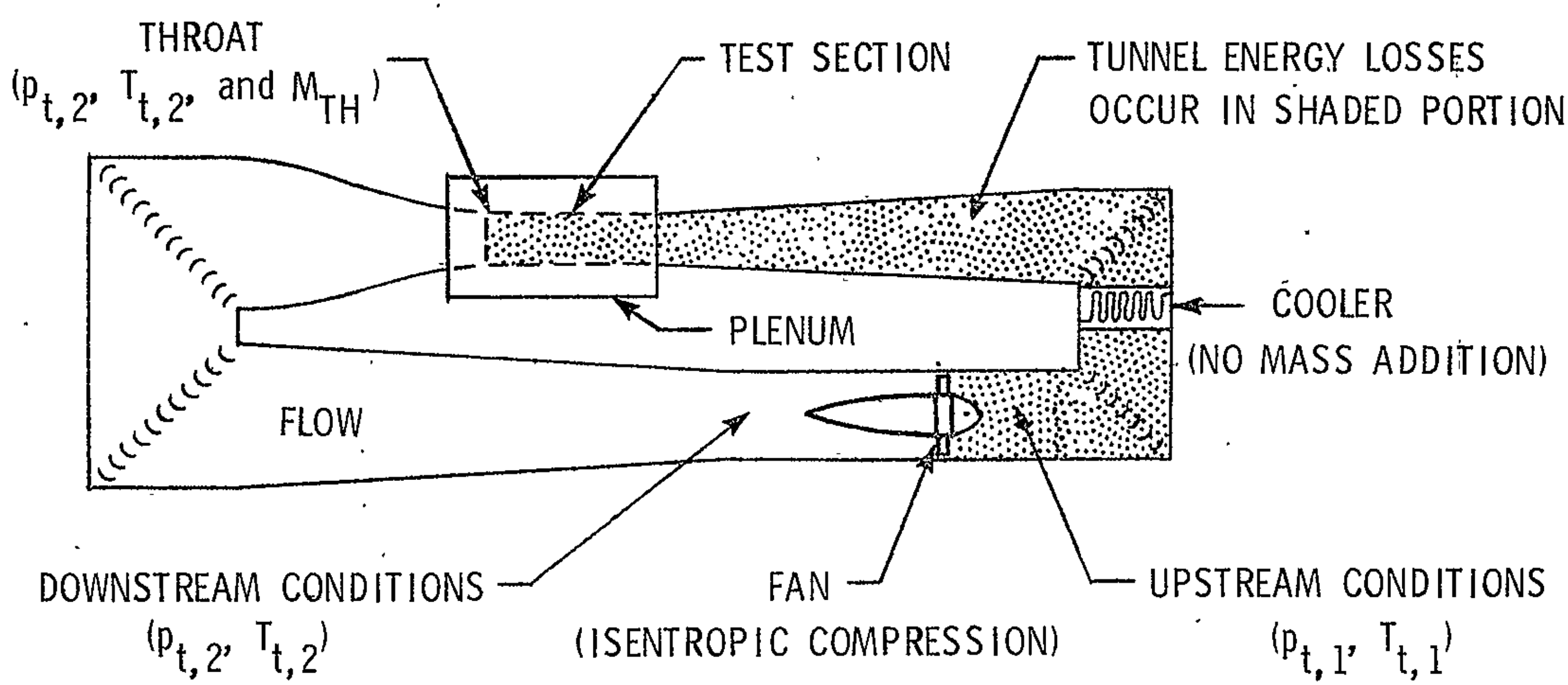


Figure 2. Analytical model of tunnel.

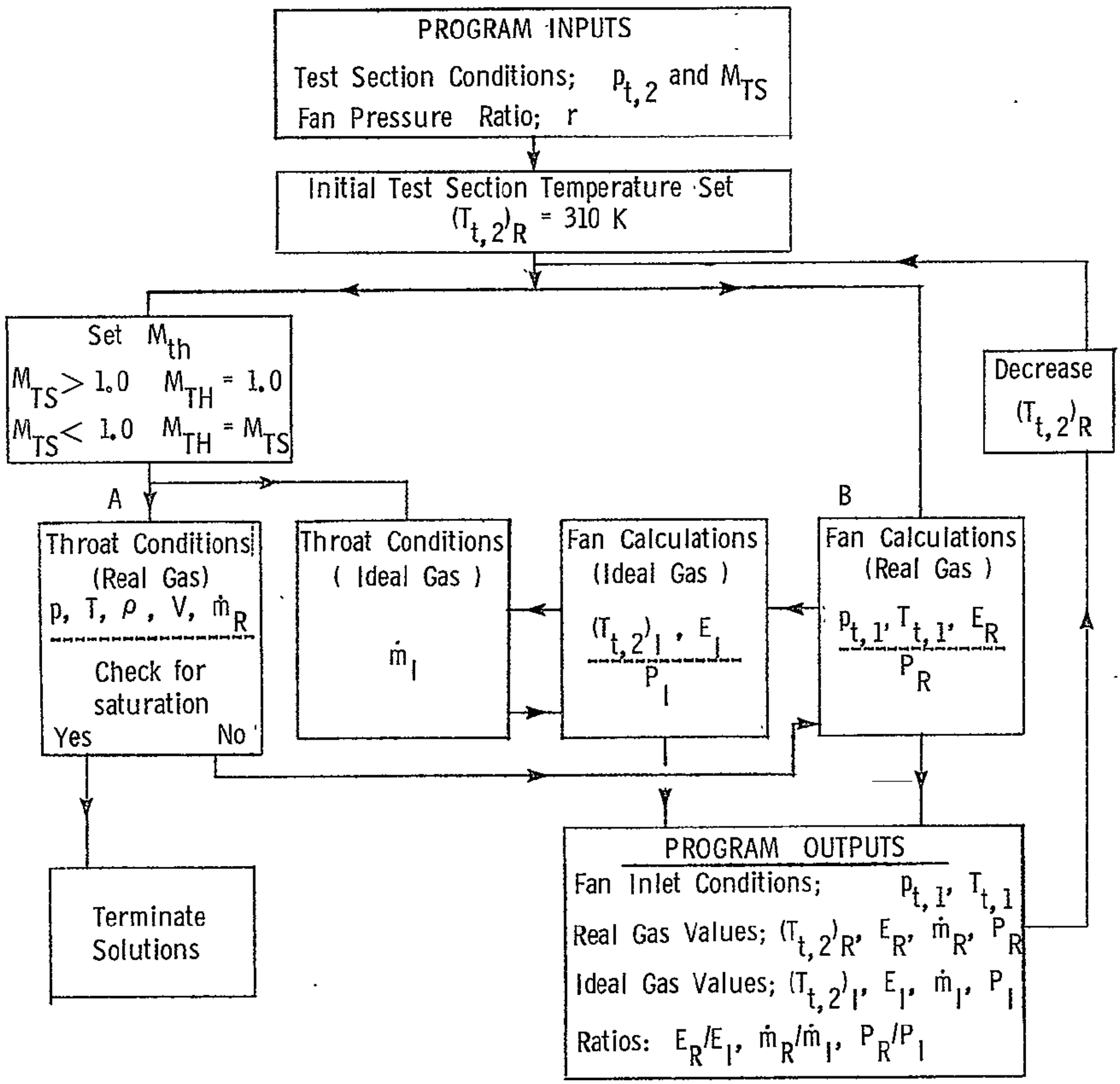


Figure 3. Flow chart for isentropic power requirements program.

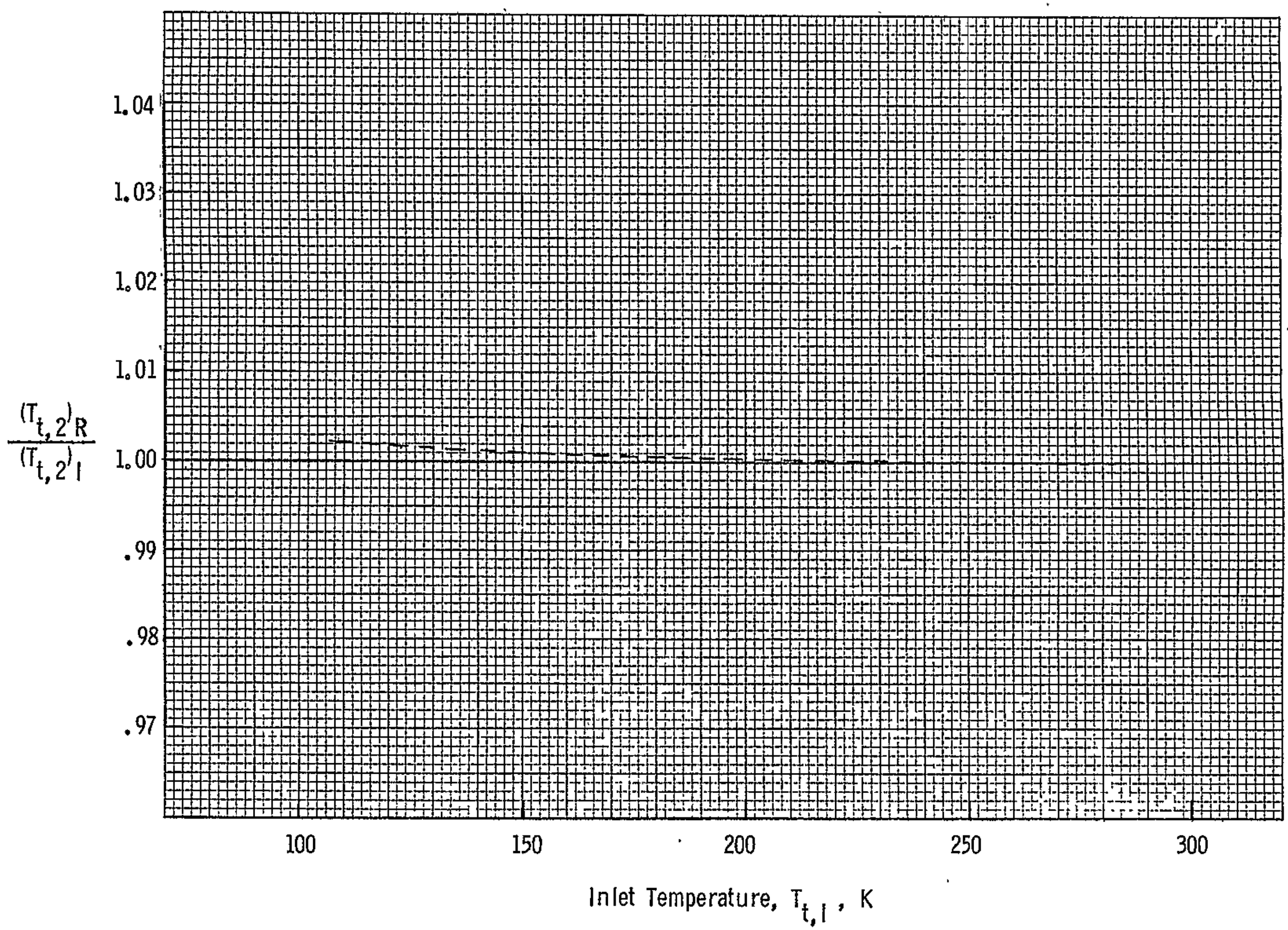
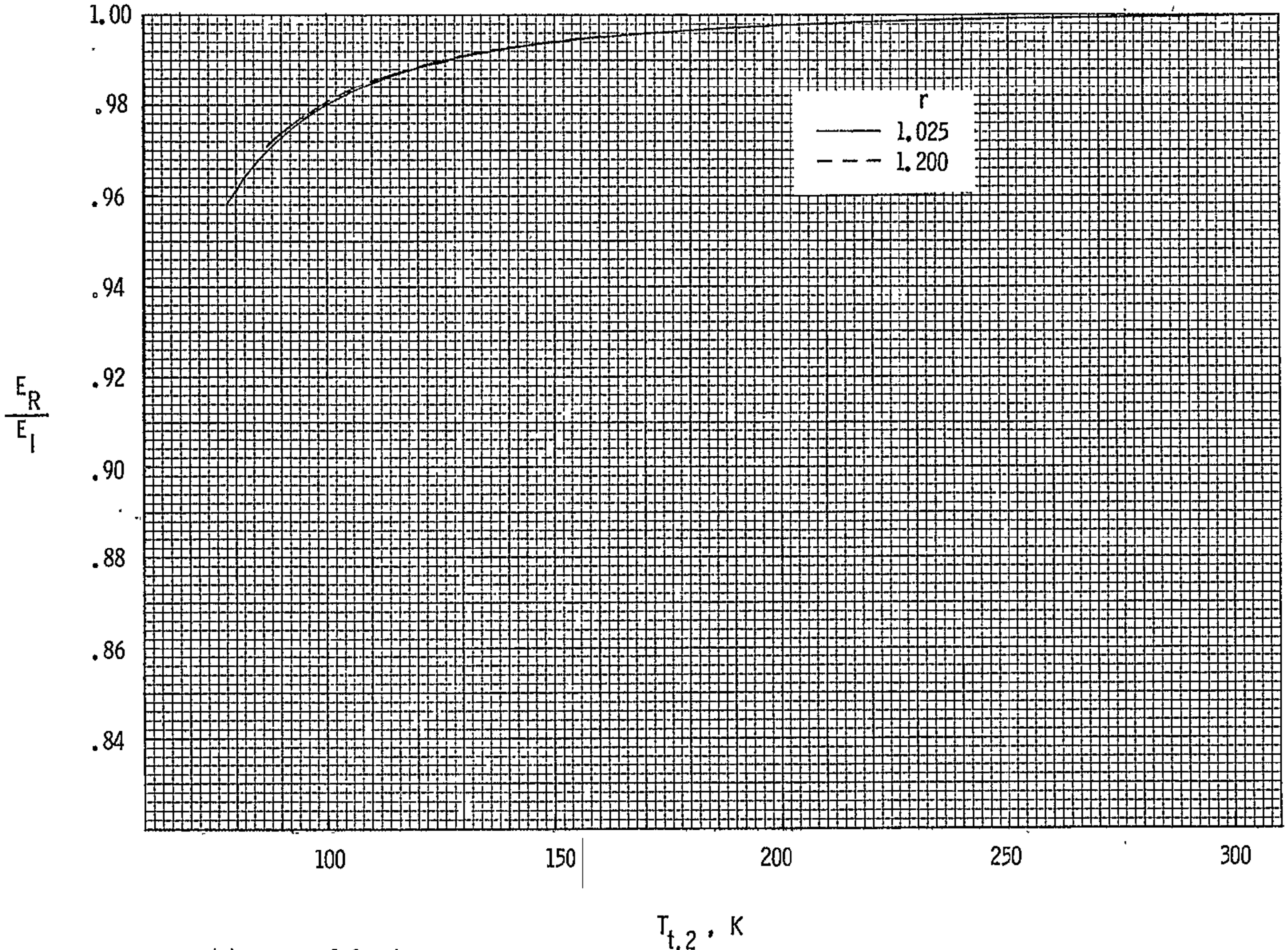
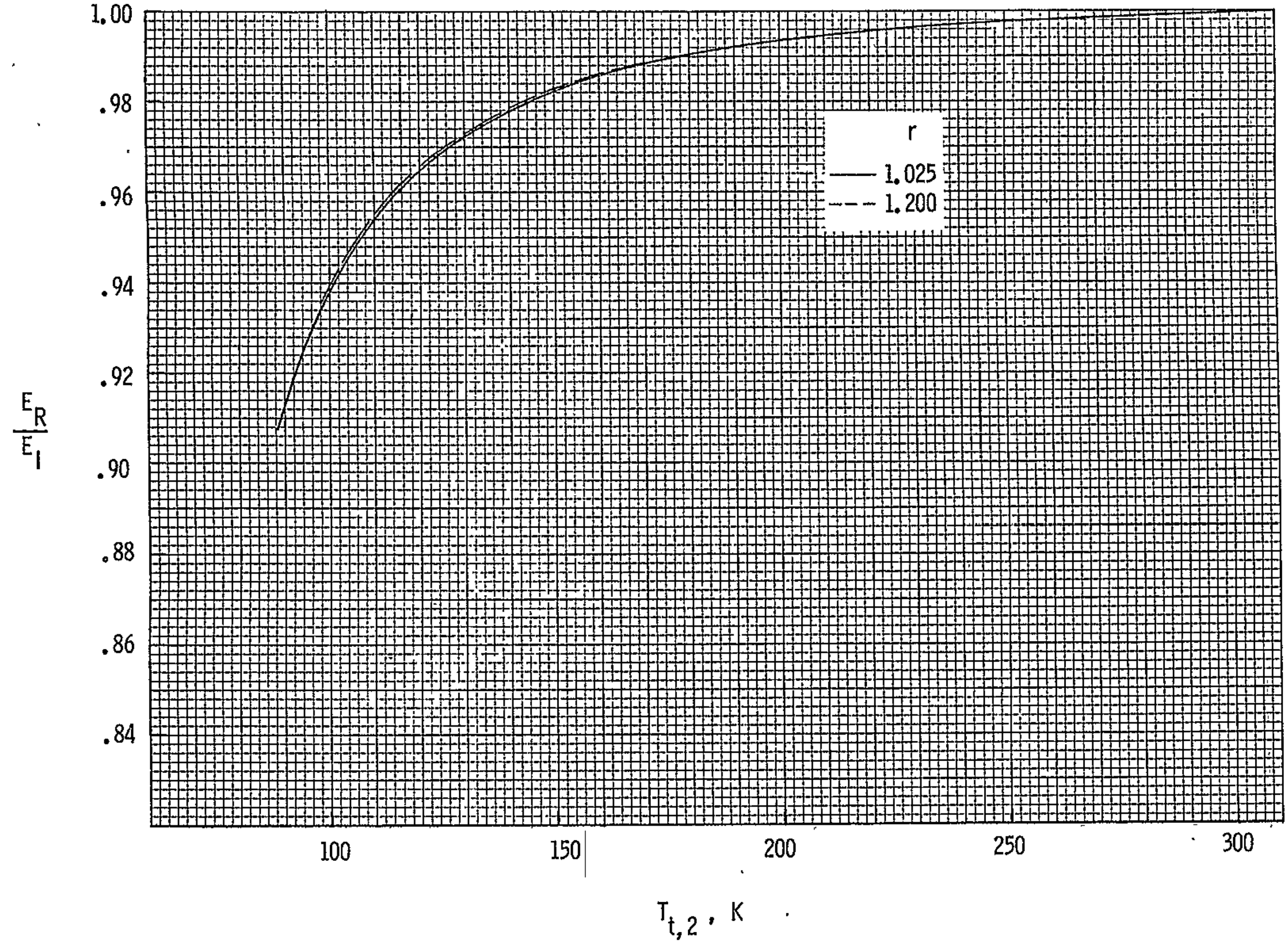


Figure 4. Relative value of downstream stagnation temperature as a function of inlet stagnation temperature. $p_{t,2}$ = 8.8 atm and r = 1.20.



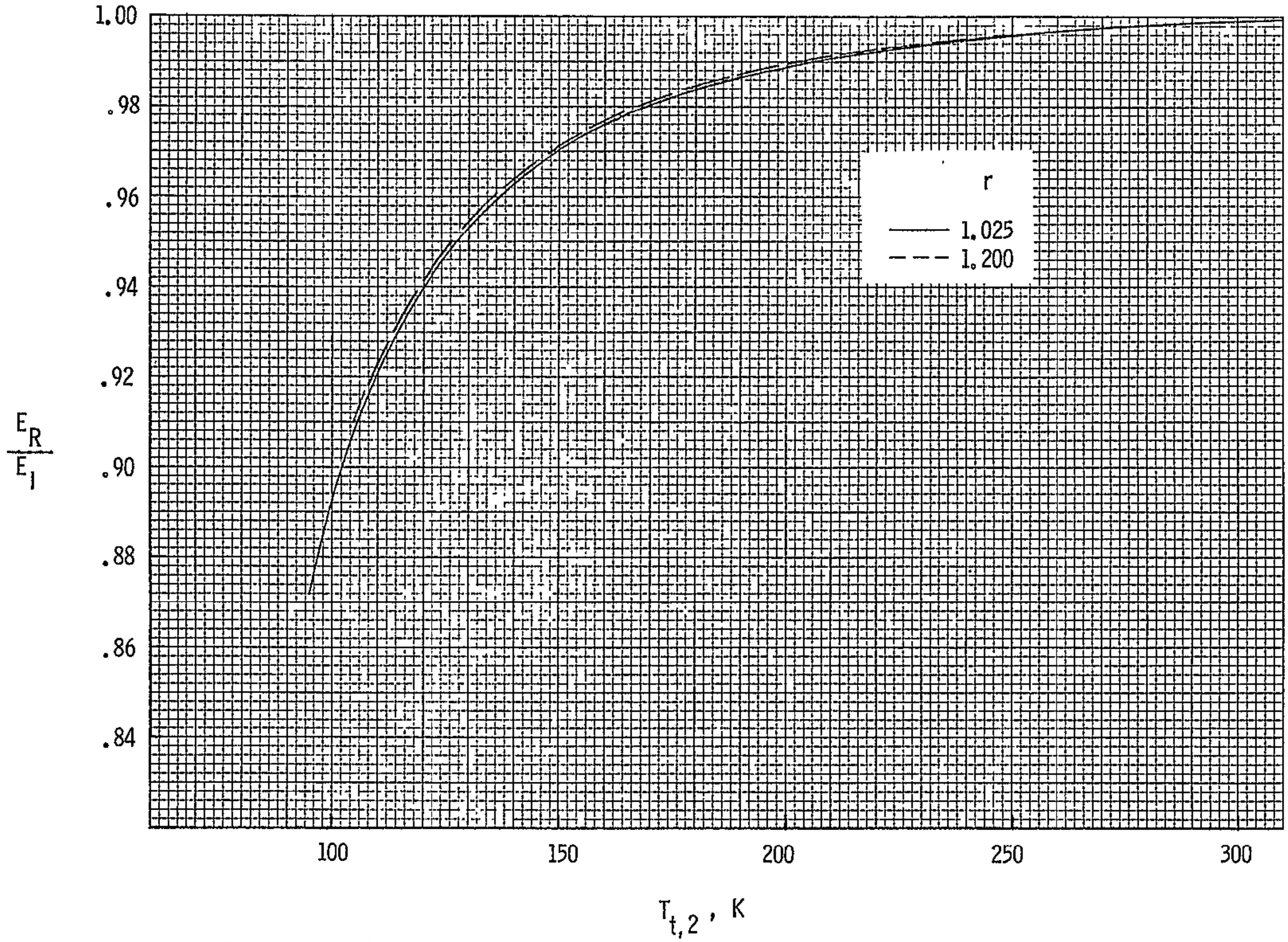
(a) $p_{t,2}$ = 1.0 atm

Figure 5. Energy for isentropic compressions of nitrogen. [Relative to ideal gas values]



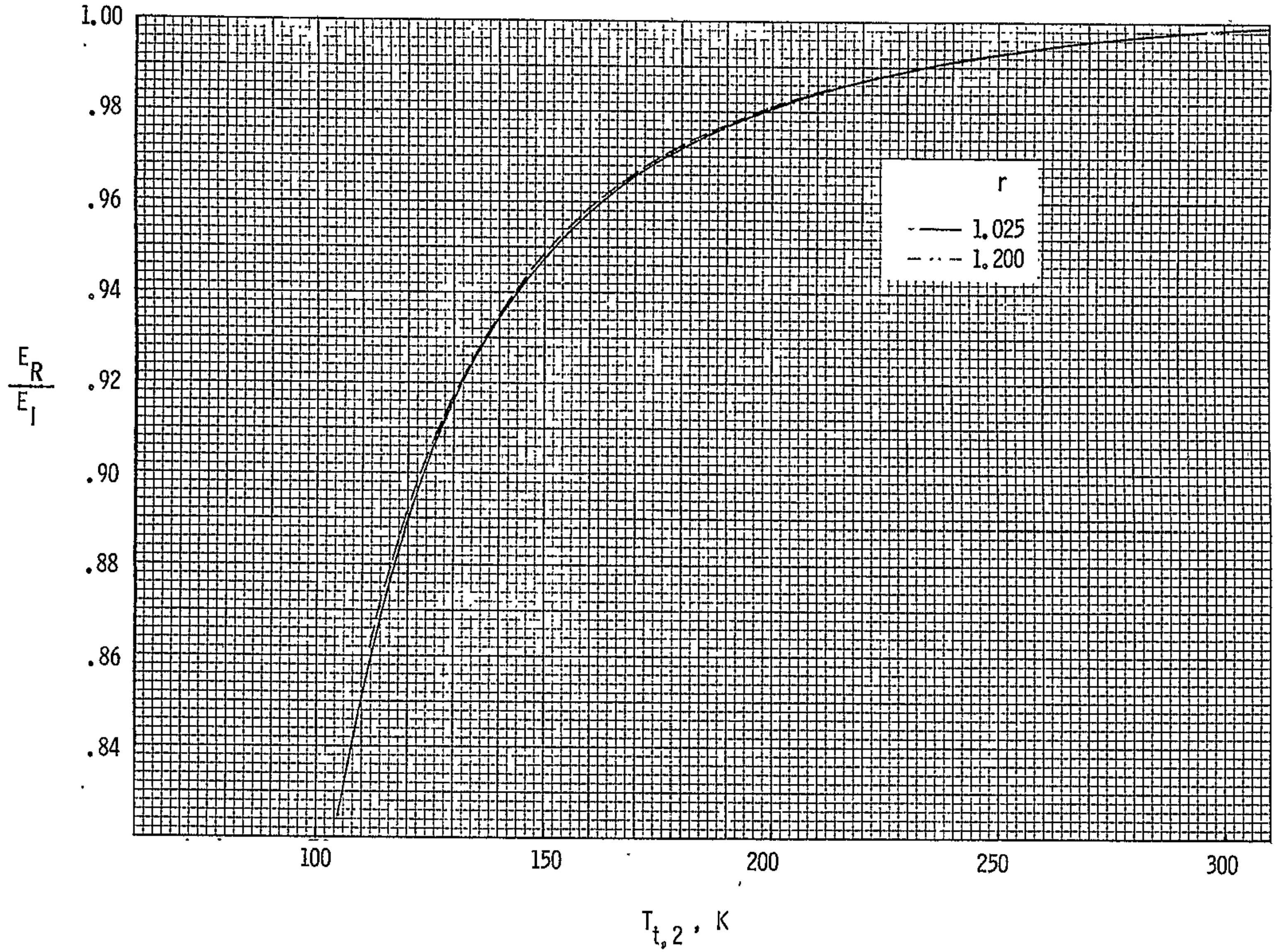
(b) $p_{t,2}$ = 3.0 atm

Figure 5. Continued.



(c) $p_{t,2}$ = 5 atm

Figure 5. Continued.



(d) $p_{t,2}$ = 8.8 atm

Figure 5. Concluded.

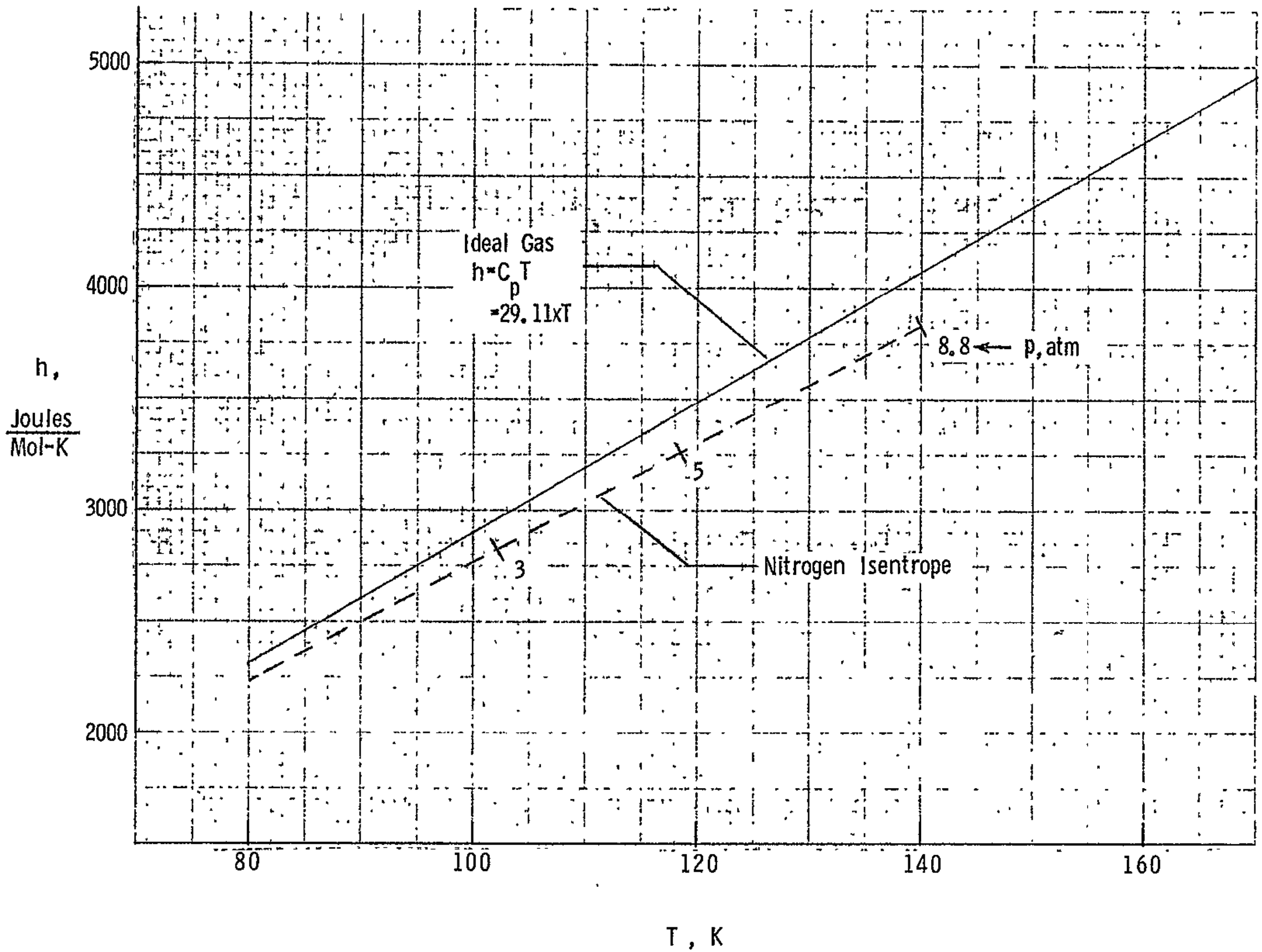


Figure 6. Variation of enthalpy with temperature along isentropes.

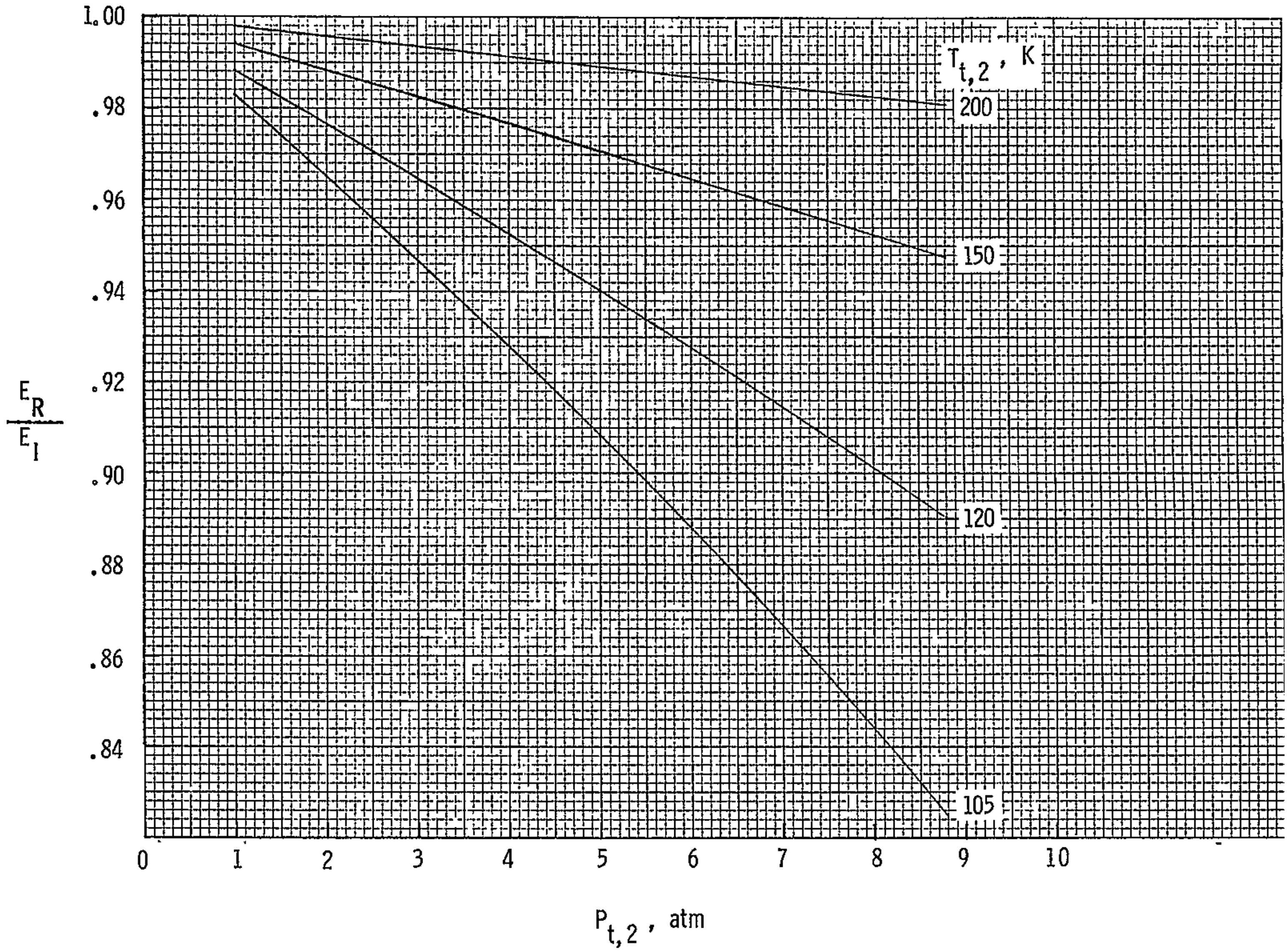
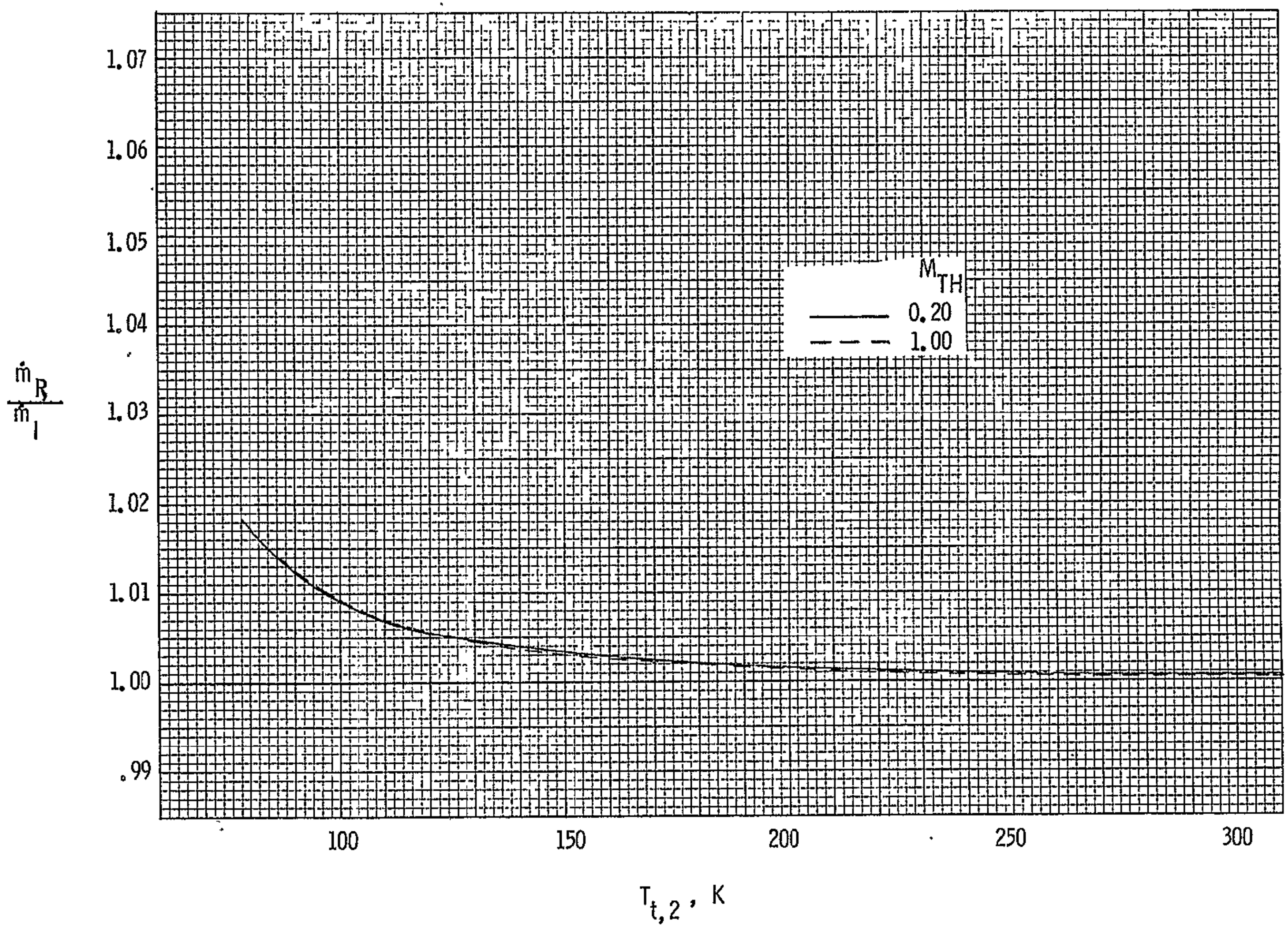
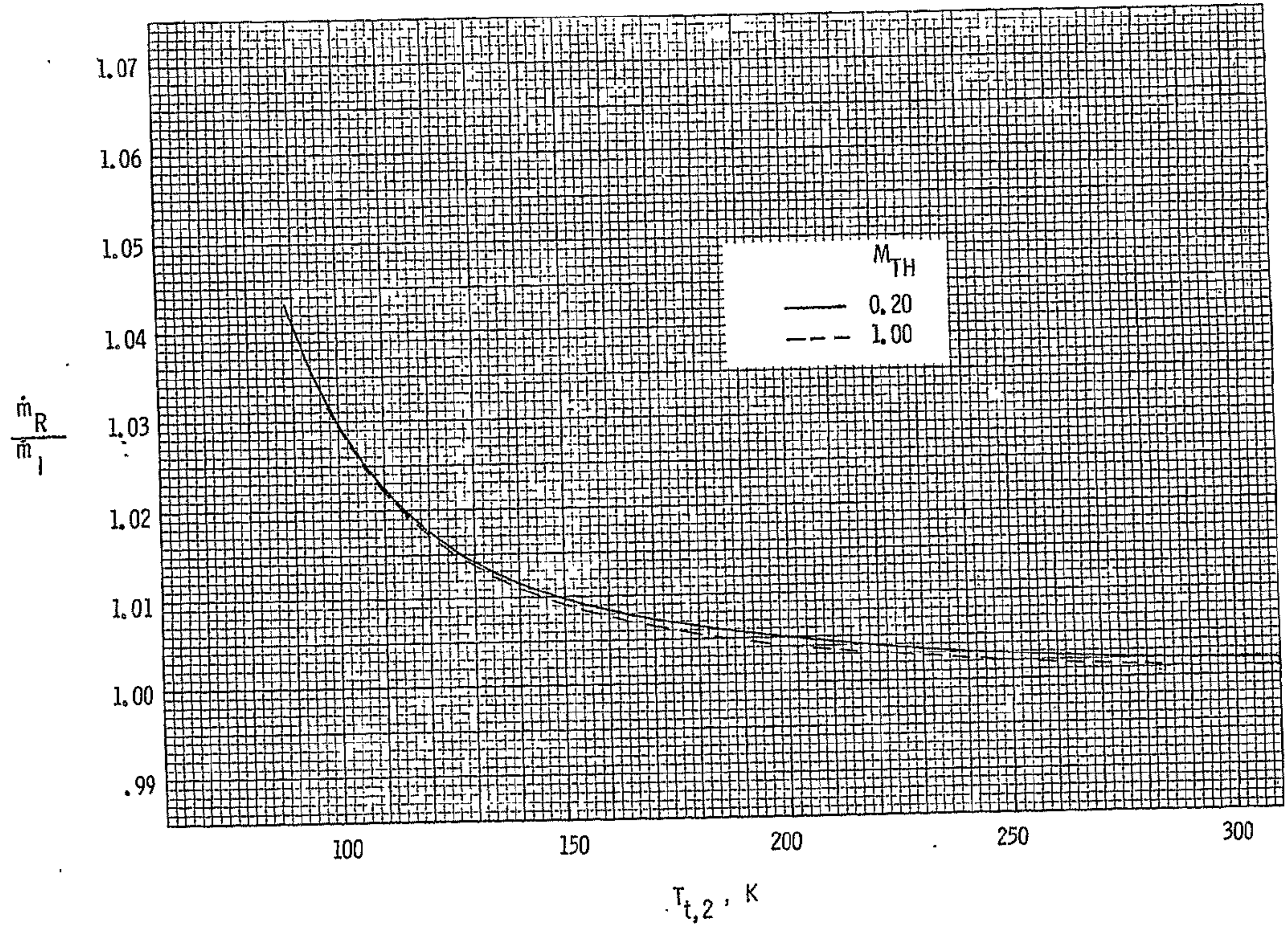


Figure 7. Variation of isentropic compression energy for nitrogen with stagnation pressure.
[Relative to ideal gas values, r = 1.025]



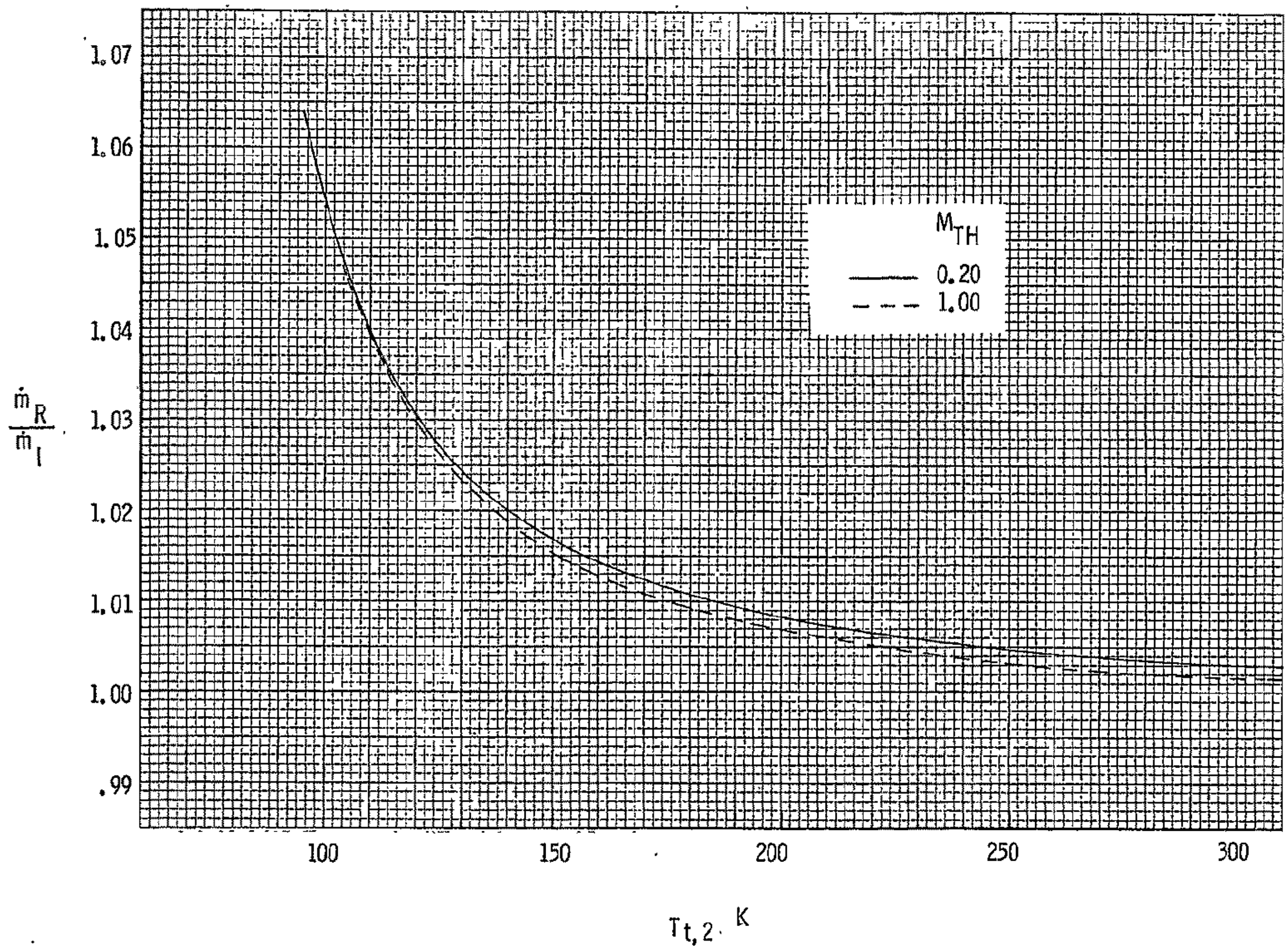
(a) $p_{t,2}$ = 1.0 atm

Figure 8. Relative mass flow rates for various stagnation temperature and pressures of tunnel throat.



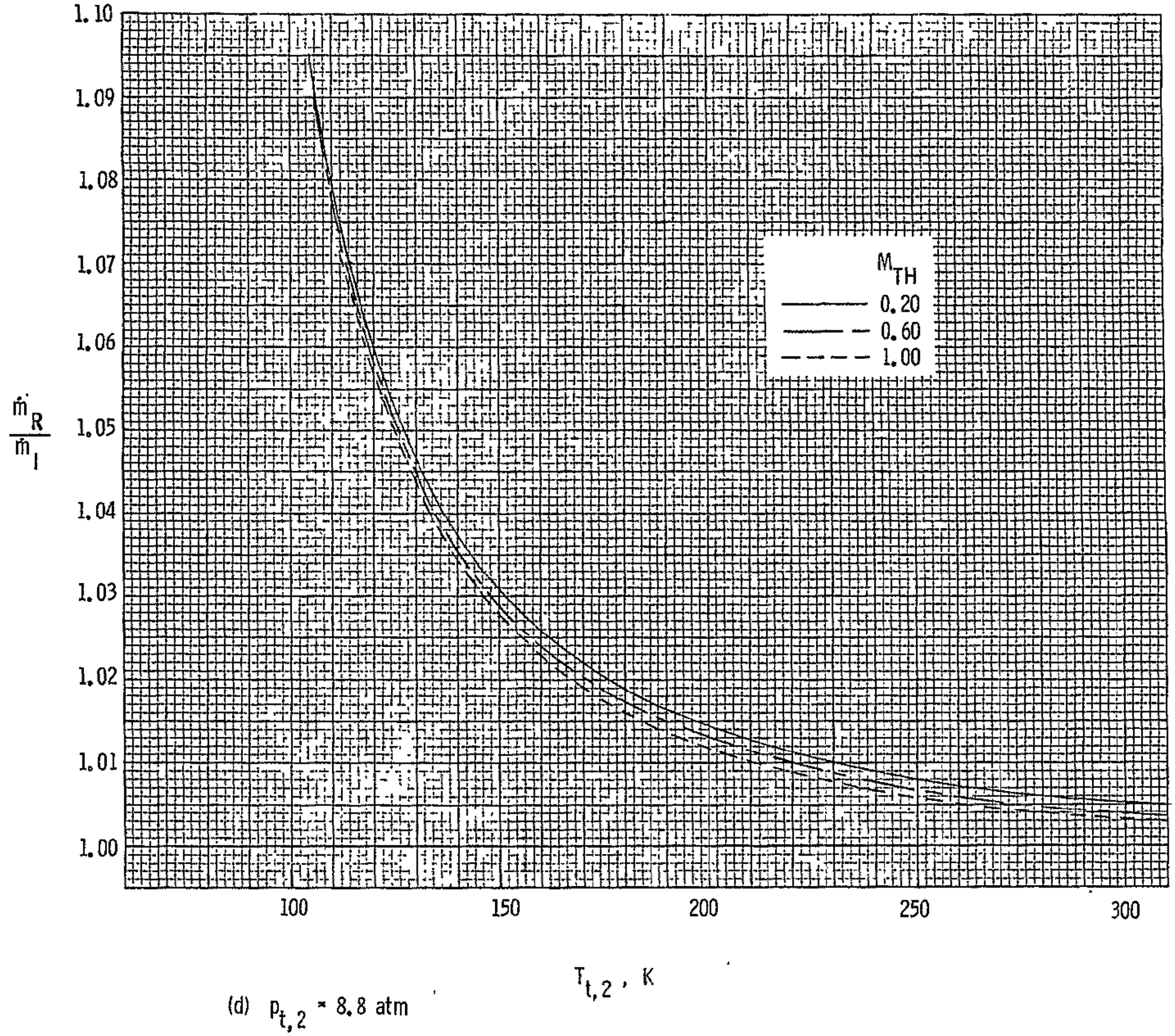
(b) $p_{t,2}$ = 3.0 atm

Figure 8. Continued.



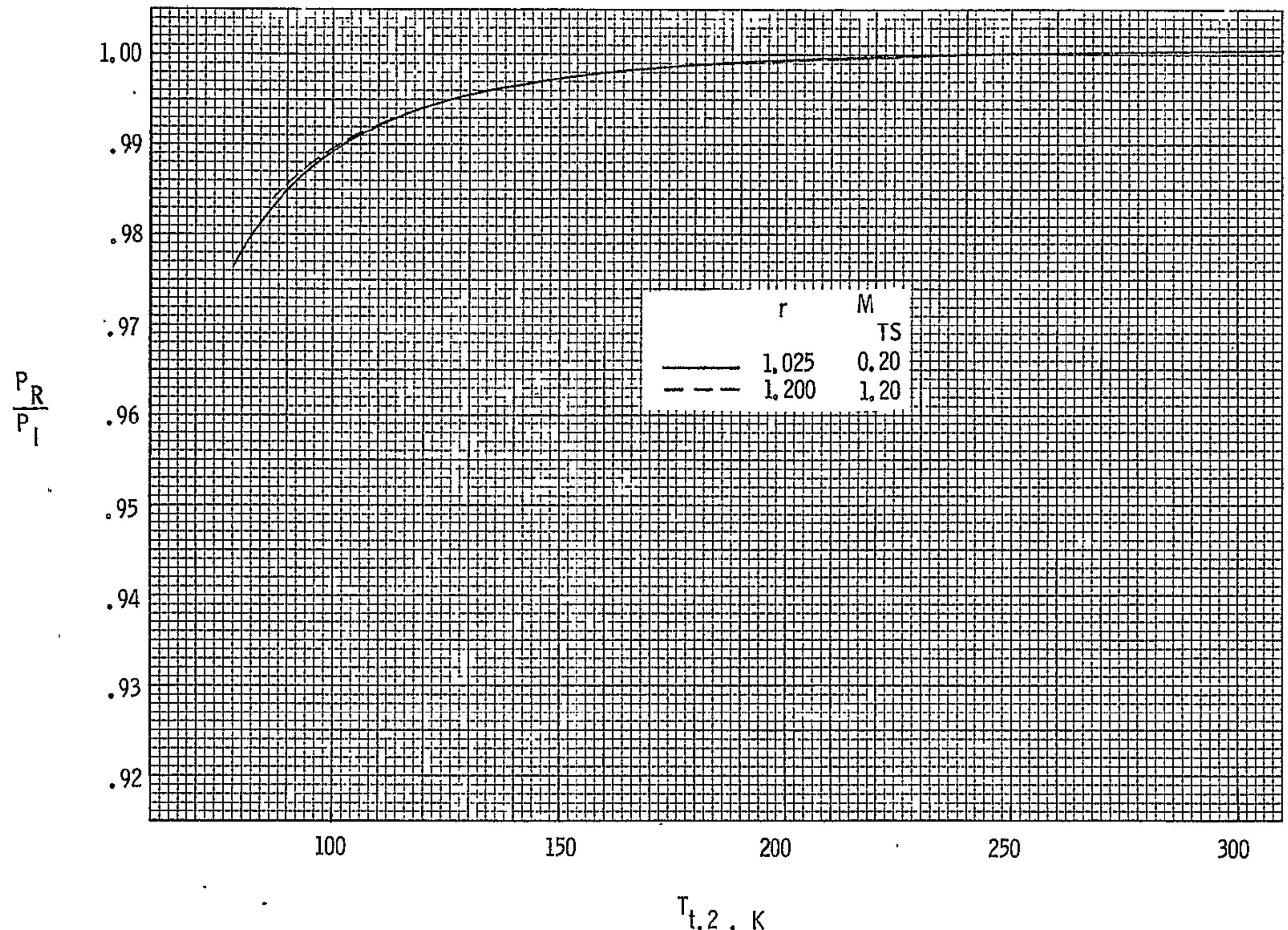
(c) $p_{t,2} = 5.0$ atm

Figure 8. Continued.



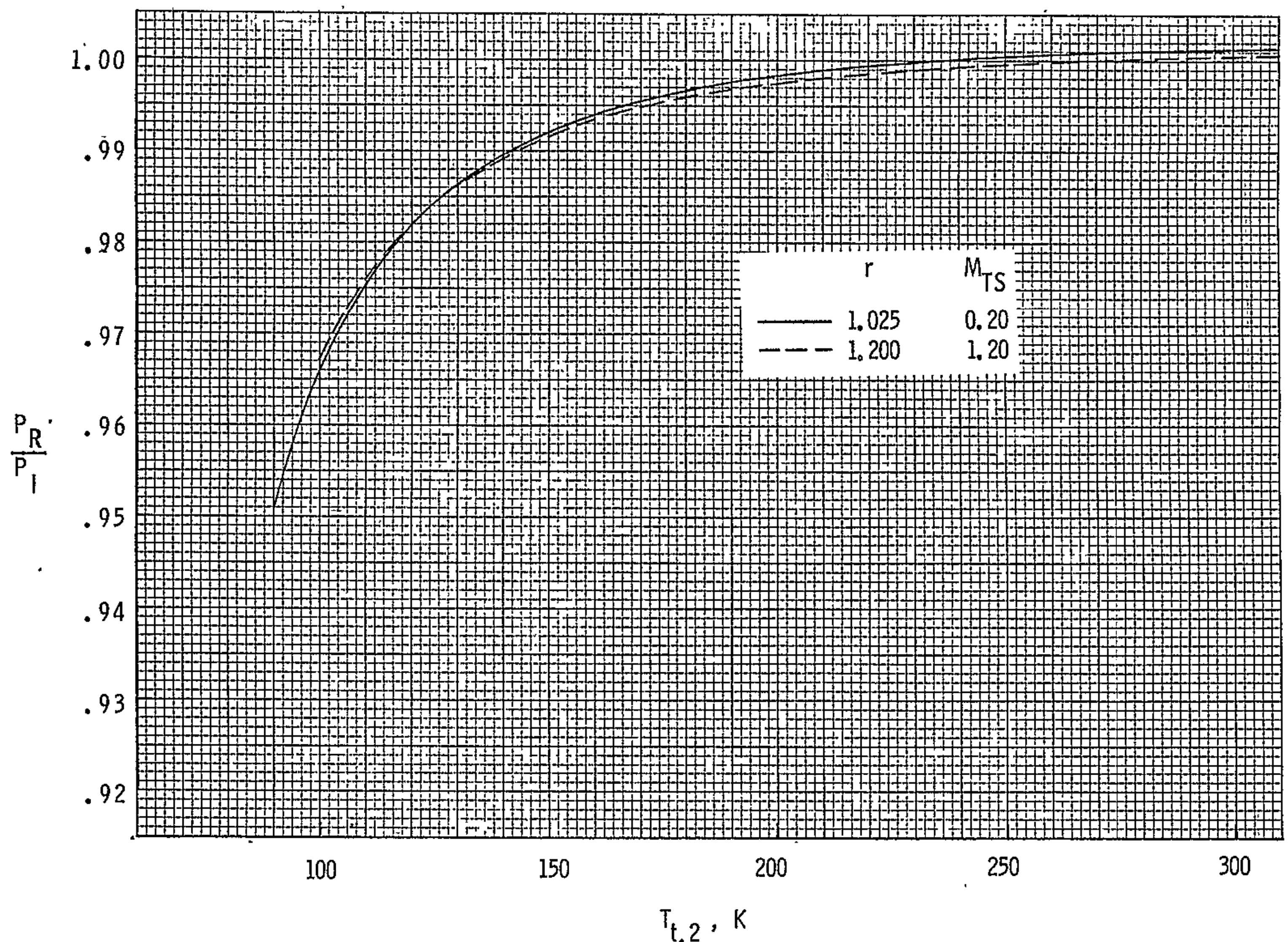
(d) $p_{t,2} = 8.8$ atm

Figure 8. Concluded.



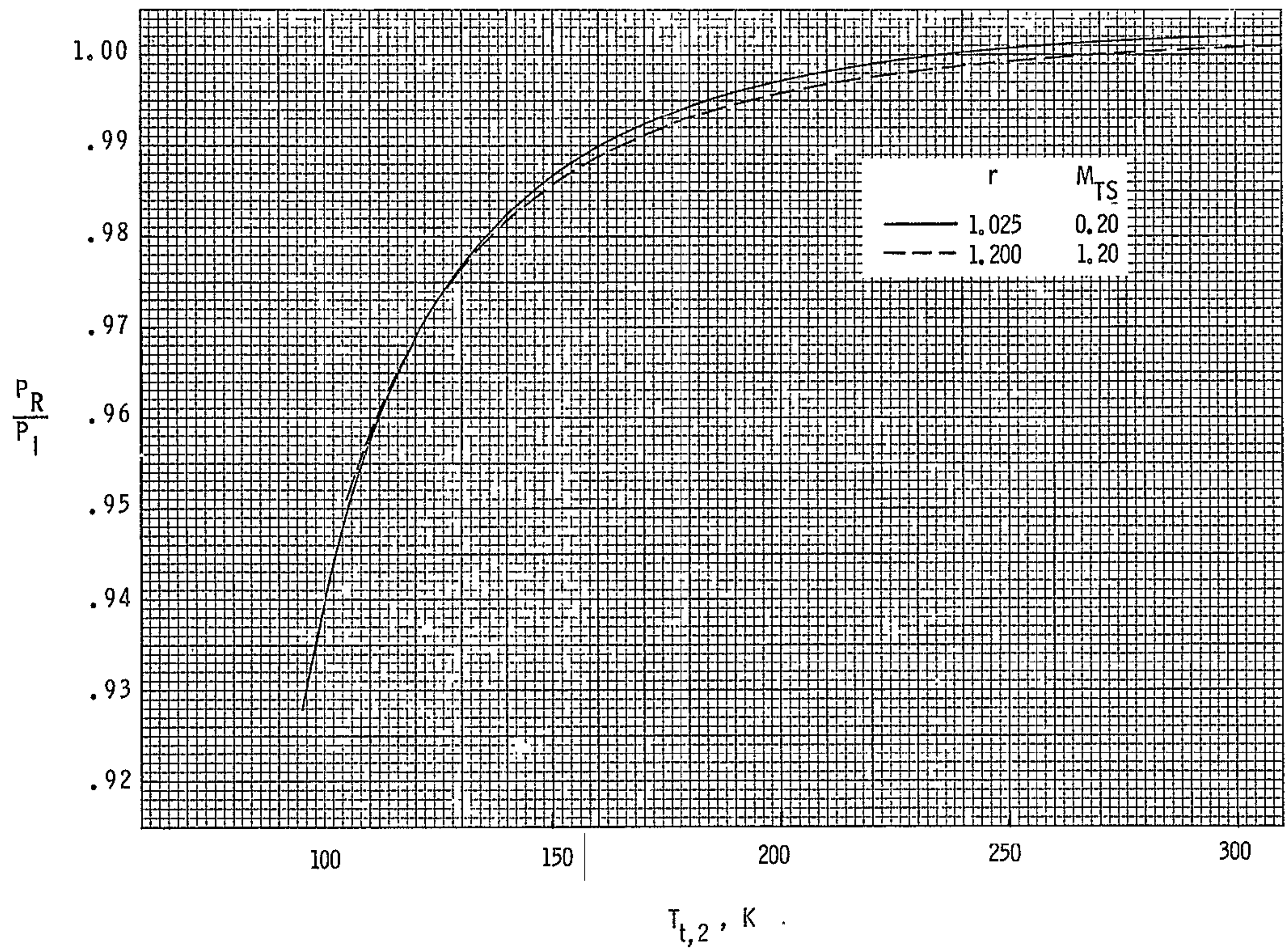
(a) $p_{t,2}$ = 1.0 atm

Figure 9. Relative isentropic power values for various stagnation temperatures and pressures.



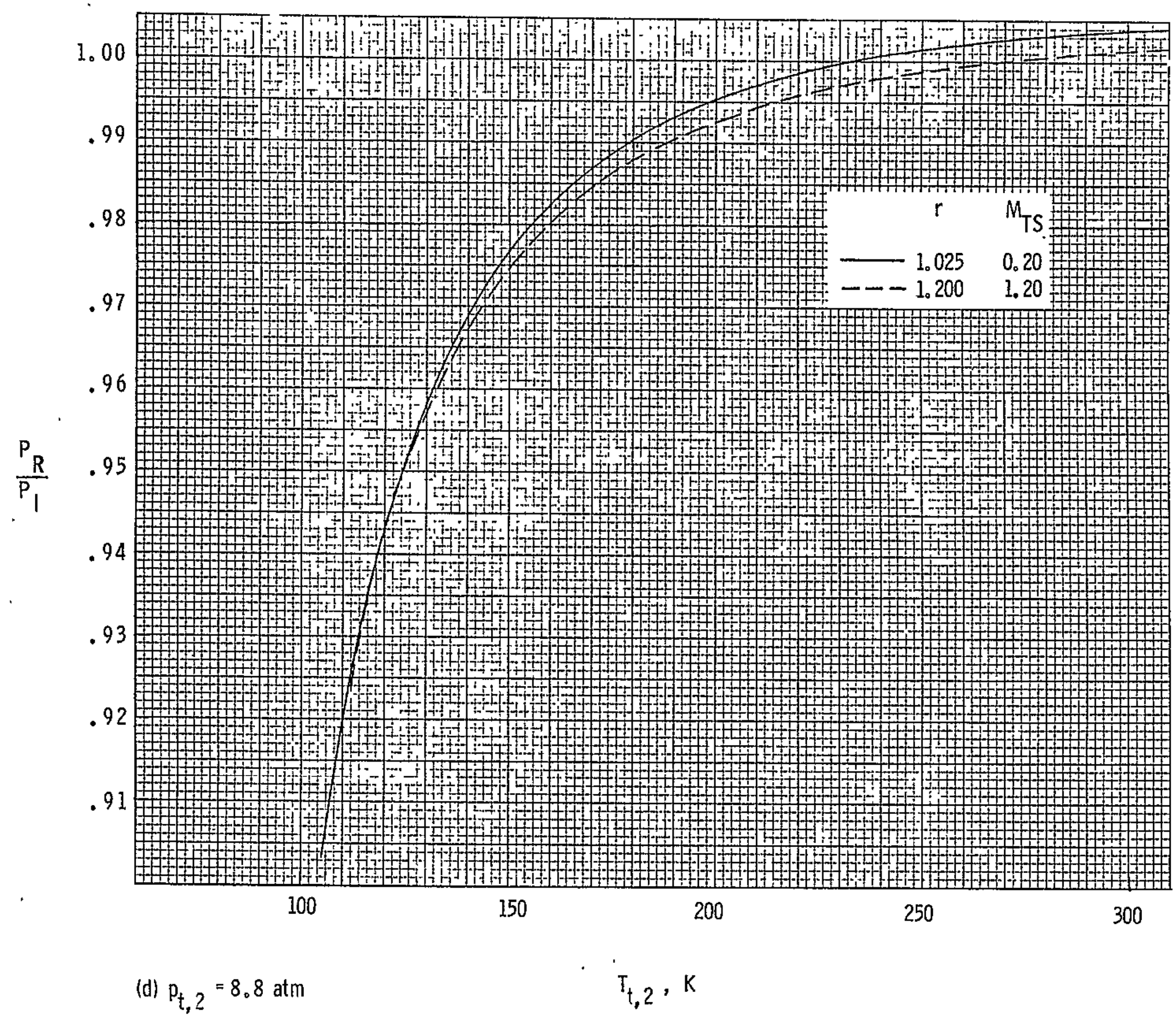
(b) $p_{t,2}$ = 3.0 atm

Figure 9. Continued.



(c) $p_{t,2}$ = 5.0 atm

Figure 9. Continued.



(d) $p_{t,2}$ = 8.8 atm

Figure 9. Concluded.

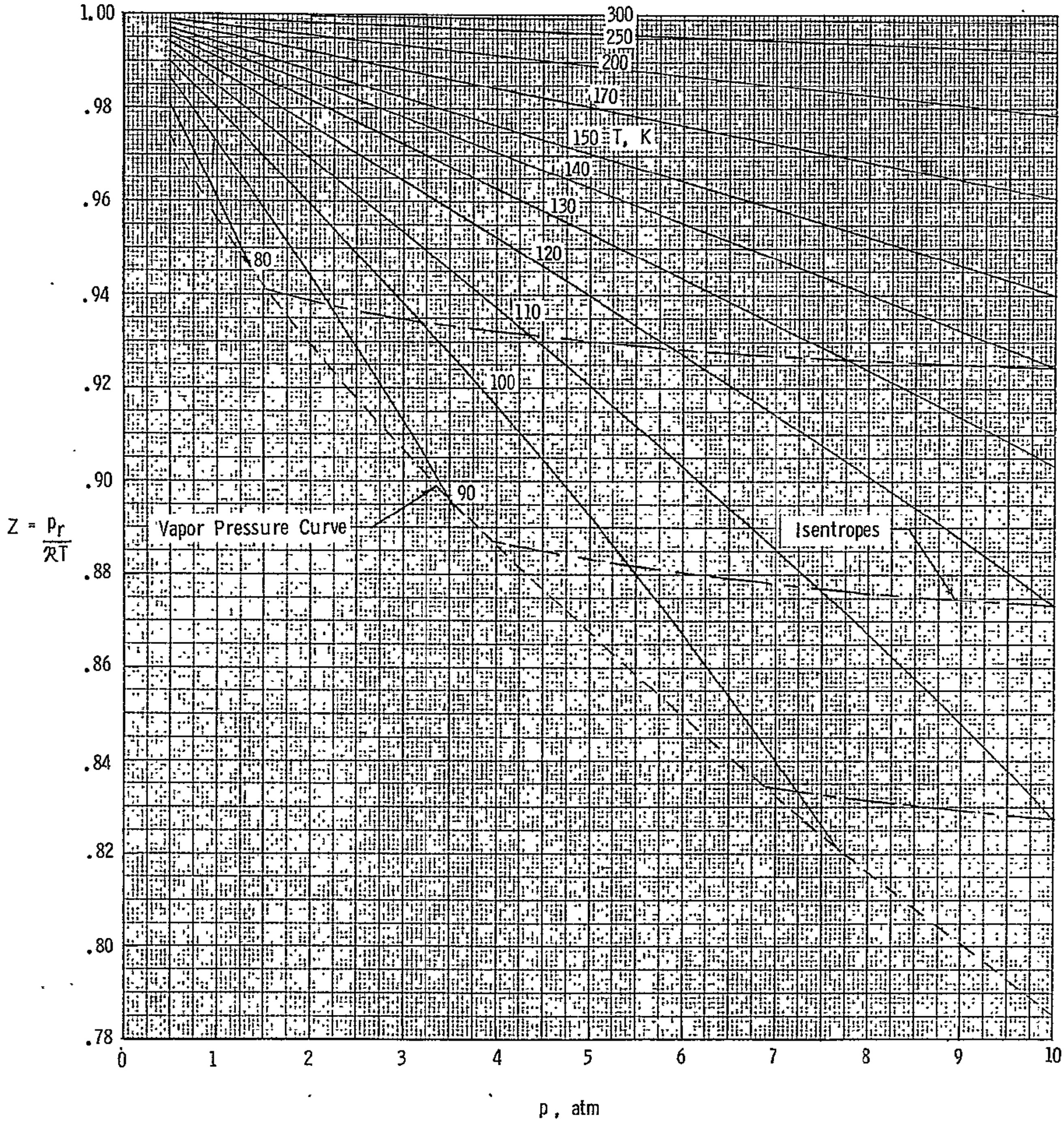


Figure 10. Compressibility factor for nitrogen (Ref. 7).

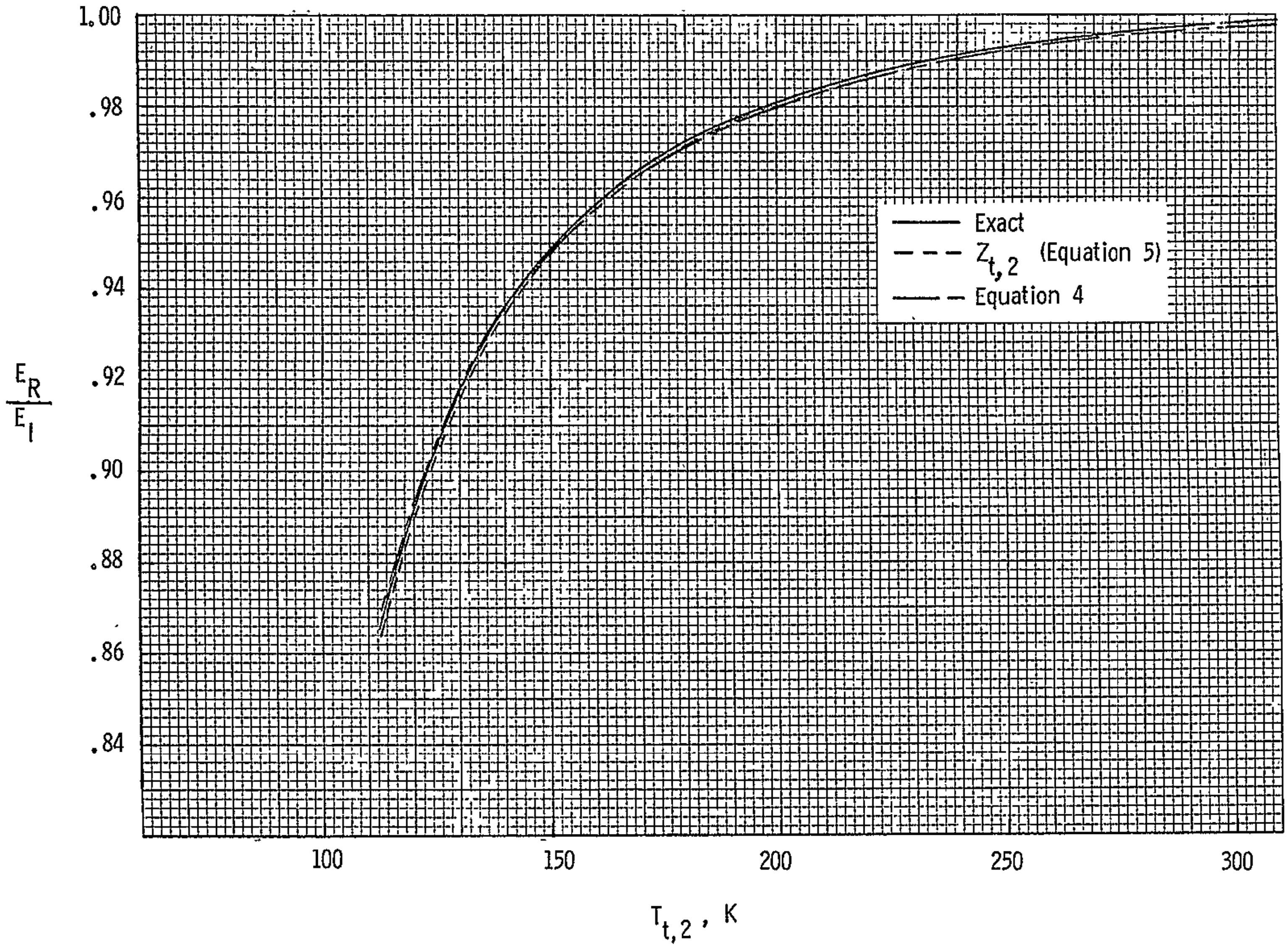


Figure 11. Estimates of the energy for isentropic compressions of nitrogen compared with the exact values. [$p_{t,2}$ = 8.8 atm, r = 1.20]

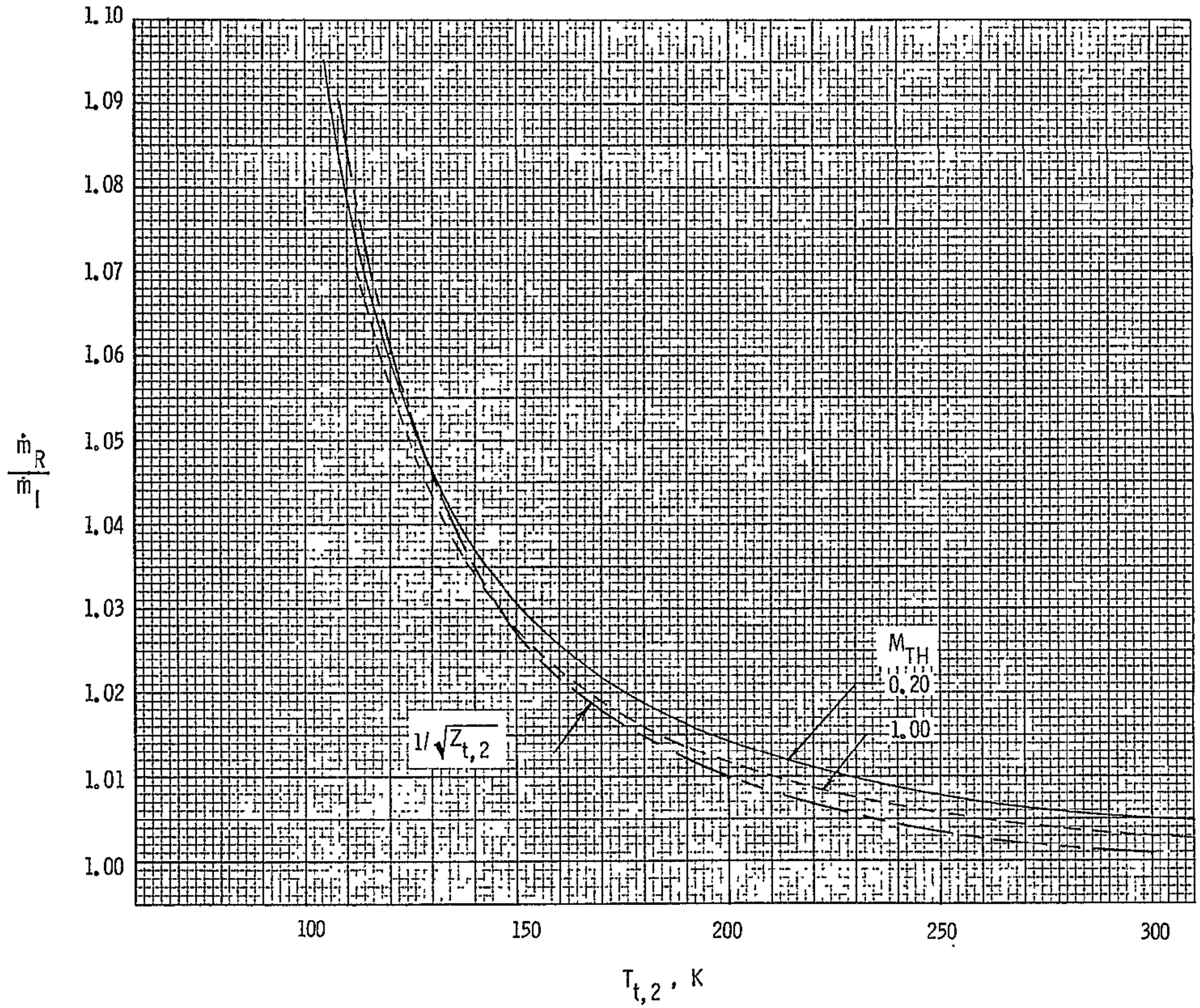


Figure 12. An approximation for the real-gas mass flow rates of nitrogen (isentropic flow).

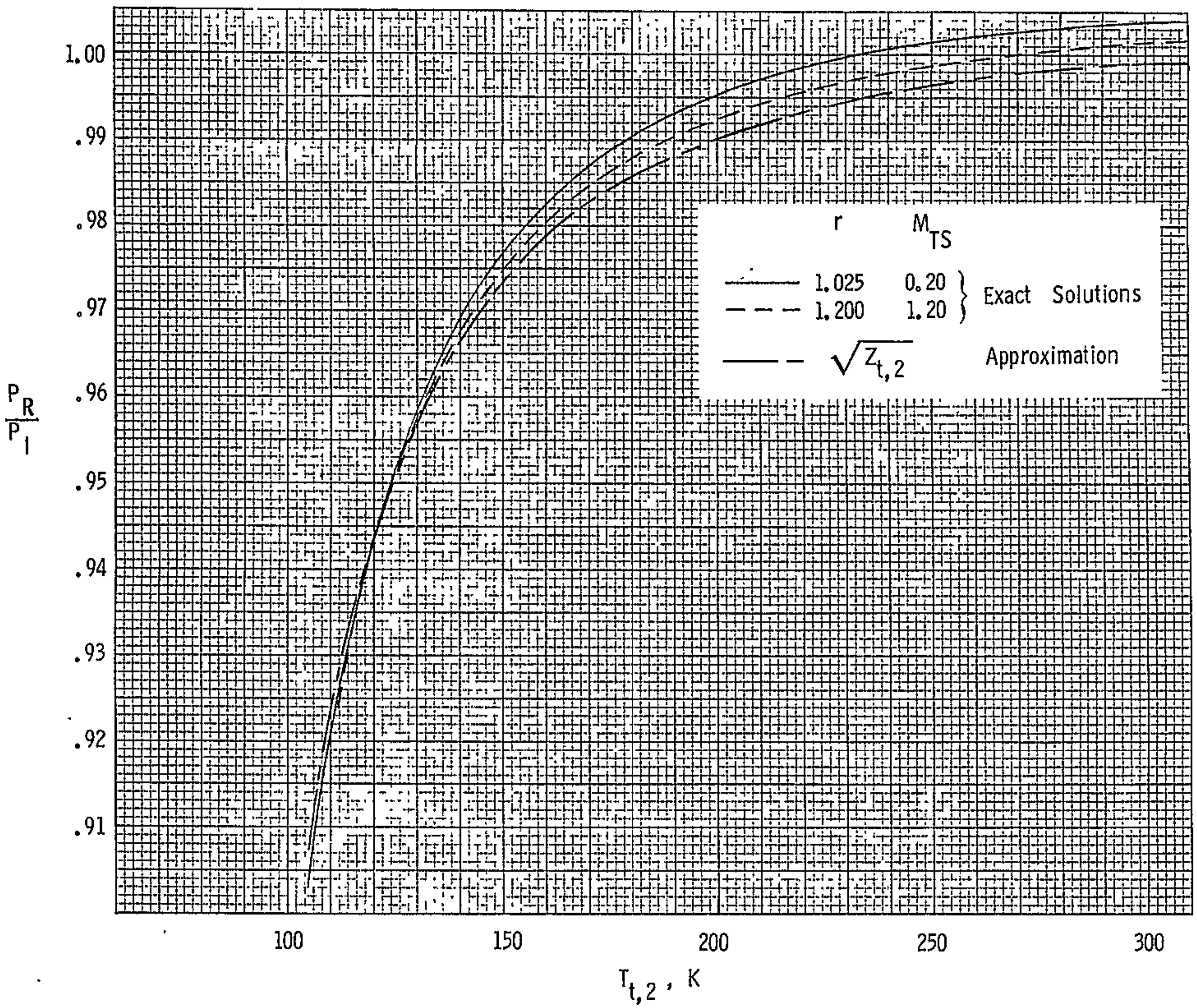


Figure 13. An approximation for the power required for isentropic compressions of nitrogen.

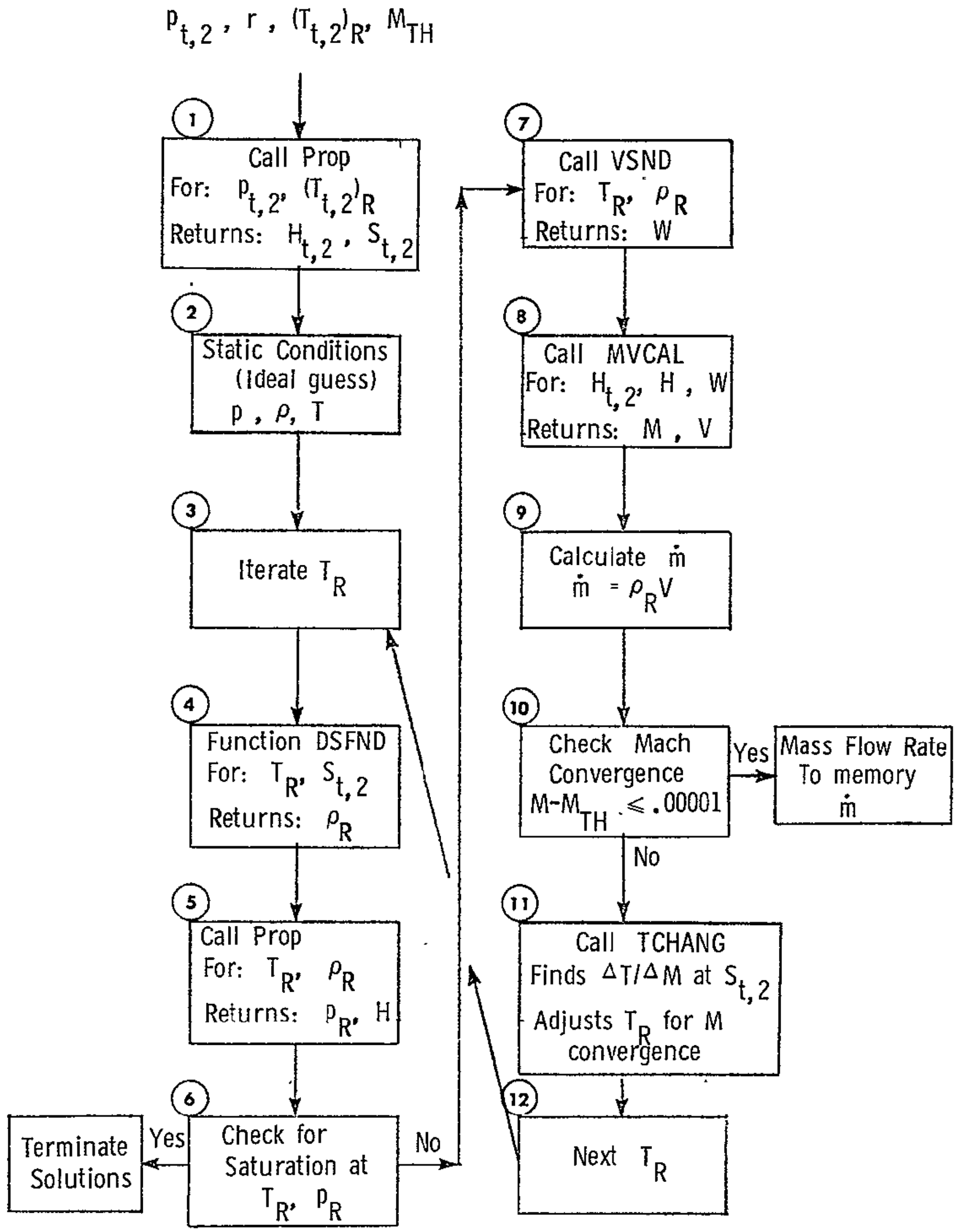


Figure 14. Flow chart of real-gas calculations of tunnel throat conditions.

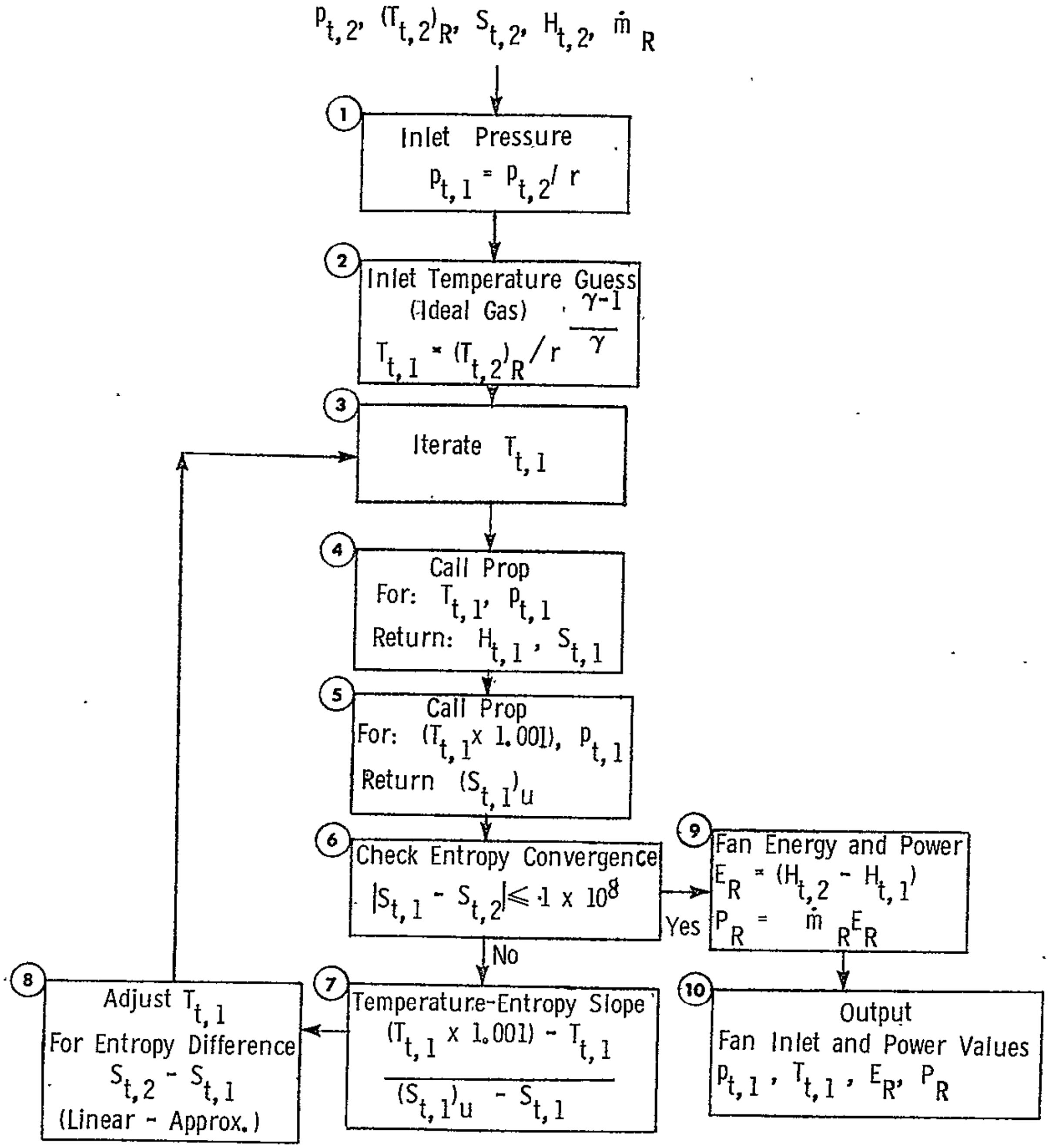


Figure 15. Flow chart for real-gas calculations of fan parameters.