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A THEORETICAL REAL-GAS ANALYSIS OF THE EXPANSION TUNNEL

Glenn D. Norfleet and F. C. Loper
ARO, Inc.

June 1966

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FOREWORD

The work reported herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 62410034, Project 7778, Task 777806.

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This technical report has been reviewed and is approved.

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ABSTRACT

A theoretical real-gas analysis of the expansion tunnel is presented. A digital computer program, developed for this investigation, is discussed, and Fortran listings and flow charts are included. Tunnel performance, test gas slug length, and "working" parameters are given for several expansion area ratios. Driver temperature and energy requirements are given for specific cases.

CONTENTS

ILLUSTRATIONS

TABLE

NOMENCLATURE

A	Cross-sectional area of tube
a	Acoustic speed
c_p	Specific heat at constant pressure
d	Tube inside diameter
e	Driver energy parameter, $\Delta E/A_{6A}\Delta t_r$
h	Enthalpy
ℓ	Length
ℓ_1, ℓ_4, ℓ_8	Tube lengths (see Fig. 1)
ℓ_t	Test gas slug length at time of secondary diaphragm rupture
M	Mach number
M_S	Shock Mach number
p	Pressure
p_i	Arc driver gas pressure prior to arc discharge

R	Gas constant
S	Entropy
T	Temperature
T_i	Arc driver gas temperature prior to arc discharge
U	Velocity
U_S	Shock velocity
x	Axial distance along tube
Z	Compressibility factor
γ	Ratio of specific heats
ΔE	Driver power supply stored energy
Δt_r	Ideal run time
Δt_w	Wave transit time (see Fig. 1)
η	Arc driver efficiency, effective driver energy addition/ stored energy
ξ	Driver power factor, $\Delta E/\ell_1 A_1$
ρ	Density

SUBSCRIPTS

1, 2, 3, etc.	Denote various flow regions (see Fig. 1)
a	Standard conditions
(max)	Maximum
o	Stagnation value
(opt)	Optimum
r	Reference condition

DUAL SUBSCRIPTS

Example: $p_{ij} = p_i/p_j$

SECTION I
INTRODUCTION

An aerodynamic test device utilizing an unsteady expansion to accelerate shock heated gas was first proposed by Resler and Bloxsom (Ref. 1) and was treated briefly by Hertzberg et al. (Ref. 2). Trimpi (Ref. 3) made a detailed theoretical study of the expansion tube, a device in which the entire expansion from the shock heated condition to the test condition is performed unsteadily. In both Refs. 2 and 3 it was suggested that an area change could be added downstream of the unsteady expansion so that part of the expansion would be performed steadily. Trimpi and Callis (Ref. 4) later did a perfect gas analysis of such a device, which is called an expansion tunnel. The basic wave diagrams for both the expansion tube and tunnel are shown in Fig. 1.

For a given density level the test gas velocity obtainable with an expansion tube is approximately twice that obtained by a shock tunnel with the same driver (Ref. 3), as shown in Fig. 2. In spite of this considerable performance gain, little effort has been made to develop an operable expansion tube. To a large degree this hesitancy comes from the expected problems associated with the device.

One of the more questionable aspects of the expansion tube is the uniformity of the test gas. Some insight into the problem can be gained from Fig. 3, which gives the ratio of the test gas slug length after shock heating to the tube diameter. This figure shows that the test gas is in close proximity to the secondary diaphragm at the time of rupture. Although the secondary diaphragm can be very thin, it does require a finite time to rupture. There is, then, a shock wave reflected from the diaphragm which very quickly weakens to the vanishing point. Since the diaphragm will be bulged, this reflection will not be planar. At least the initial portion, and possibly all, of the test gas passes through this shock wave which is not uniform in either space or time.

For the perfect gas case the addition of the steady expansion, as in the expansion tunnel, is very effective in alleviating the test gas slug length problem.[1] The steady expansion is detrimental, however, in terms of test gas velocity obtainable with a given driver.[2] The optimum expansion tunnel design will probably require some compromise between maximum test gas slug length and maximum velocity.

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[1]See Fig. 22 of Ref. 4.

[2]See Fig. 5 of Ref. 4.

The investigation reported herein was undertaken in order to determine significant expansion tunnel performance parameters based upon a real air[3] test gas and to generate the proper working charts for future expansion tunnel design and operation (Appendix I).

SECTION II
CALCULATIONS

2.1 EXPANSION TUNNEL CALCULATIONS

This investigation is concerned with the theoretical possibilities of an expansion tunnel as a high velocity flight duplication[4] device. It is meaningful, then, to determine the significant parameters such as shock strengths, pressures, and tube lengths in terms of duplication altitude and flight velocity. The bulk of these computations was done with a digital computer program which is briefly described below. A detailed description including the Fortran listing and flow diagram is given in Appendixes II and III. The test gas slug length, ℓ_t, and accelerating tube charge pressure were calculated by hand as described in Sections 2.1.2 and 2.1.3, respectively.

2.1.1 The Expansion Tunnel Program

The expansion tunnel program is designed to determine flow parameters and tube lengths of interest for given altitude, velocity, and expansion area ratio. The input and output data for this program are shown in Table I. The expansion tunnel portion of Fig. 1 shows the various flow regions.

The general procedure is as outlined below.

1. For a given flight altitude, free-stream pressure and temperature are obtained by table look-up using the data of Ref. 5. Enthalpy, h_{6A}, and entropy, S_{6A}, are calculated using the perfect gas equations:

$$h_{6A} = c_p T_{6A}$$

$$S_{6A} - S_r = c_p \; ln \frac{T_{6A}/T_r}{\left(\frac{p_{6A}}{p_r}\right)^{\frac{\gamma-1}{\gamma}}}$$

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[3]Thermodynamic and chemical equilibrium was assumed for all calculations included herein.

[4]Duplication herein refers to the complete matching of ambient properties and ambient chemistry together with the required flow velocity.

The perfect-gas equations are valid for altitudes of interest.

2. The continuity and energy equations for the steady isentropic expansion from 6 to 6A are combined, yielding

$$\rho_6 A_6 (2h_{o_{6A}} - 2h_6)^{1/2} = \rho_{6A} U_{6A} A_{6A}$$

This equation and the equation of state, represented by the Table of Thermodynamic Properties (Refs. 6 and 7) are solved (for S constant) simultaneously for ρ_6 and h_6.

3. The unsteady expansion from 2 to 6 and the shock crossing 1 to 2 must be performed simultaneously since the limit of the expansion is determined by the shock crossing.

For the unsteady isentropic expansion,

$$U_6 - U_2 = -\int_{h_2}^{h_6} \left(\frac{dh}{a}\right)_S$$

From the tables of thermodynamic properties (Refs. 5 and 6) through the unsteady expansion:

$$a = f_1 (h, S)$$

at 2:

$$p_2 = f_2 (h_2, S_2)$$

$$\rho_2 = f_3 (h_2, S_2)$$

Across the shock, M_{S_1}:

$$p_2 + \rho_2 (U_{S_1} - U_2)^2 = p_1 + \rho_1 U_{S_1}^2 \quad \text{(momentum equation)}$$

$$h_2 + 1/2 (U_{S_1} - U_2)^2 = h_1 + 1/2 U_{S_1}^2 \quad \text{(energy equation)}$$

$$\rho_2 (U_{S_1} - U_2) = \rho_1 U_{S_1} \quad \text{(continuity equation)}$$

For the gas in region 1:

$$p_1 = \rho_1 R_1 T_1 \quad \text{(ideal gas equation of state)}$$

The charge gas temperature, T_1,[5] and enthalpy, h_1, are inputs to the program. The above equations are solved for the required flow parameters in regions 1 and 2, assuming the unsteady expansion to be isentropic.

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[5] For the calculations reported herein, T_1 = 296°K.

The accelerating tube length is calculated from

$$\ell_8/\Delta t_r = U_6 (M_6 - 1)$$

The tube length ratio ℓ_1/ℓ_8 is optimum[6] when the (U + a) wave reflected from the 2 - 3 interface overtakes the tail of the expansion at the test section as shown in Fig. 1. The time required for the passage of this reflected wave, $\Delta t_w/\ell_8$, is calculated by integration through the unsteady expansion. The technique used to determine ℓ_1/ℓ_8 is described in Appendices II and III and is similar to that of Ref. 8.

The theoretical model of this program was based upon the following simplifying assumptions:

1. Air in regions 1 and 6A is assumed to be ideal.
2. Air in regions 2 and 6 is assumed to be in thermodynamic equilibrium.
3. Flow is inviscid and one dimensional throughout.
4. Diaphragm rupture is instantaneous with no losses.
5. The expansion nozzle has no length and therefore zero "start" time.

2.1.2 Test Gas Slug Length

The test gas slug length, ℓ_t, was calculated from the appropriate form of the continuity equation,

$$\rho_2 \ell_t A_2 = \rho_{6A} U_{6A} \Delta t_r A_{6A}$$

2.1.3 Accelerating Tube Charge Pressure

The accelerating tube charge pressure, p_8, was determined for a given a_8 using U_6 and p_6 from:

$$p_8 = p_7 (p_8/p_7) = p_6 (p_8/p_7)$$

and

$$p_6 = p_7 \qquad \text{(across interface)}$$

The ratio of p_8/p_7 was obtained from Ref. 9 for a given

$$U_6/a_8 = U_7/a_8 \qquad \text{(across interface).}$$

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[6]i.e., minimum ℓ_1 for maximum run time with a given ℓ_8.

2.2 DRIVER CALCULATIONS

The loss in performance associated with the steady expansion can, within limits, be offset by using a higher performance driver. While driver design, per se, is not within the scope of this investigation, a knowledge of driver requirements becomes important in assessing the significance of the performance loss.

Of particular interest are driver pressure, temperature, and energy requirements. Driver pressure and temperature were calculated using an existing shock tube program, but driver energy (and driver optimization based upon energy requirements) was determined by hand calculations.

2.2.1 The Shock Tube Program

The shock tube program used in this study determines flow conditions for given charge conditions in a two- or three-stage shock tube. The program was used to determine driver charge conditions for a given M_{S_1} and p_1. This solution is obtained in the usual manner of expanding the driver gas to match pressure and velocity at the 2 - 3 interface. The shock crossing is performed much as is done in the expansion tunnel program except that the thermodynamic properties are obtained by an empirical surface fit (Ref. 10) to the data of Ref. 11. The basic thermodynamic data used in the two machine programs differ in that the data for the expansion tunnel program include intermolecular force effects whereas the data for the shock tube program do not. The shock tube program was used only to determine shock strength, M_{S_1}, for given driver and driven tube conditions. Experience has shown that values of M_{S_1} calculated with either set of data are in good agreement. The inconsistency in thermodynamic properties applies only to calculations involving the driver, and there its effects are felt to be insignificant.

This program will accept driver/driven area ratios of any value; however, for $A_{41} < 1$ and low values of p_{41}, upstream-facing secondary shocks are possible. If such a shock is standing in the area change, as opposed to moving downstream, the program will not give a solution. In such cases the solution was obtained by hand calculations.

Program calculations are based upon the following simplifying assumptions:

1. Gases are assumed to be perfect except for the shock heated region 2 which is taken as real air in thermodynamic equilibrium.

2. Flow is inviscid and one dimensional throughout.

3. Diaphragm rupture is instantaneous with no losses.

2.2.2 Driver Energy and Optimization

Driver energy, which becomes highly significant in the case of arc heating since its magnitude is reflected directly in the cost of a power supply, was calculated assuming:

1. Helium as the driver gas (perfect gas assumed).

2. The power supply is of the fast discharge type, with a discharge time of the order of 100 μsec. Arc efficiency data (Fig. 4) were obtained from Refs. 12 and 13 and are applicable to a fast discharge system.

Driver energy per unit volume for a constant volume energy addition process is given by

$$\frac{\Delta E}{A_4 \ell_4} = \frac{1}{\gamma_4 - 1} \frac{p_4}{\eta} \frac{T_4 - T_i}{T_4}$$

Multiplying by the tube length and area ratios yields the energy parameter, e,

$$e \equiv \frac{\Delta E}{A_{6A} \Delta t_r} = \frac{1}{\gamma_4 - 1} \frac{p_4}{\eta} \frac{T_4 - T_i}{T_4} \left(\frac{A_6}{A_{6A}}\right) \left(\frac{A_4}{A_1}\right) \left(\frac{\ell_4}{\ell_1}\right) \left(\frac{\ell_1}{\ell_8}\right) \left(\frac{\ell_8}{\Delta t_r}\right)$$

where p_4 and T_4 were given by the shock tube program

$\frac{\ell_4}{\ell_1}$ was calculated by hand using local values of velocity and acoustic velocity from the shock tube program

$\frac{\ell_8}{\Delta t_r}$ and $\frac{\ell_1}{\ell_8}$ were given by the expansion tunnel program

η was taken from Fig. 4

T_i was assumed to be 296°K

and $A_6 = A_1$

There are an infinite number of combinations of T_4, p_4, and A_{41} which will yield identical theoretical driver performance. In order to give meaning to energy requirements, it is necessary to choose the combination of these variables which will yield the given performance while using minimum energy, i. e., the driver must be optimized. In order to optimize the driver, a power factor is defined as:

$$\xi = \frac{\Delta E}{A_1 \ell_1} = \frac{\Delta E}{A_4 \ell_4} \frac{A_4}{A_1} \frac{\ell_4}{\ell_1}$$

The driver is optimized when, for a given M_{S_1}, p_1, and T_1, the value of ξ (driver energy per driven tube unit volume) is minimum. The actual optimization process consisted of choosing values of T_4 and A_{41}, calculating p_4, and then varying T_4 and A_{41} until a minimum was reached in ξ.

SECTION III
RESULTS[7]

3.1 PERFORMANCE

Performance calculations in terms of velocity and altitude were made for expansion area ratios of 1, 10, 100, and 1000. Required shock strength, M_{S_1}, charge pressure, p_1, and compressibility factor, Z_2, are presented in Fig. 5. The parameters M_{S_1} and p_1 were chosen because of their wide acceptance as independent variables in shock tube work (particularly in shock-crossing calculations). Their values give a general indication of driver requirements. The value of Z_2 is an indication of the level of dissociation and ionization in the shock heated gas in region 2. Bray (Ref. 14) has shown that for the case of a steady expansion in which the flow upstream of the expansion is not frozen, the mole fraction of frozen constituents after the expansion is a very weak function of the ionization-dissociation level prior to the expansion.[8] If the same phenomenon occurs in an unsteady expansion, then the value of Z_2 is not necessarily indicative of the ionization-dissociation level in the expanded test gas. Until an analysis of recombination through an unsteady expansion is available, no meaningful comparison of test gas ionization-dissociation level for different expansion area ratios can be made.

3.2 DRIVER REQUIREMENTS

In order to investigate driver requirements in more detail, driver temperature, T_4, was calculated for a constant area driver using helium at a pressure, p_4, of 5000 atm. The results are shown in Fig. 6. The drivers considered here represent rather severe requirements, but their design is believed to be within the present "state of the art". The high temperature helium drivers would probably be arc heated, although the densities are somewhat higher than normal for arc drivers.

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[7]Additional results, in the form of working graphs for tunnel design and operation, are presented in Appendix I.

[8]Applies specifically to frozen atomic oxygen.

The driver energy optimization was done for a helium driver for the specific case of $M_{S_1} = 10$, $p_1 = 10$, and $T_1 = 296°K$. The variation of the power factor, ξ, with driver temperature and area ratio is shown in Fig. 7. For a maximum driver pressure of 5000 atm, the optimum occurs at a temperature, T_4, of about 5000°K and an area ratio $A_{41} \approx 1$. The driver energy parameter, e, is shown for the optimum driver in Fig. 6. Note that these energies are for constant shock strength and charge pressure, p_1, and not constant performance. Although they cannot be used to compare energy requirements as a function of expansion area ratio, they do give single point energy requirements for an optimum driver and, therefore, some insight into power supply requirements.

In order to compare energy requirements for various expansion ratios, it is necessary to optimize the driver at the same performance level for each expansion area ratio. This gives a different value of M_{S_1} and p_1 for each value of A_{6A}/A_6. In order to simplify the optimization it is assumed that the optimum area ratio, $A_{41\,(opt)}$, is equal to one. This assumption is reasonable for shock strengths, M_{S_1}, near 10 and pressures, p_1, near 10 atm since the constant temperature curves of Fig. 7 are very flat in the region near $A_{41} = 1$.

Optimum driver temperature and pressure were calculated for the performance level of $U_{6A} = 30,000$ ft/sec and altitude = 150,000 ft ($9.3 \leq M_S \leq 12.6$, $1.2 \leq p_1 \leq 10.4$ atm). Energy required for the optimum case is shown as a function of the expansion area ratio in Fig. 8. The inclusion of driver area ratio in the optimization would produce second-order changes in the curve; however, it is doubtful that this would be significant in view of the large variation of energy with expansion tunnel area ratio.

One point concerning the inviscid flow assumption seems worthy of mention here. There are two viscous effects which can greatly affect the driver energy requirements:

1. Shock attenuation (energy loss)
2. Decreased run time (mass loss).

In order to offset shock attenuation in both the driver and accelerating tubes, a more energetic driver gas will have to be used. In addition a longer driven tube, and therefore a longer driver, will be required to recover the run time lost by boundary-layer effects (see Refs. 15 and 16). In terms of driver energy requirements the two effects are additive, and it is likely that for high ℓ/d tubes the inviscid calculation will significantly underpredict driver energy requirements.

3.3 RUN TIME

Run time per unit length of driven and accelerating tube is presented in Fig. 9. Driver length is not included since it is not defined by altitude alone, but depends upon the particular driver conditions chosen. Usually, its length will be small compared to the combined length of the accelerating and driven tubes. It should be emphasized that the run time presented here assumes an instantaneous nozzle start. Although $\Delta t_r/(\ell_1 + \ell_8)$ increases with increasing expansion ratios, the effect of expansion area on the actual run time will depend to a large degree on the nozzle starting process. No attempt was made in this study to determine nozzle start times; however, the "perfect start" perfect gas case is treated in Ref. 4.

3.4 TEST GAS SLUG LENGTH

Figure 10 gives the length of the test gas slug at the time of secondary diaphragm rupture. The parameter on the right, ℓ_t/d_1, is the ratio of the test gas slug length to the diaphragm diameter for an accelerating tube length-to-diameter ratio of 200. The maximum value of ℓ_8/d_8, and therefore ℓ_t/d_1, is determined by viscous effects and is unknown. However, from shock tube experience, an ℓ_8/d_8 of 200 is quite large. Even for the large ℓ/d and an expansion ratio of 1000, the test gas slug length is only one-tenth of the diaphragm diameter for high velocities.

SECTION IV
CONCLUDING REMARKS

In order to better illustrate the effect of the steady expansion, summary plots (Figs. 11 and 12) were made for a specific case. For comparison purposes the perfect gas results of Ref. 4 are also shown in Fig. 12.

Performance loss by the addition of the area change for an altitude of 150, 000 ft is illustrated in Fig. 11. Since the performance lines are for a constant altitude, and therefore a constant entropy, it follows that, for a given M_{S_1}, p_1 is constant. A given driver, then, would operate along a line of constant M_{S_1}.

As shown in Fig. 11, the loss in velocity for a given driver can be considerable; however, it becomes significant only when the driver is of limited potential. Figure 12a illustrates temperature requirements for a specific performance (U_{6A} = 30,000 ft/sec at a duplicated altitude of 150,000 ft) and a driver pressure of 5000 atm. For this performance point the large expansion area ratios would entail severe driver temperature requirements for drivers which heat the gas by heat transfer from surrounding surfaces.

Drivers which heat the gas directly, such as electric arc heated drivers, have temperature limits which are quite high and thus would not impose fundamental limitations for the performance shown here. Drivers operating in this mode are generally limited more by energy requirements since they add energy very rapidly and normally require an energy storage system which has a high relative cost. For a given test section size and run time, driver energy and, therefore, power supply costs decrease with increasing expansion area ratio (Fig. 12b).

For a given accelerating tube length-to-diameter ratio, ℓ_8/d_8, large gains can be made in test slug length, ℓ_t/d_1 (and hopefully flow uniformity), by using large expansion area ratios (Fig. 12c). It should be noted that the parameter actually of interest is $\ell_t/d_{1\,(max)}$ which occurs at $\ell_8/d_8 = \ell_8/d_{8\,(max)}$, and is dependent upon boundary-layer growth. No attempt is made here to include boundary-layer effects; however, perfect gas calculations for a simplified model are included in Ref. 4.

In summary, an increasing expansion area ratio causes:

1. A loss in performance if the driver is limited in temperature and pressure.
2. A gain in performance if the driver is limited only in energy.
3. An increase in the test gas slug length parameter, ℓ_t/ℓ_8.

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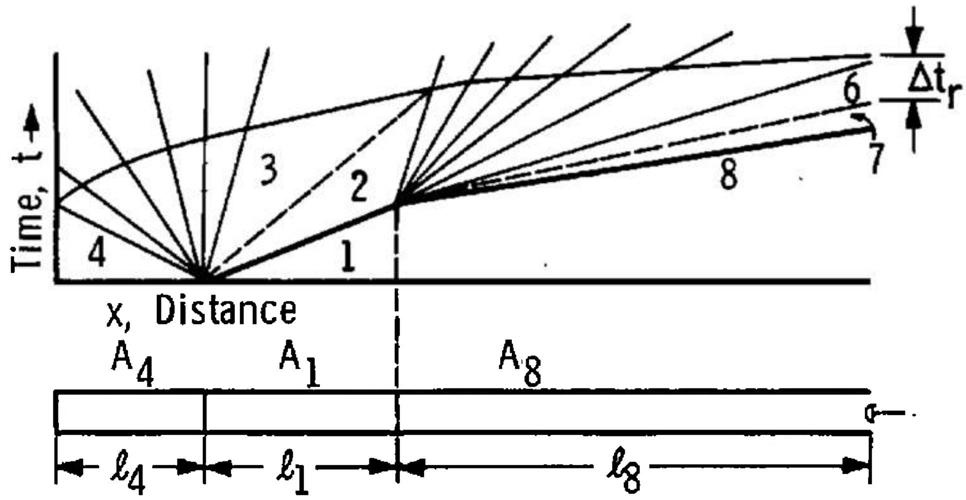
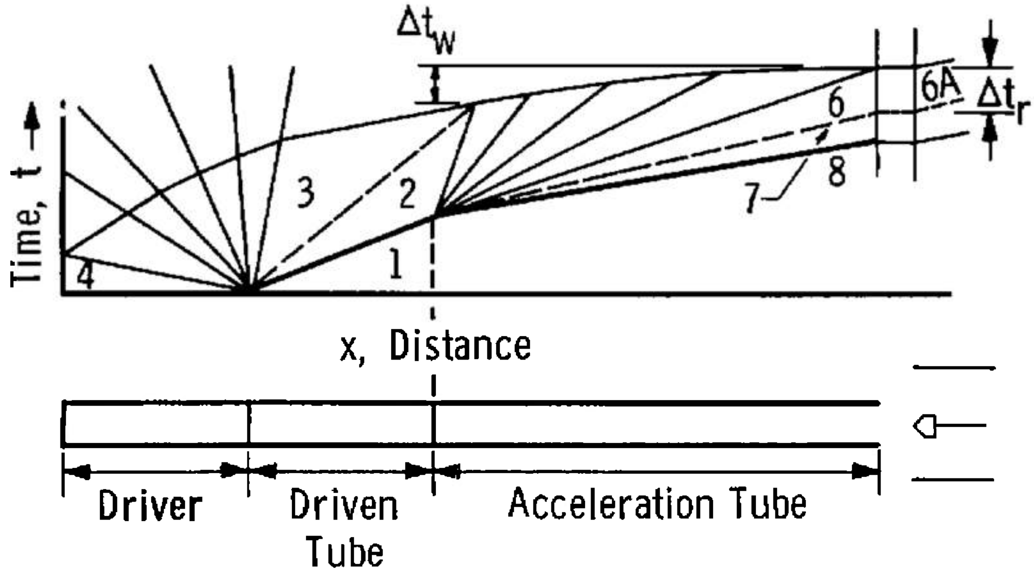


Expansion Tube



Expansion Tunnel

Fig. 1 Wave Diagrams – Expansion Tube and Expansion Tunnel

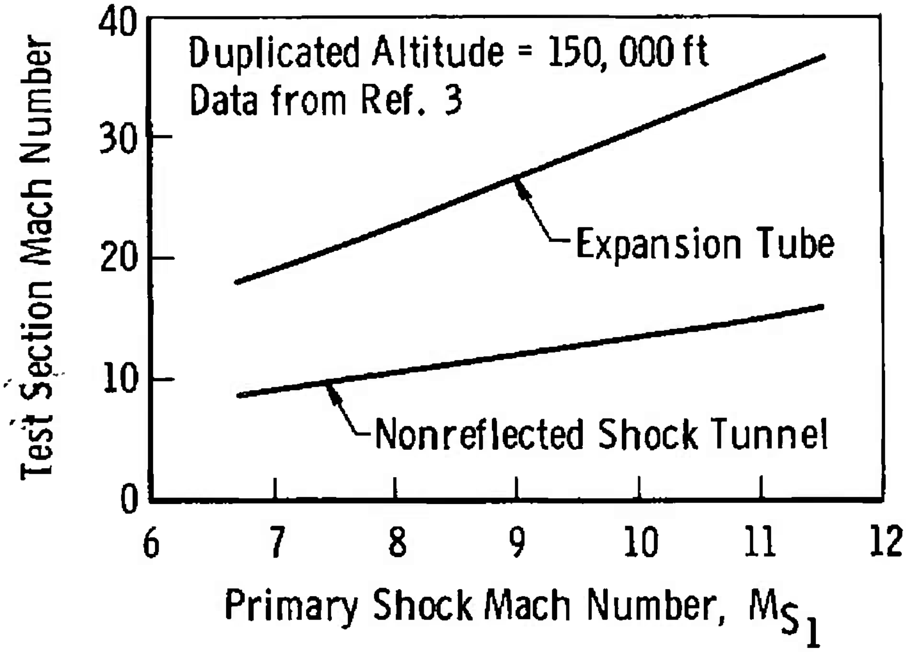


Fig. 2 Comparison of Expansion Tube and Shock Tunnel

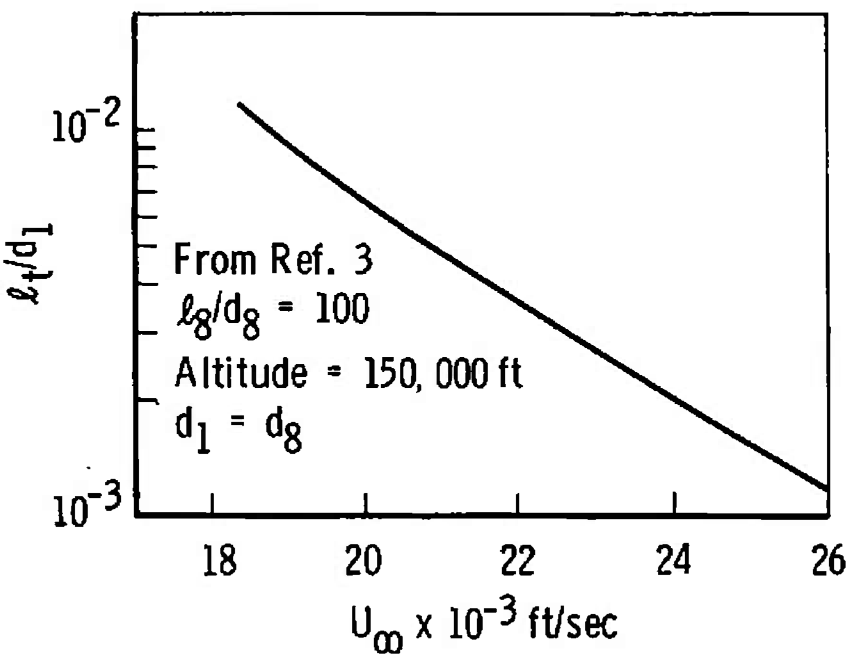


Fig. 3 Test Gas Slug Length – Expansion Tube

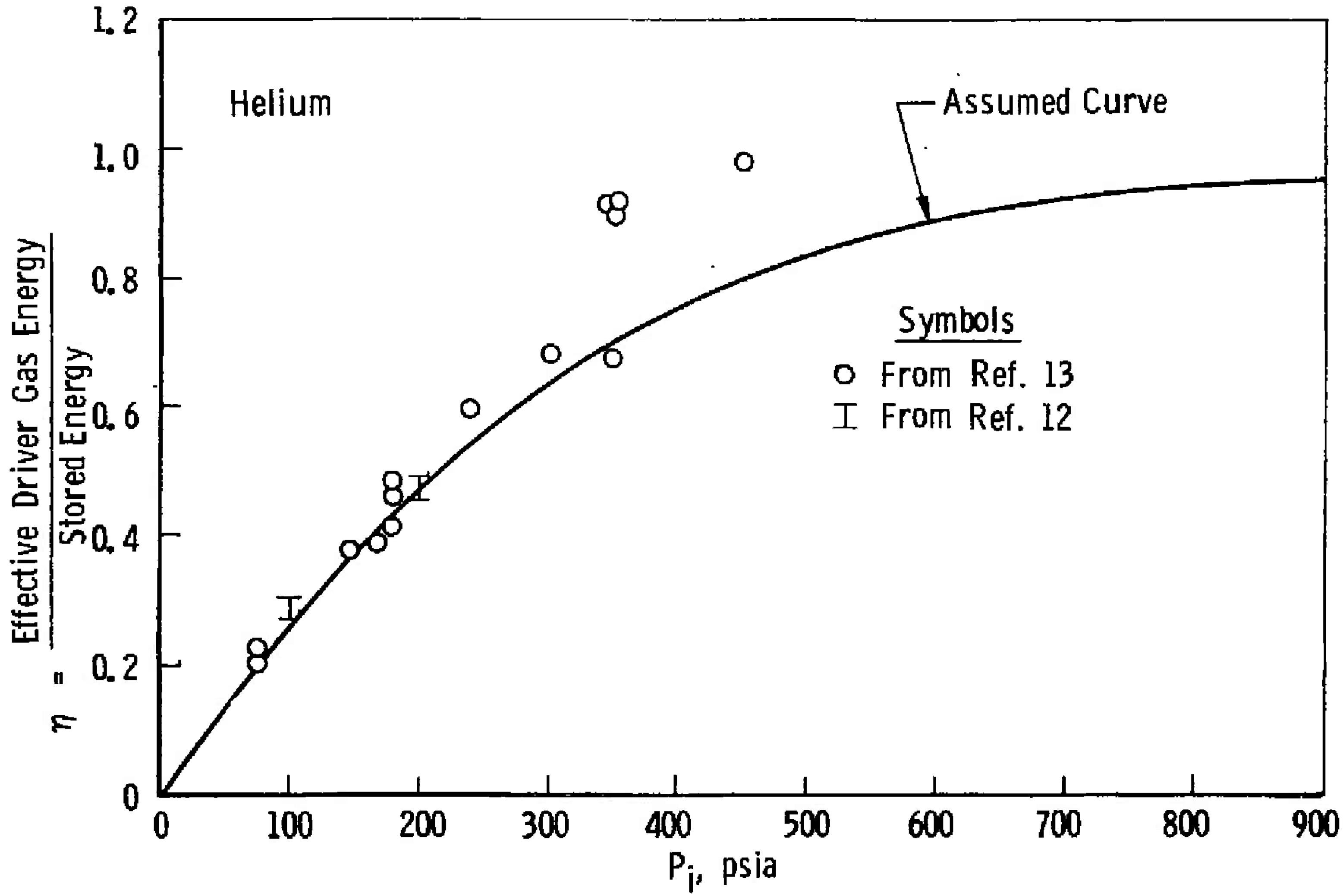
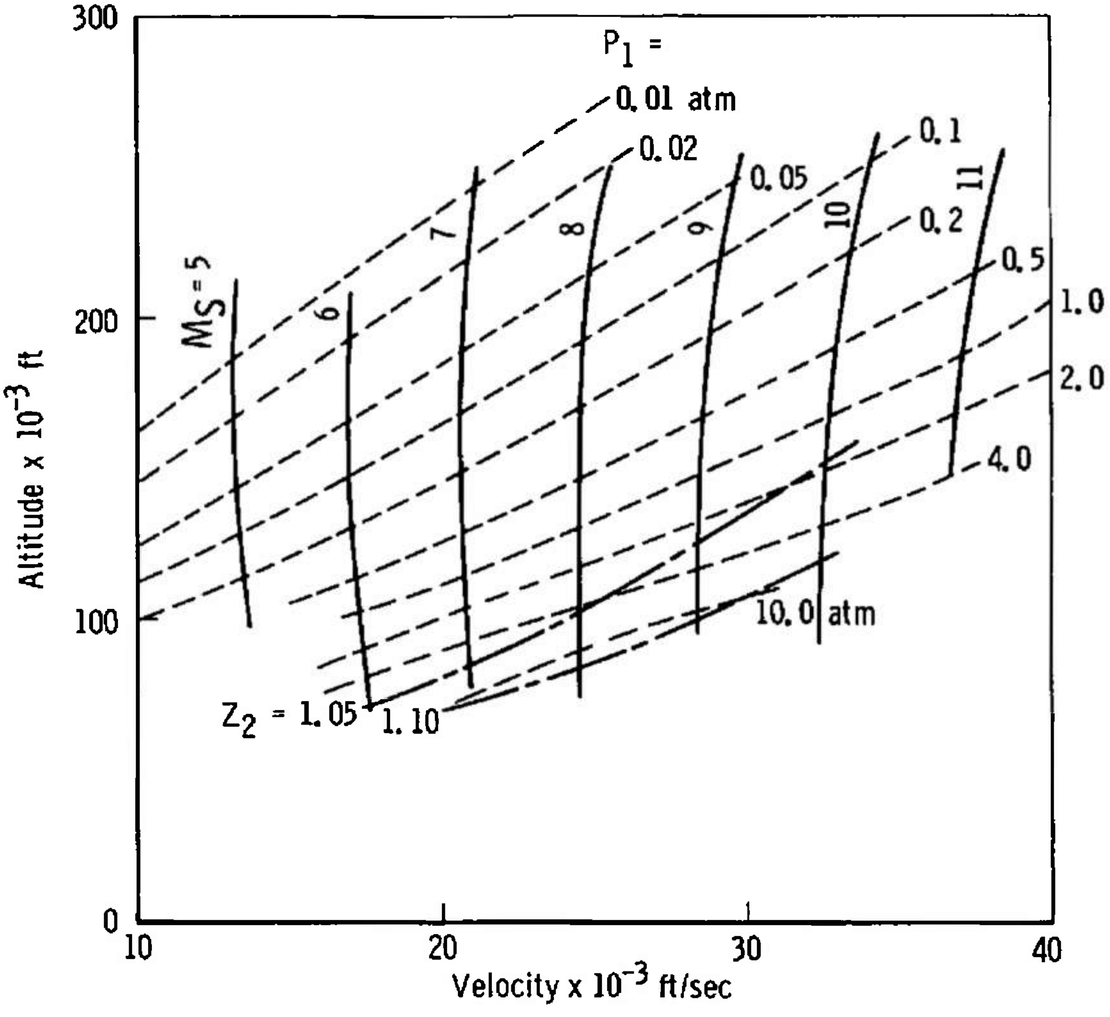
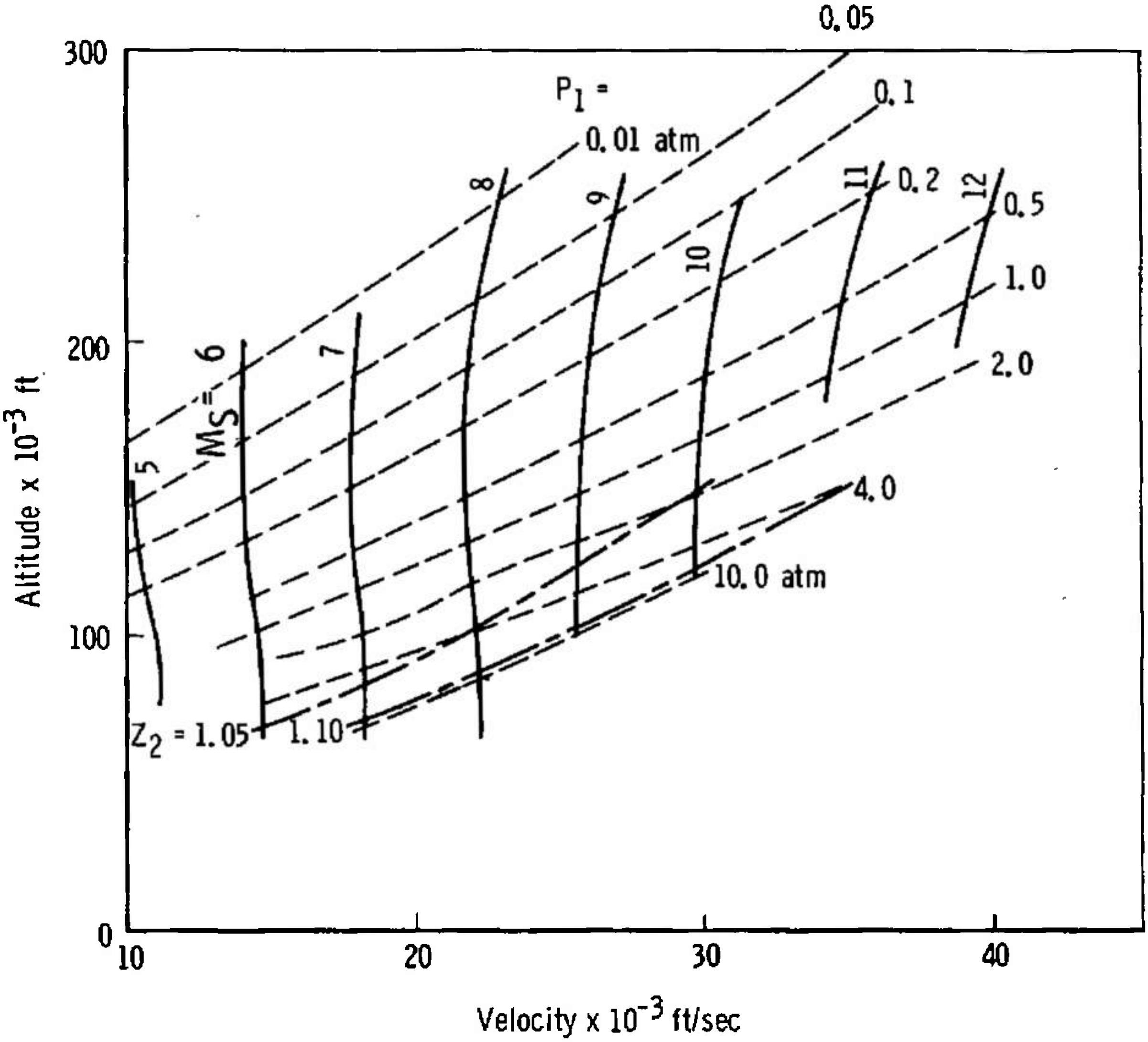


Fig. 4 Arc Driver Efficiency

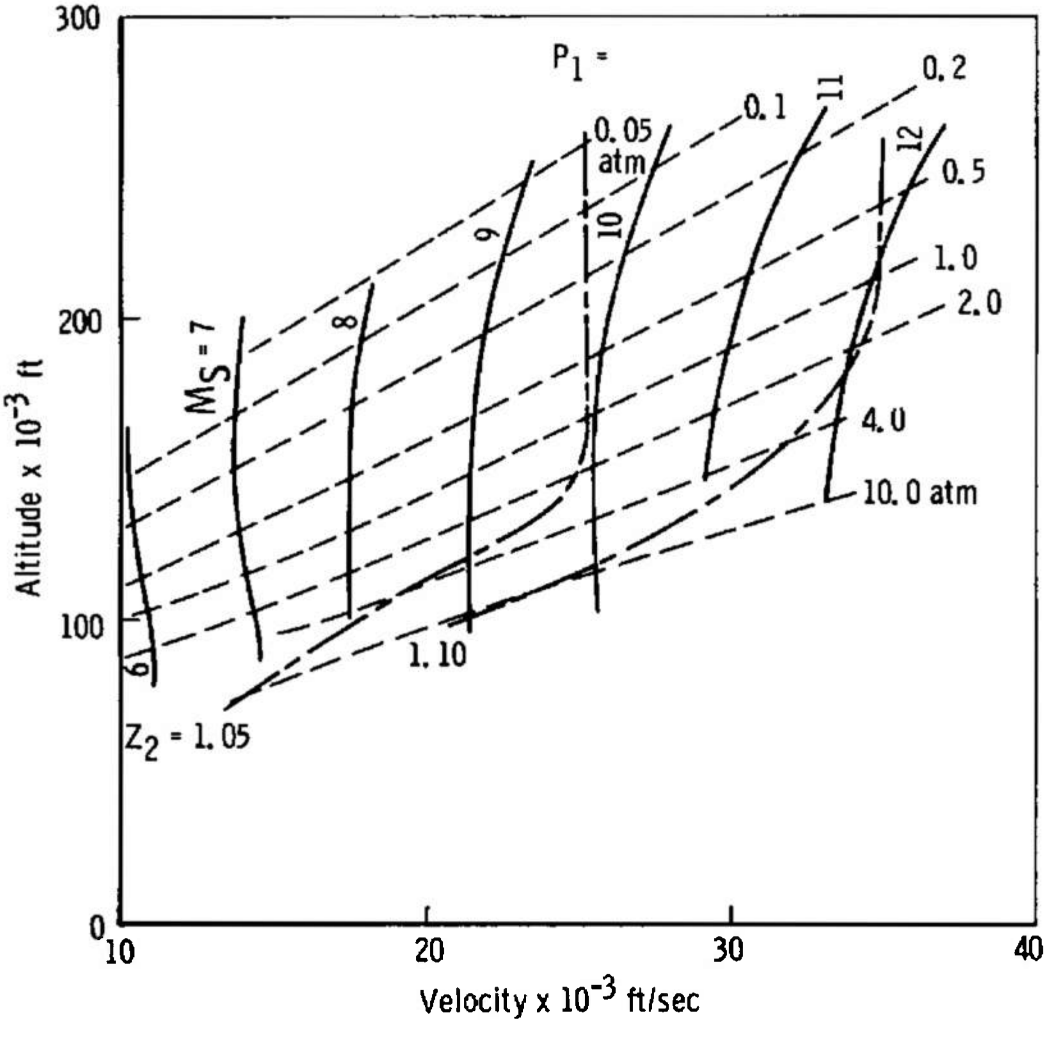


a. $A_{6A}/A_6 = 1$

Fig. 5 Performance Map

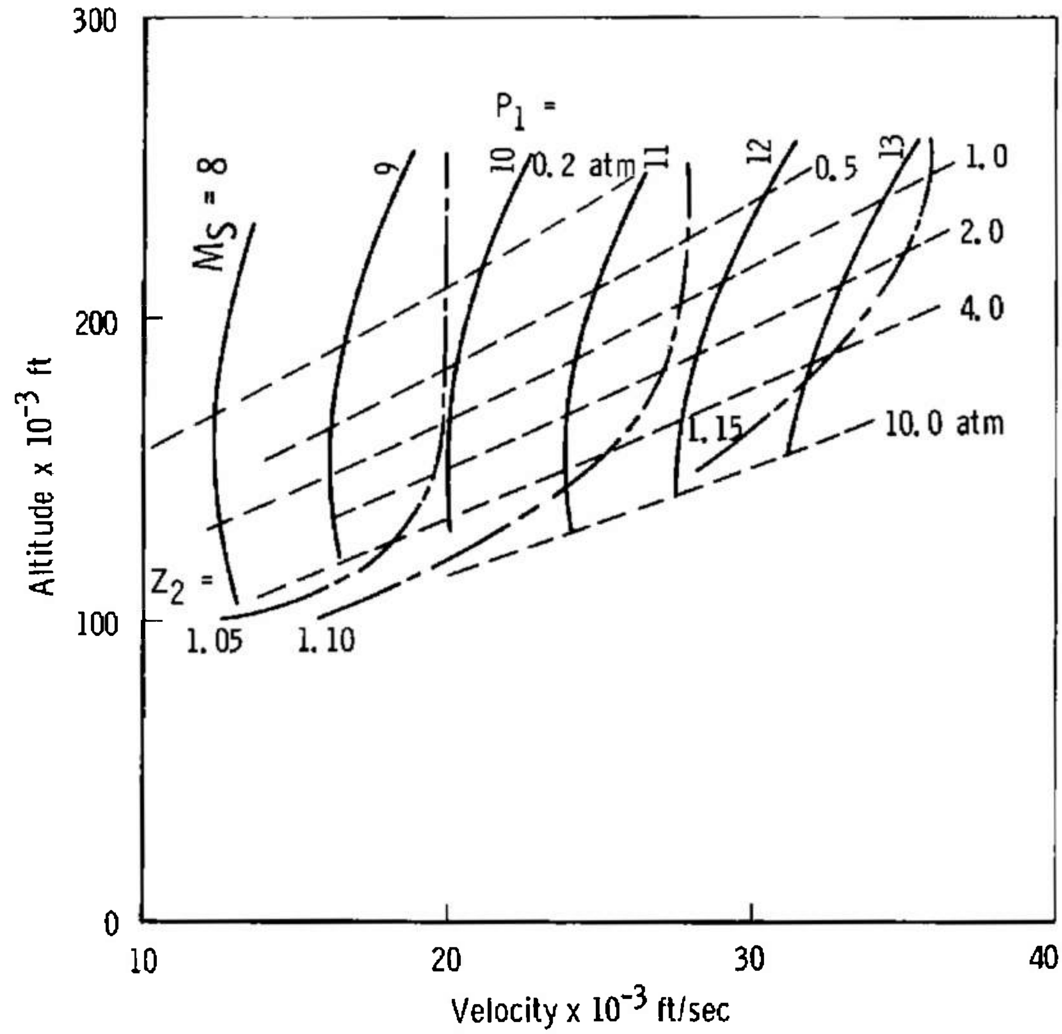


b. $A_{6A}/A_6 = 10$
Fig. 5 Continued

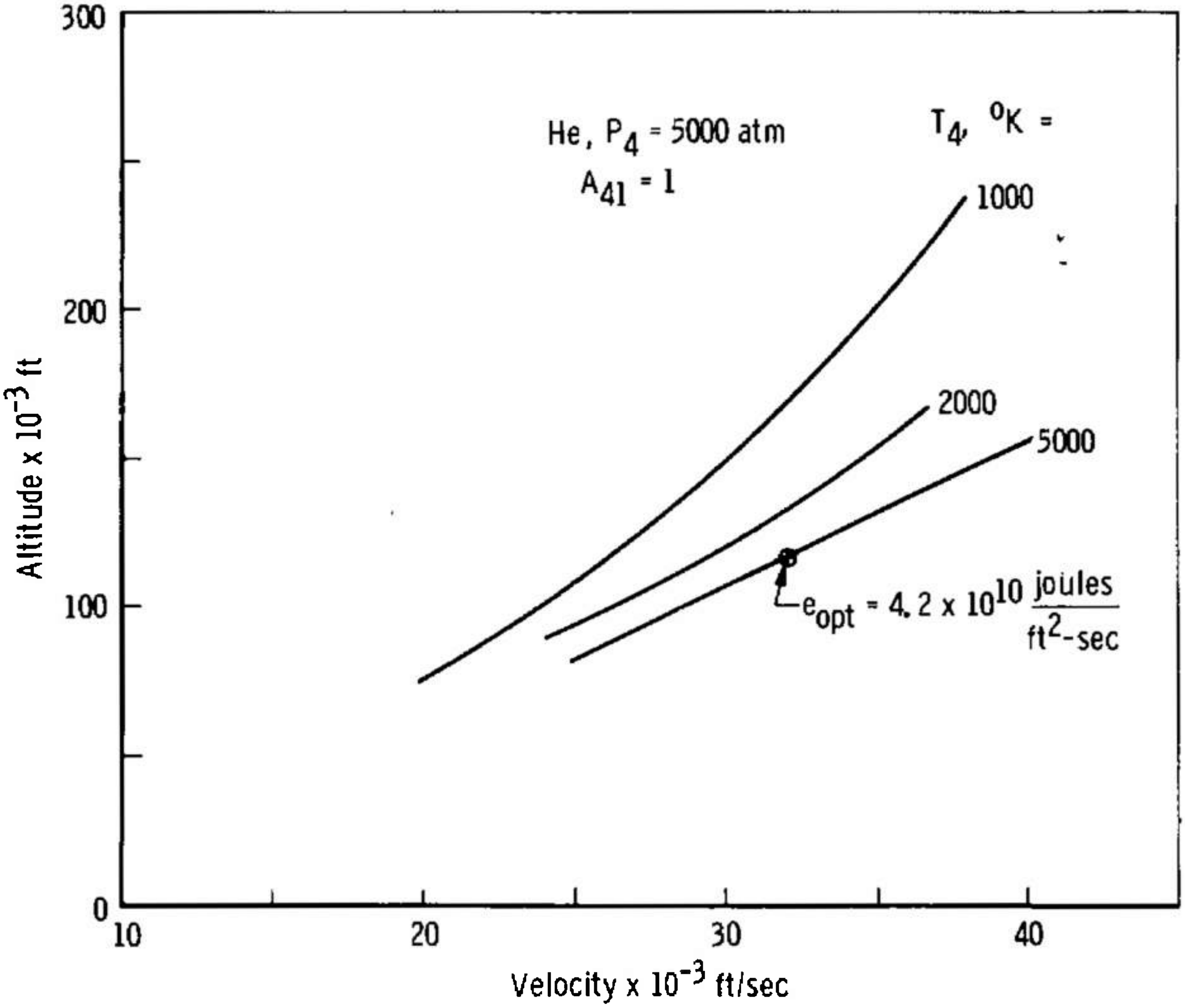


c. A_{6A}/A_6 = 100

Fig. 5 Continued

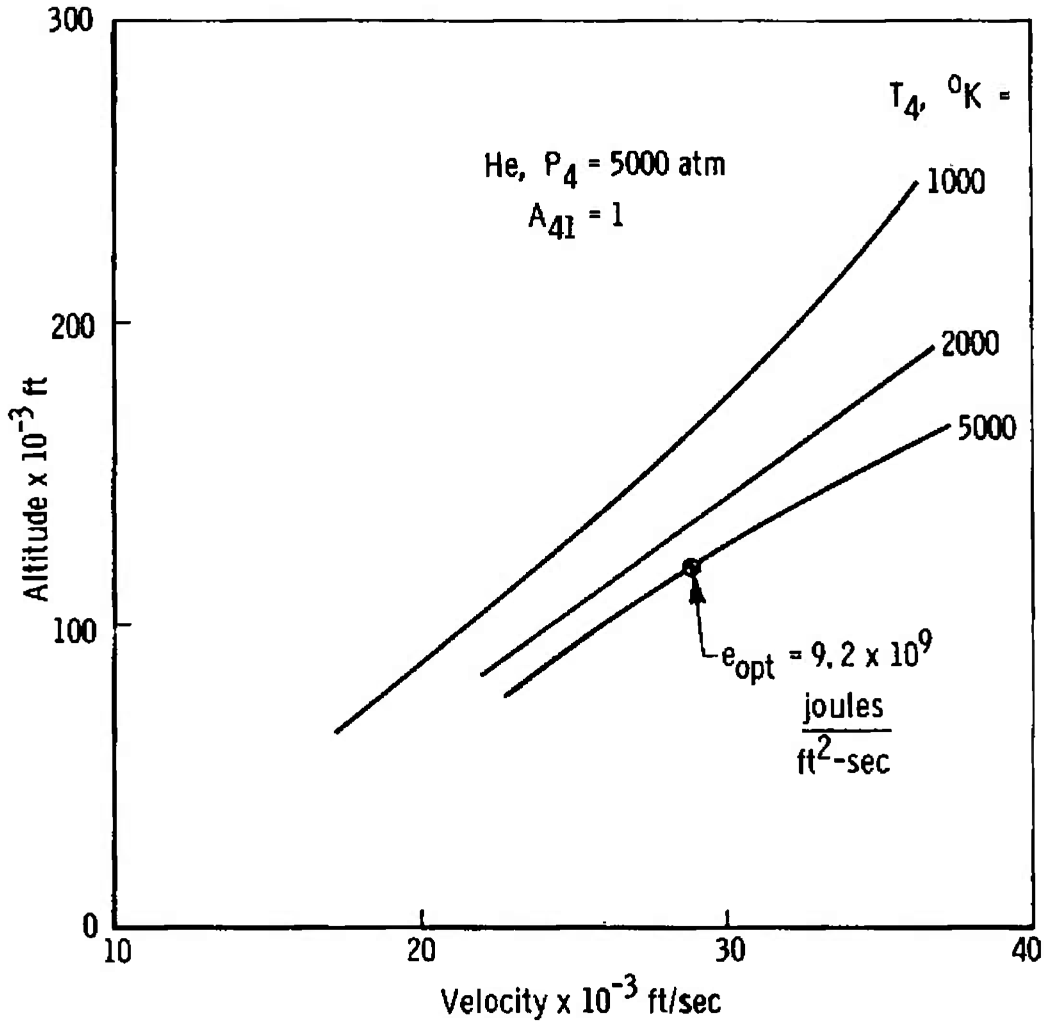


d. $A_{6A}/A_6 = 1000$
Fig. 5 Concluded

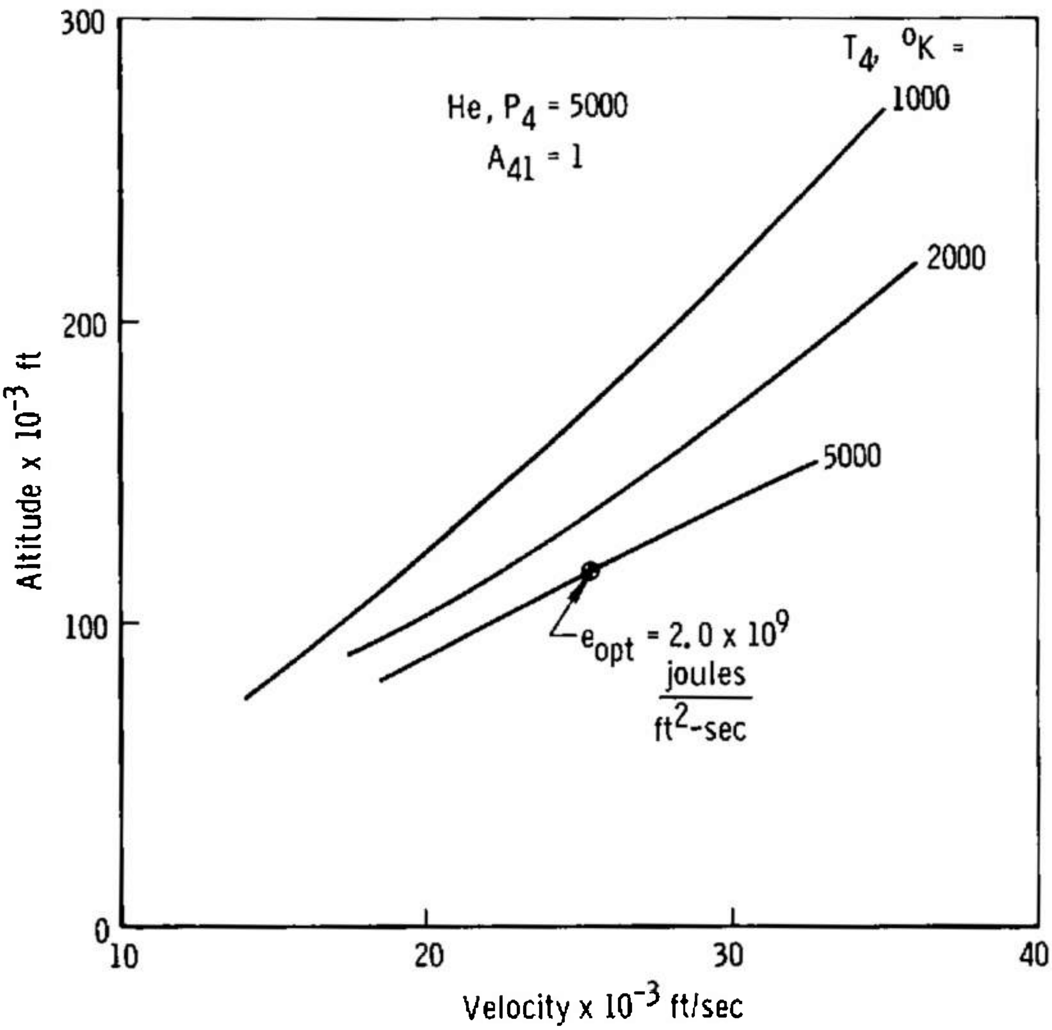


a. $A_{6A}/A_6 = 1$

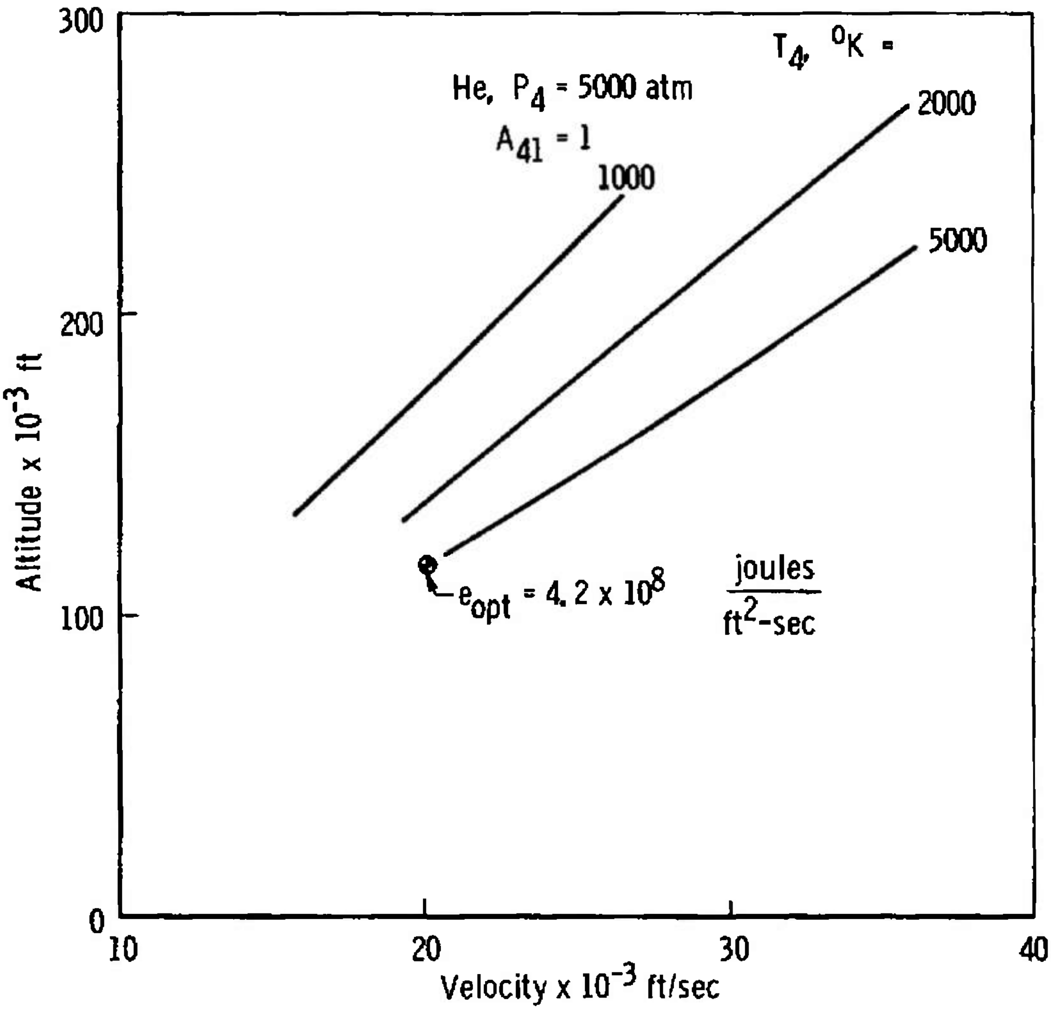
Fig. 6 Driver Requirements



b. $A_{6A}/A_6 = 10$
Fig. 6 Continued



c. $A_{6A}/A_6 = 100$
Fig. 6 Continued



d. $A_{6A}/A_6 = 1000$
Fig. 6 Concluded

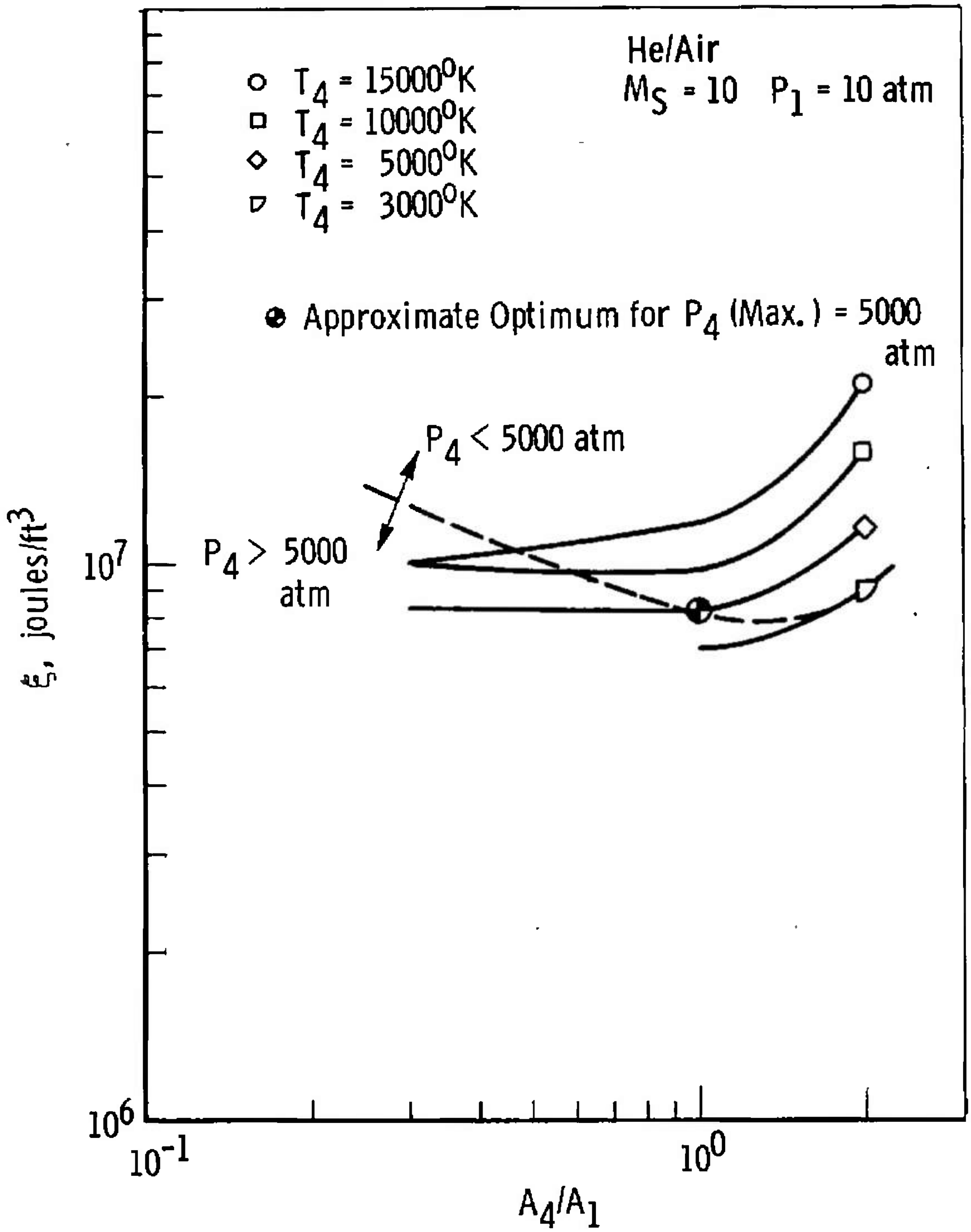


Fig. 7 Optimization of Driver

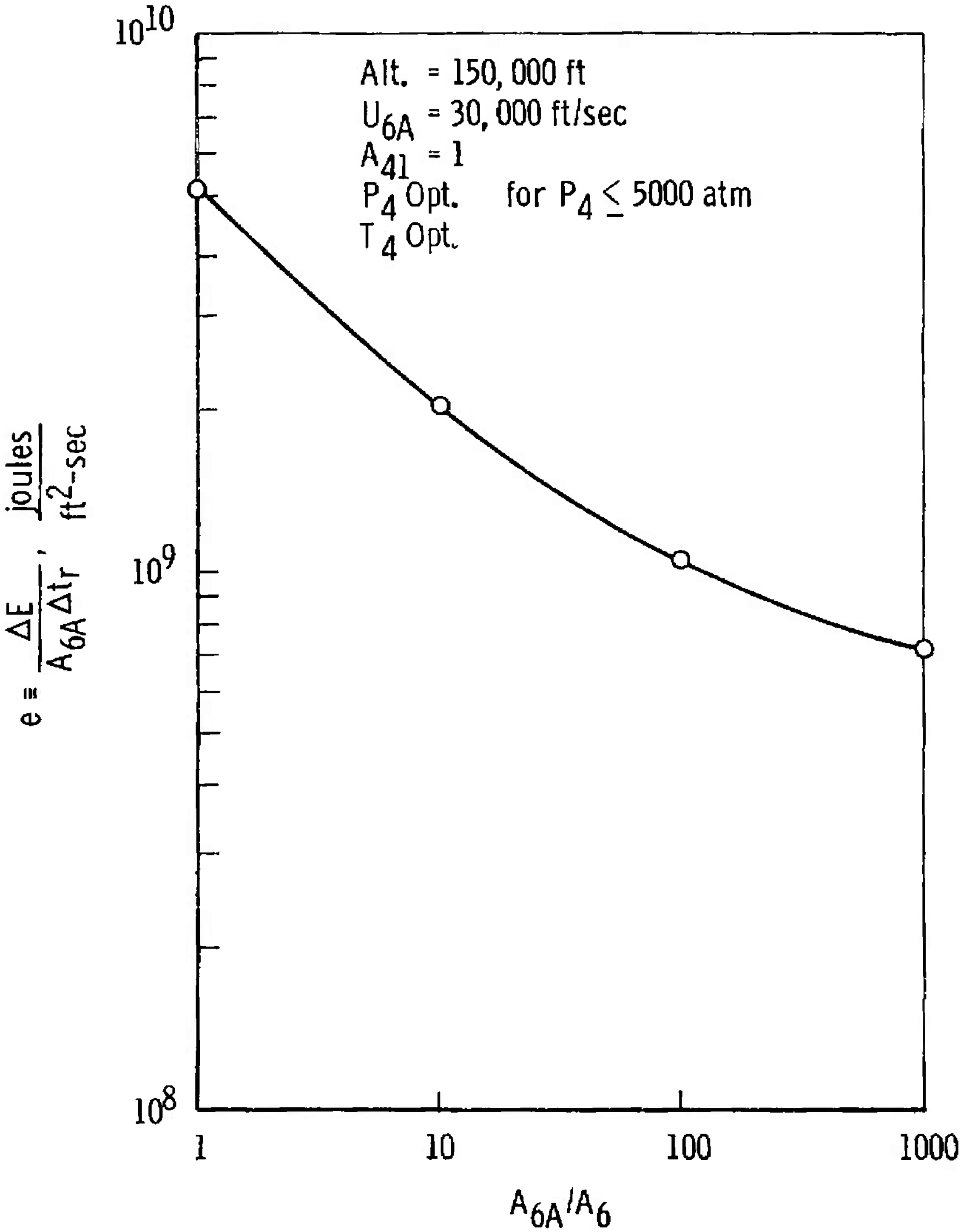


Fig. 8 Comparison of Driver Energy Requirements

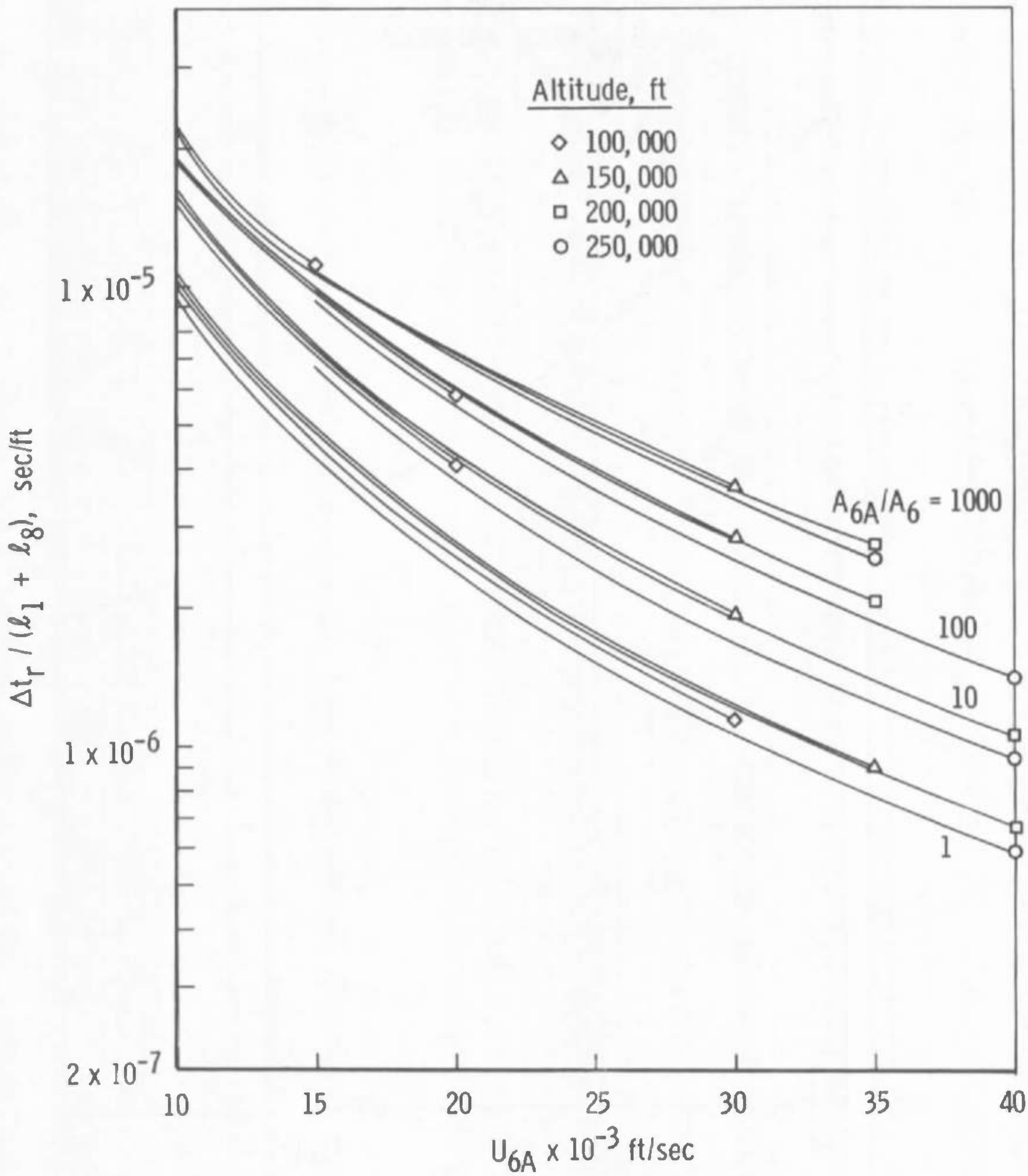


Fig. 9 Ideal Run Time

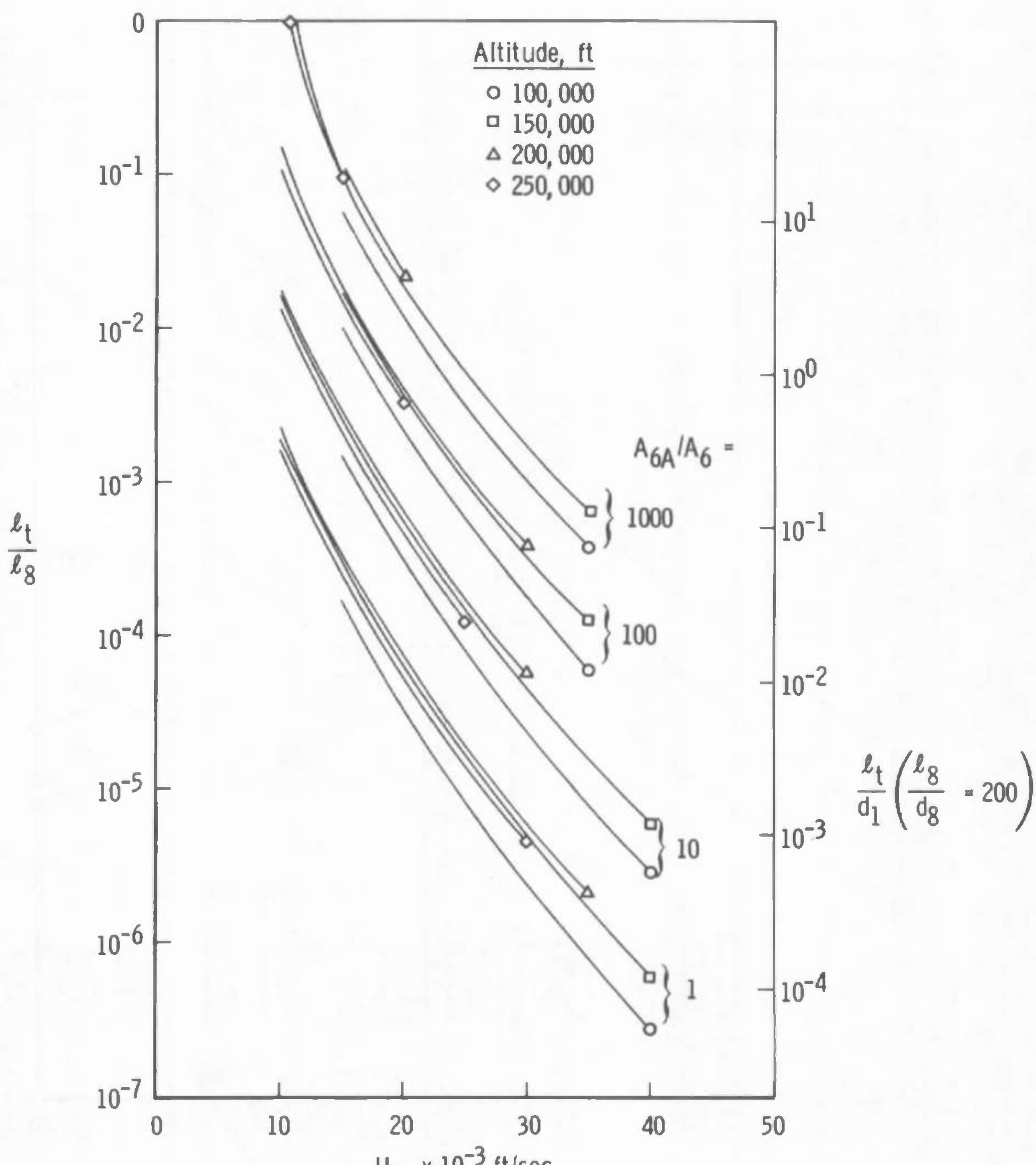


Fig. 10 Proximity of Test Gas to Secondary Diaphragm – Expansion Tunnel

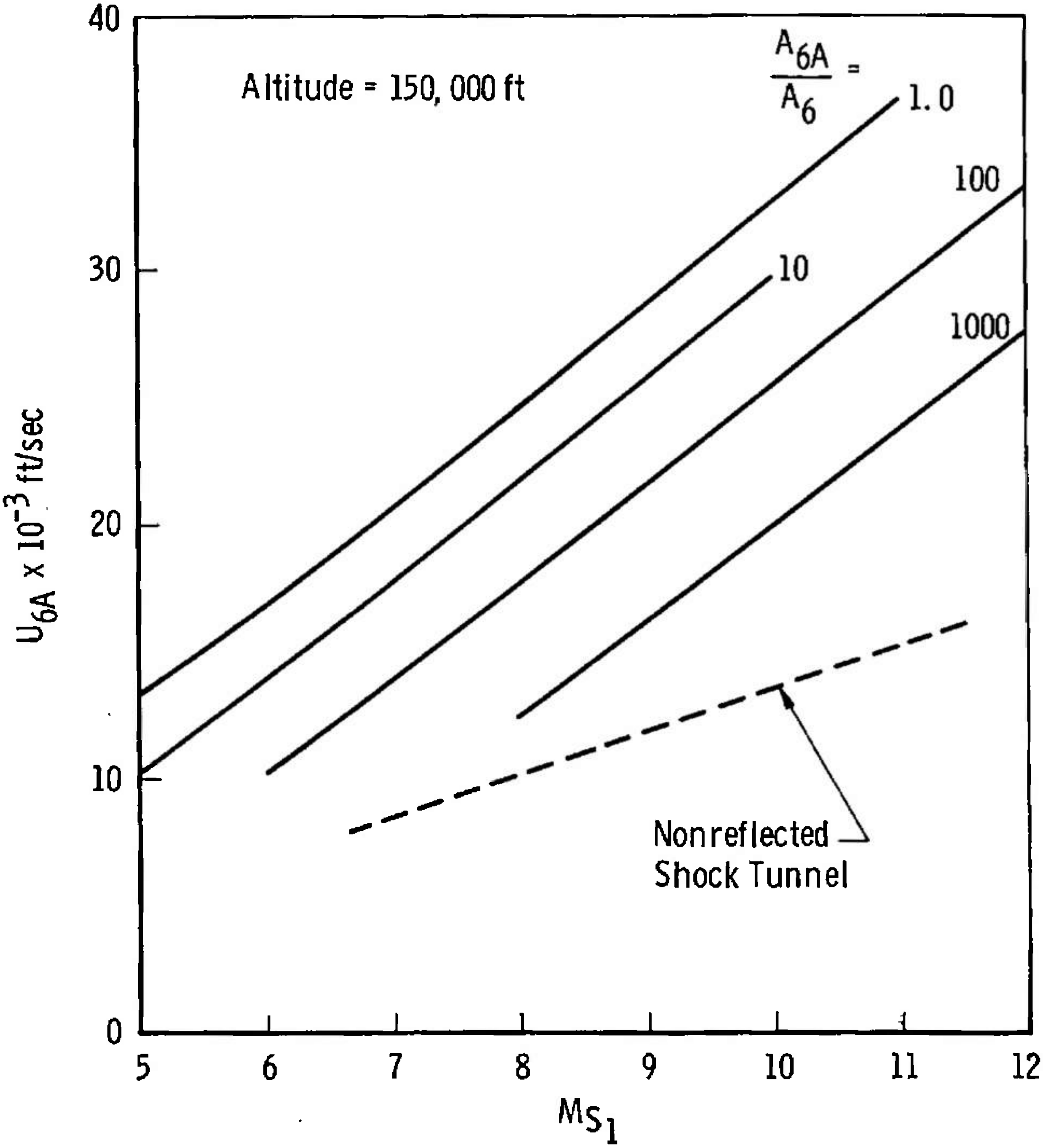


Fig. 11 Loss in Performance Caused by Steady Expansion

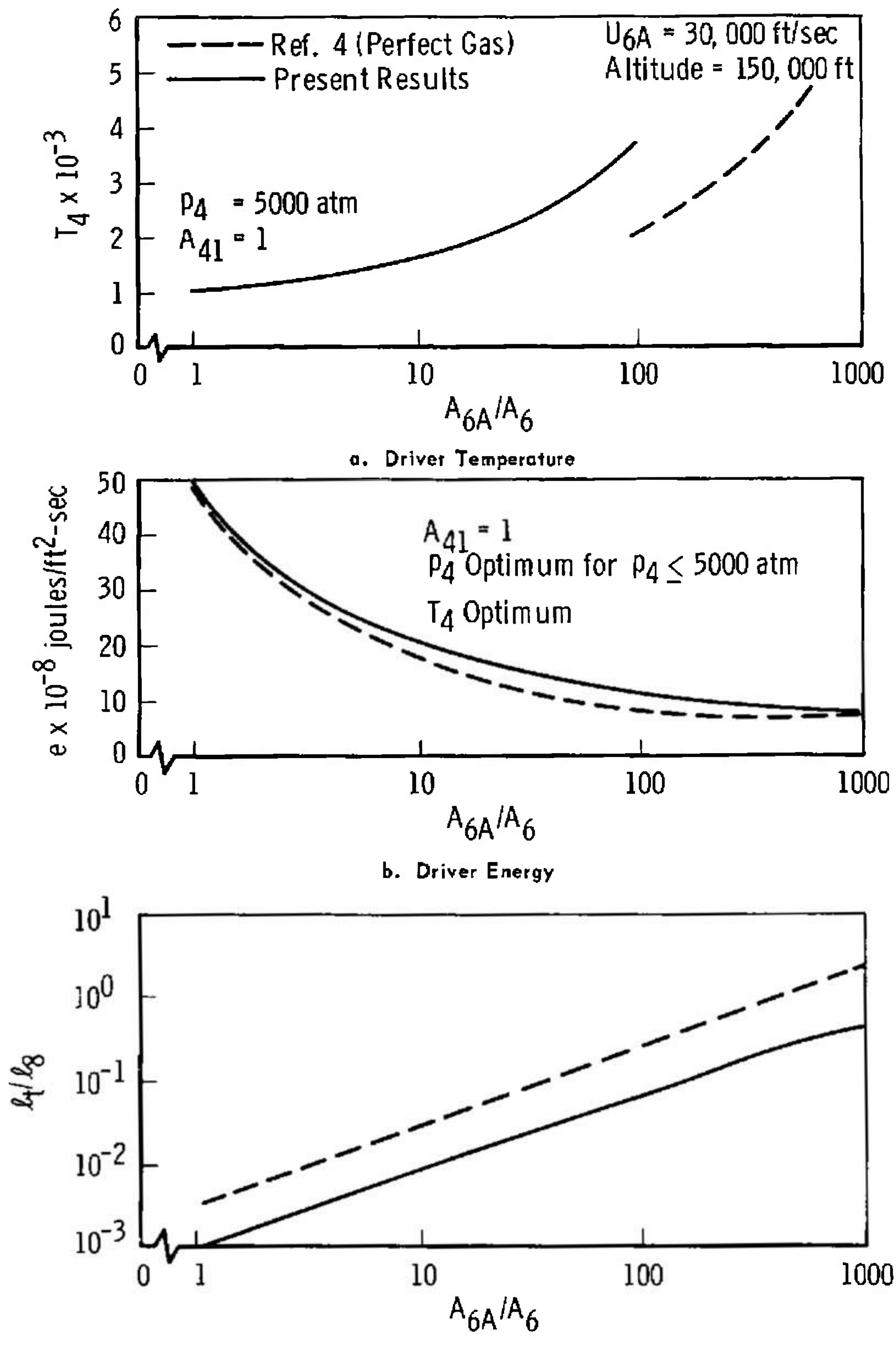


Fig. 12 Variation of Some Critical Parameters with Expansion Area Ratio

TABLE I
EXPANSION TUNNEL PROGRAM – INPUT AND OUTPUT DATA

INPUT DATA

U_{6A}	Ft (Altitude)	A_{6A}/A_6	T_1

OUTPUT DATA

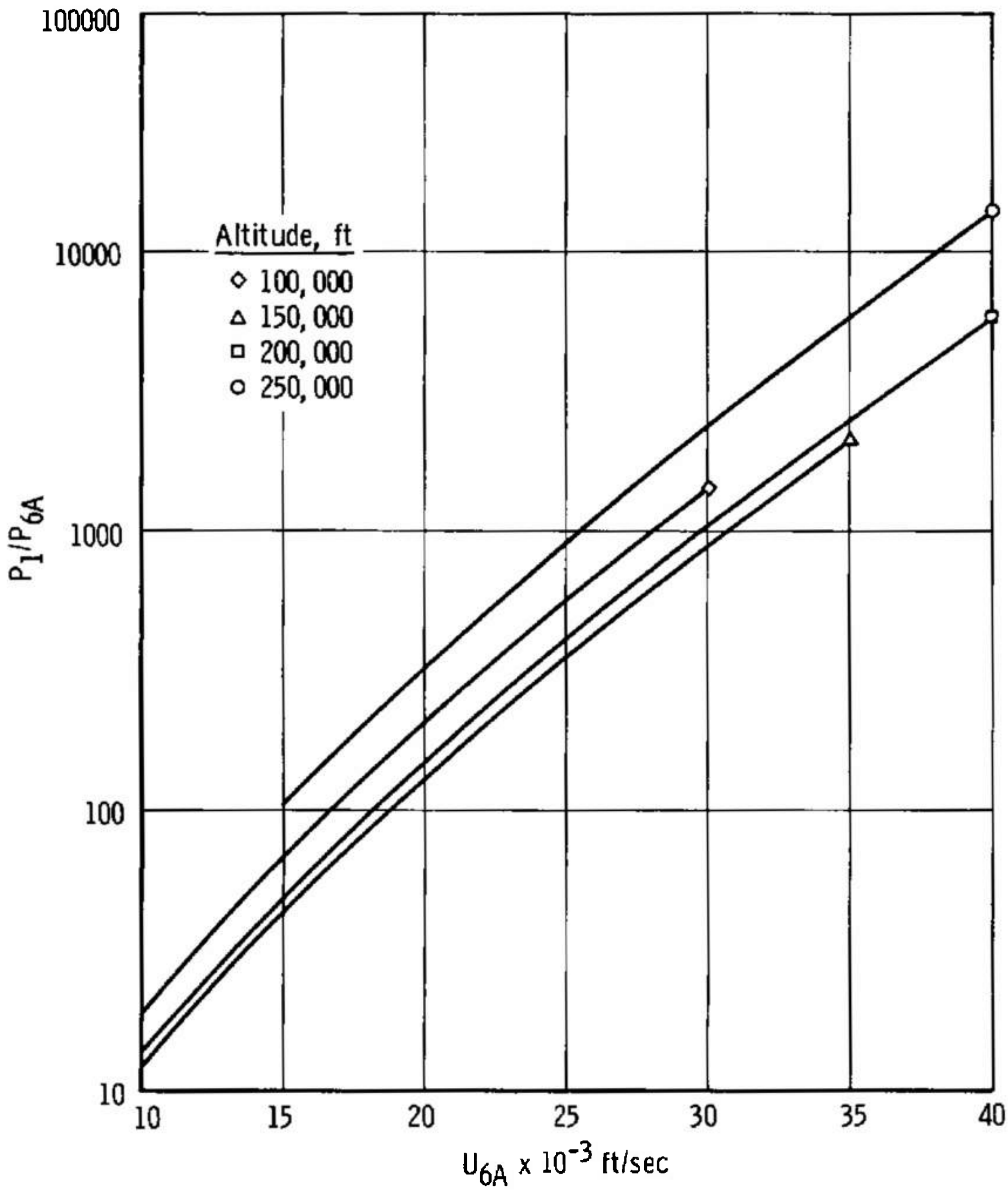
p_1	U_{S_1}	M_{S_1}	ℓ_1/ℓ_8	$\ell_8/\Delta t_r$		
p_2	U_2	T_2	ρ_2	h_2	a_2	Z_2
p_6	U_6	T_6	ρ_6	h_6	a_6	Z_6
p_{6A}	U_{6A}	T_{6A}	ρ_{6A}	h_{6A}	a_{6A}	Z_{6A}

APPENDIX I
WORKING GRAPHS

As an aid in expansion tunnel design and operation, some of the more meaningful parameters are presented in the form of working graphs. Charge pressures p_1 and p_8 are presented in Figs. I-1 and I-2, respectively. Pressure in the shock heated region, p_2, is presented in Fig. I-3. The nondimensional form, p/p_{6A}, reduces the variation with altitude to that caused by real-gas effects and acoustic velocity variation.

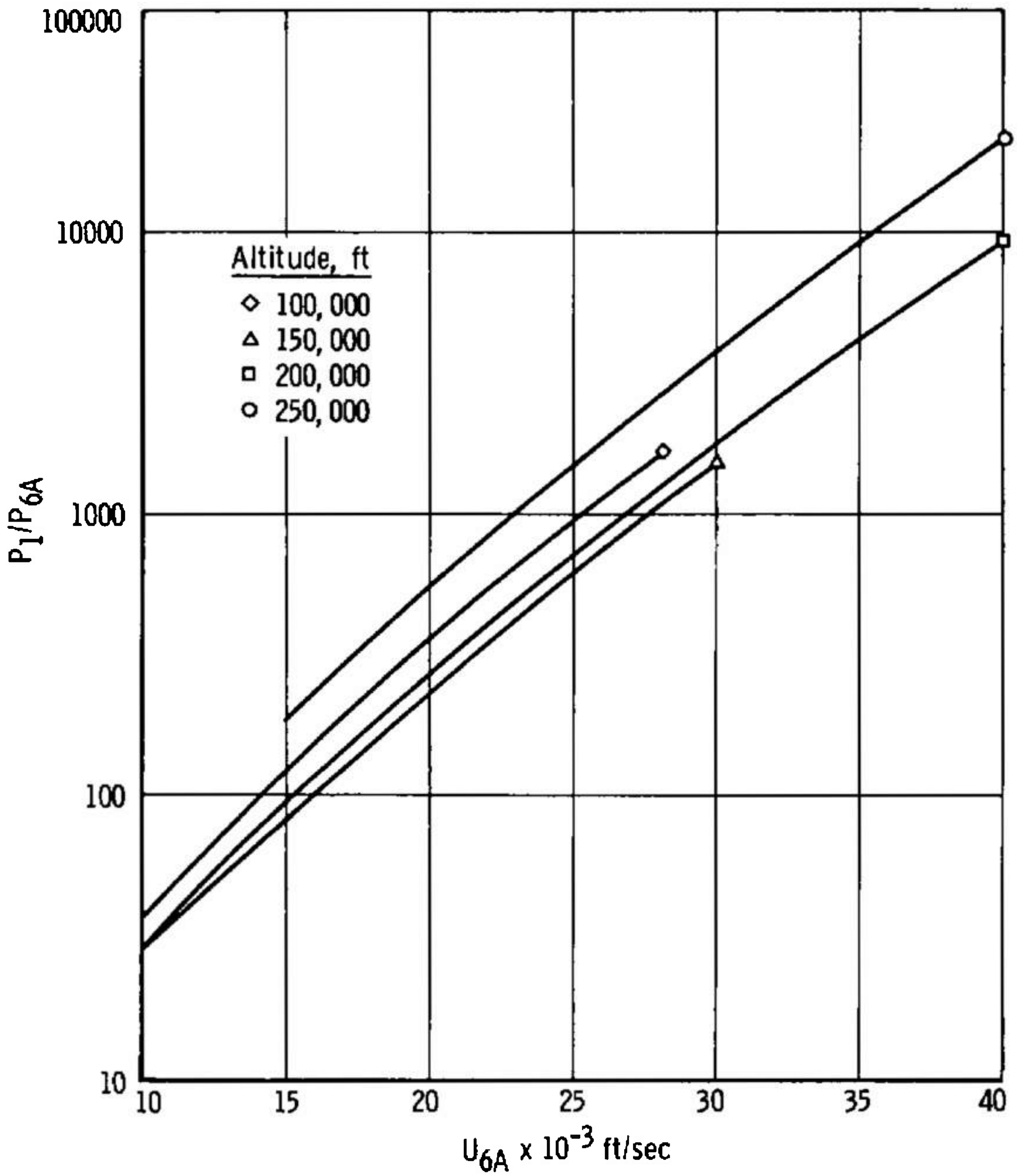
Shock strengths as a function of altitude and test gas velocity are presented in Figs. I-4 and I-5. Here again, the variation with altitude is caused by variation of acoustic velocity, a_{6A}, and real-gas effects.

The optimum driven tube length is given as a function of test gas velocity and altitude in Fig. I-6. As noted previously, viscous effects in the driven tube may increase the optimum length considerably. Accelerating tube length per unit run time is shown in Fig. I-7. The effects of viscosity on run time have not been assessed, even qualitatively, to date.

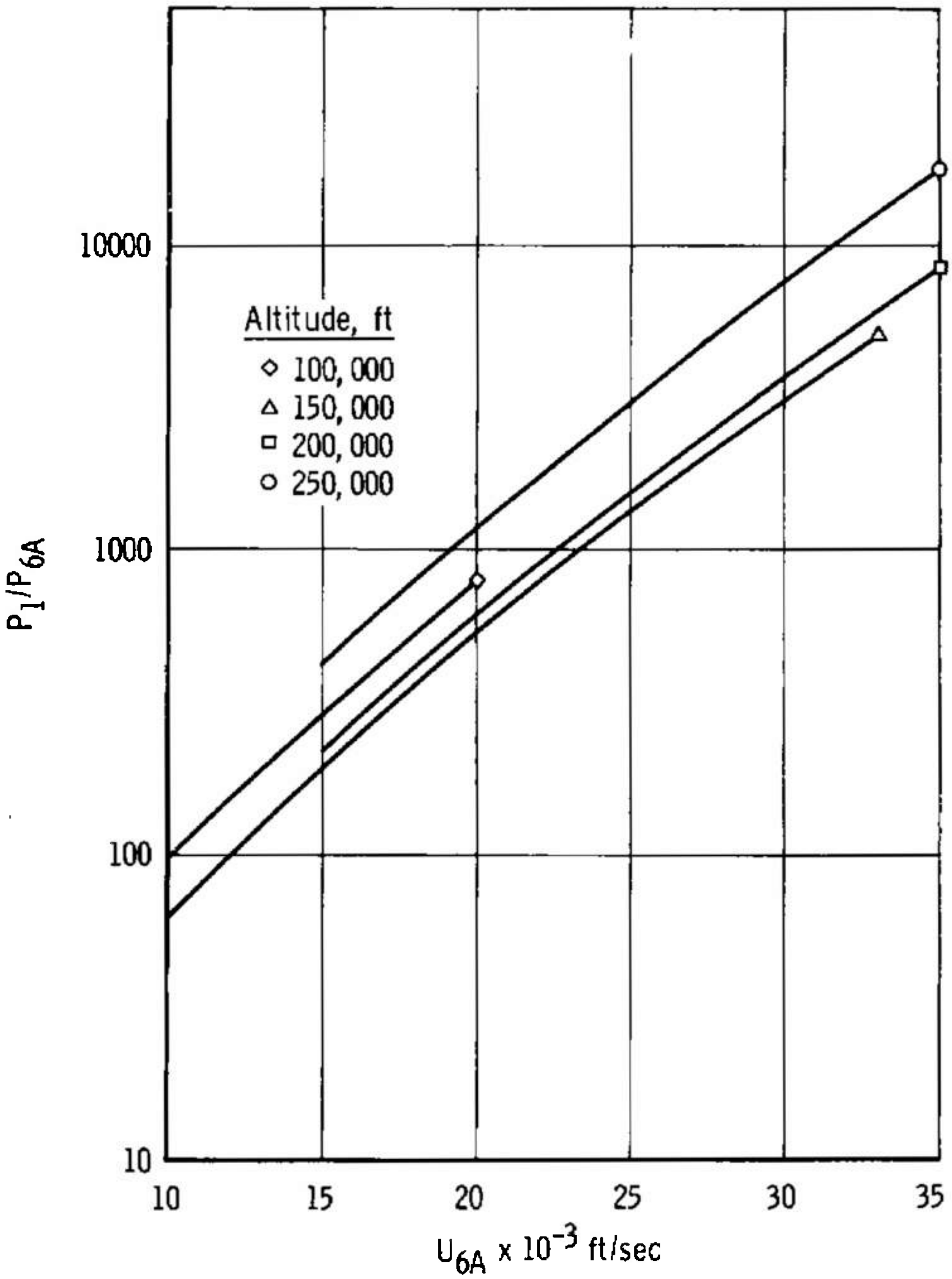


a. $A_{6A}/A_6 = 1.0$

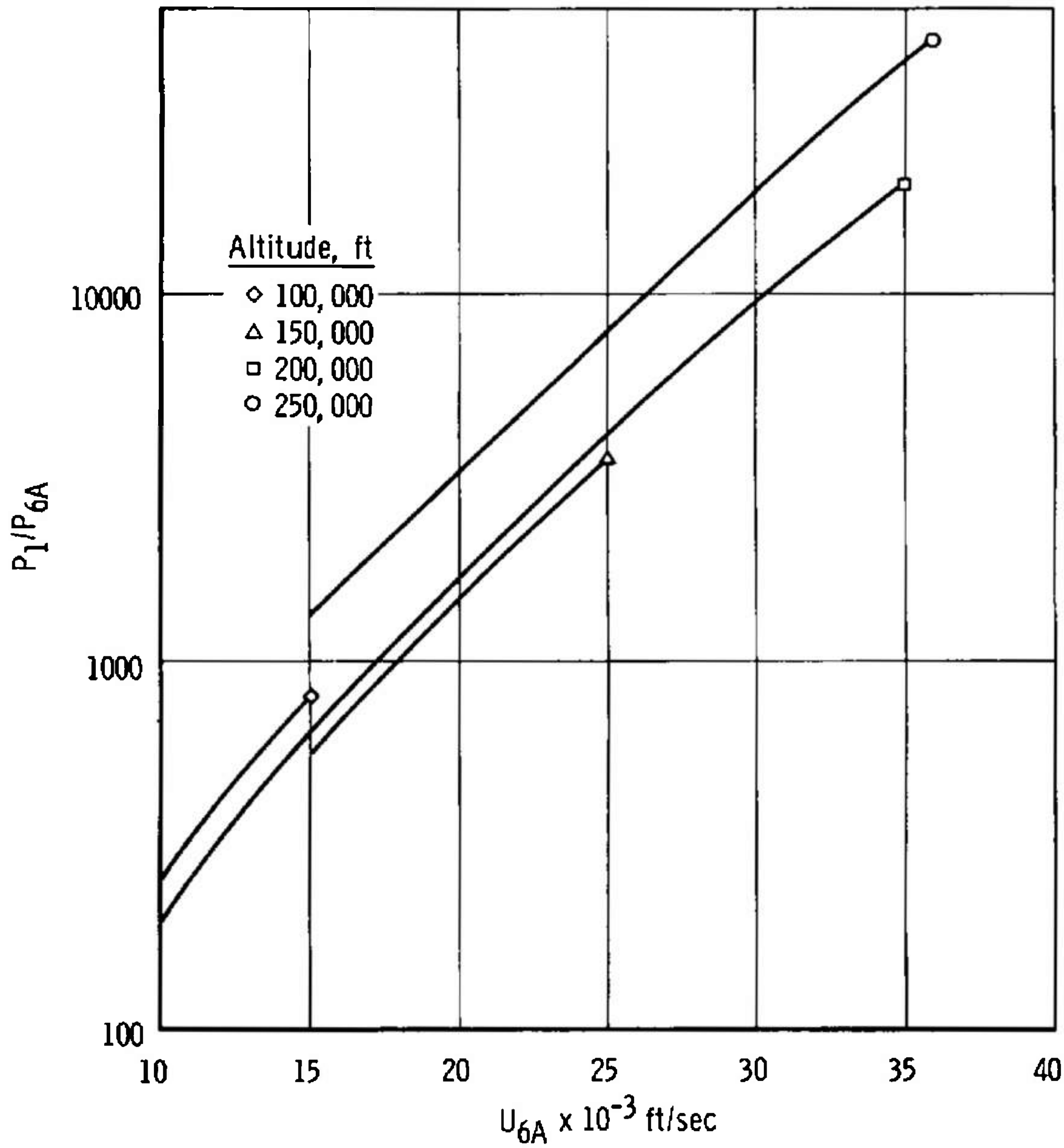
Fig. I-1 Charge Pressure – P_1



b. $A_{6A}/A_6 = 10$
Fig. I-1 Continued

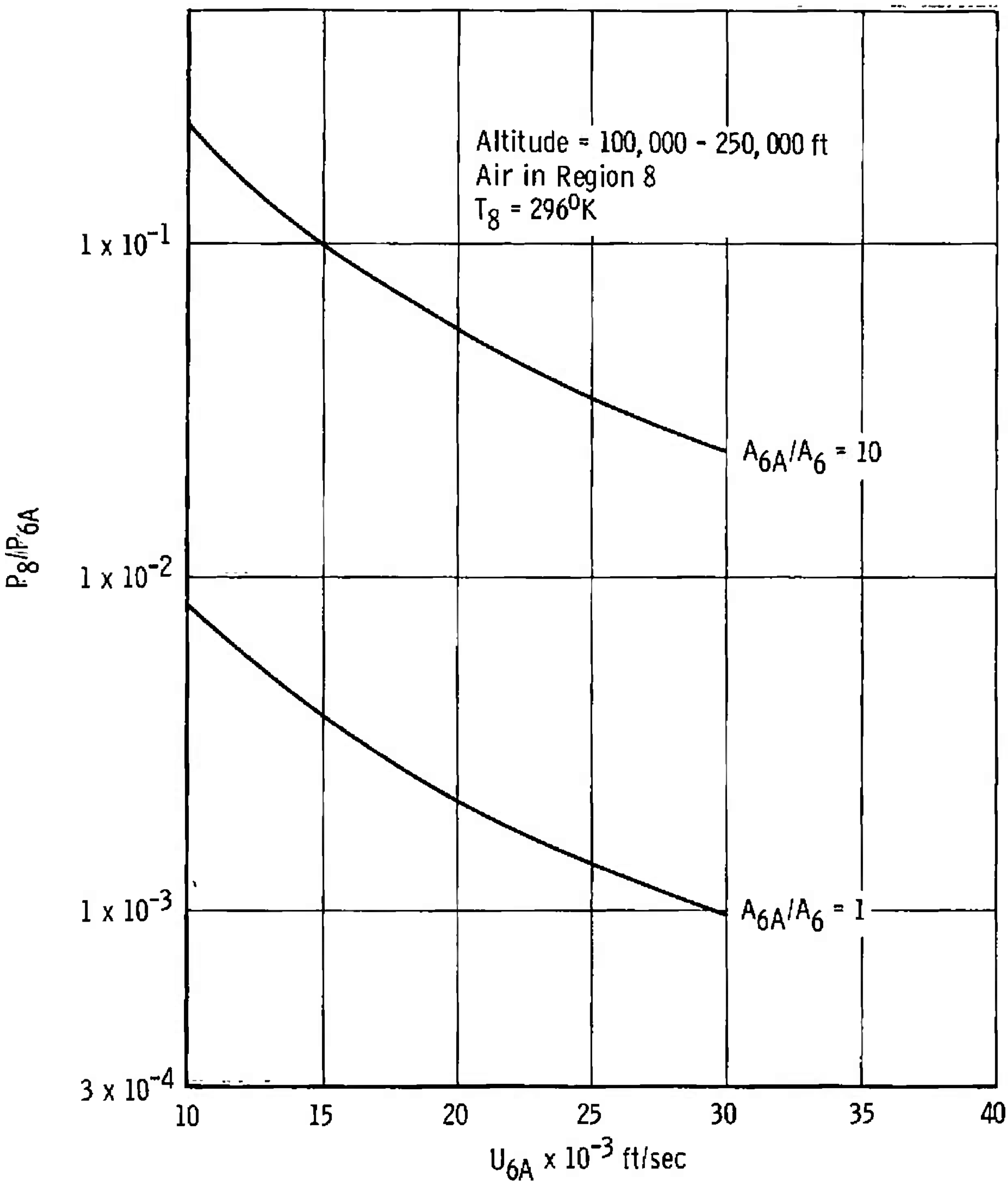


c. $A_{6A}/A_6 = 100$
Fig. I-1 Continued

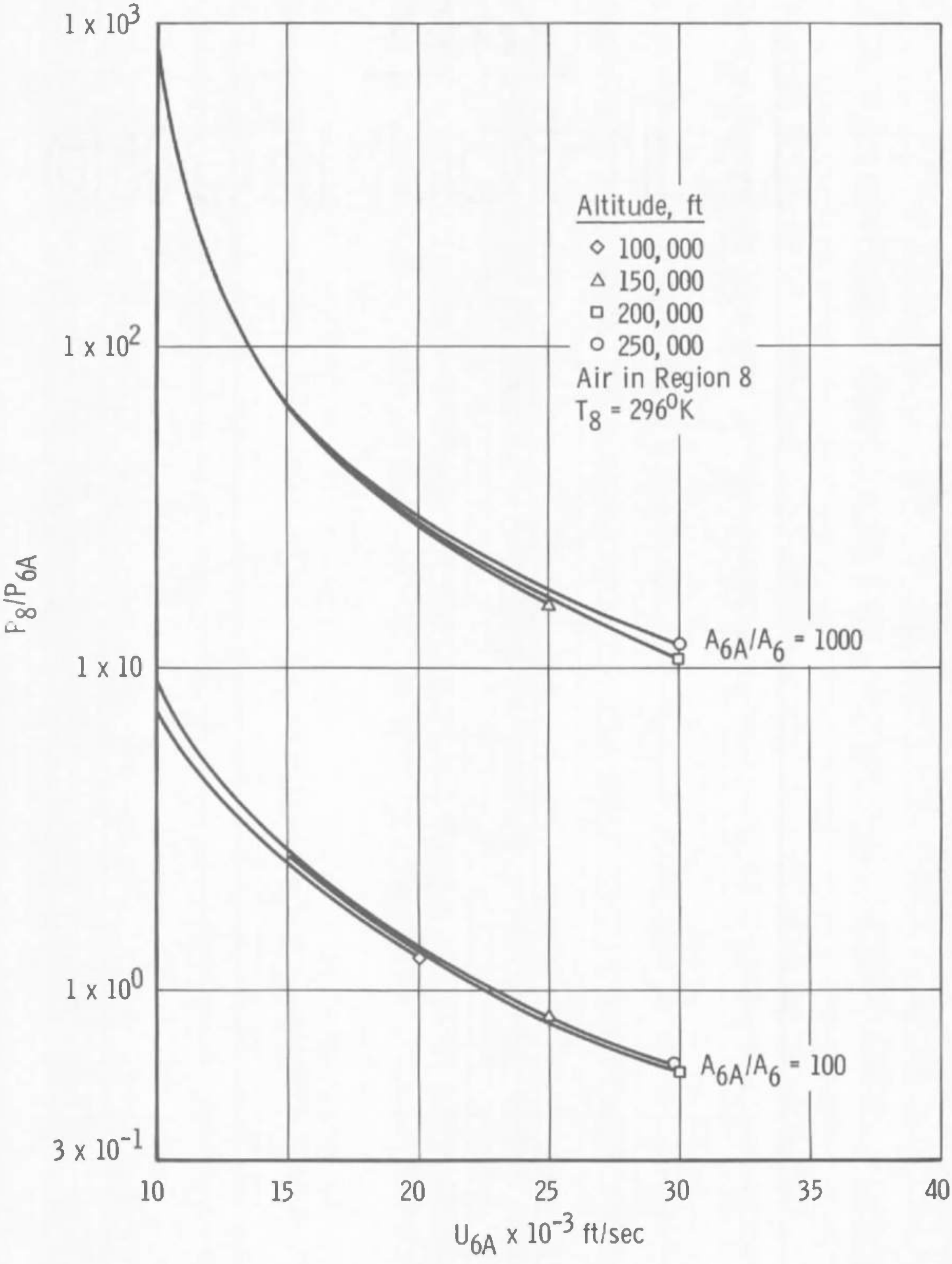


d. $A_{6A}/A_6 = 1000$

Fig. I-1 Concluded

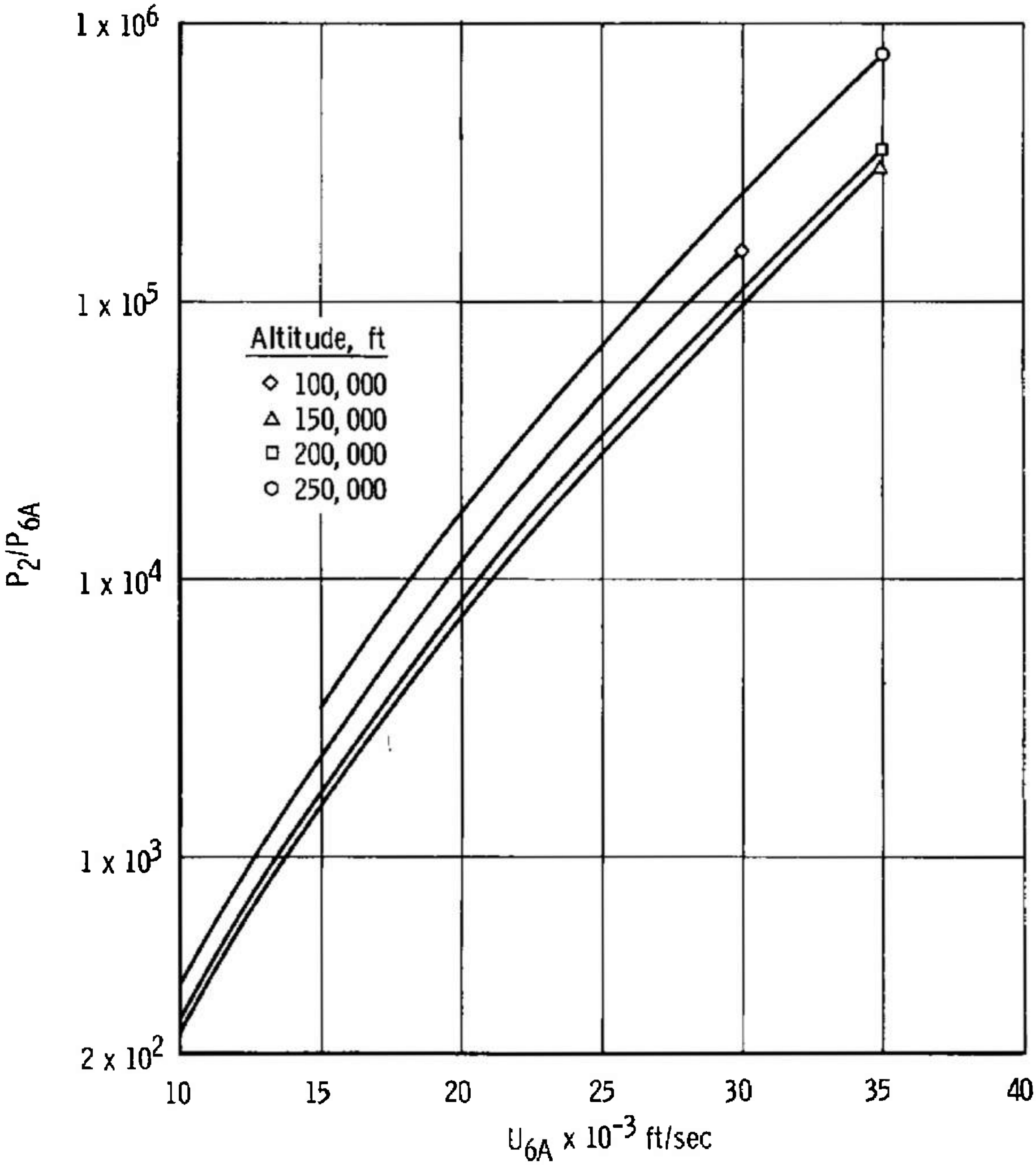


a. $A_{6A}/A_6 = 10$ and $A_{6A}/A_6 = 1$
Fig. I-2 Charge Pressure – P_8

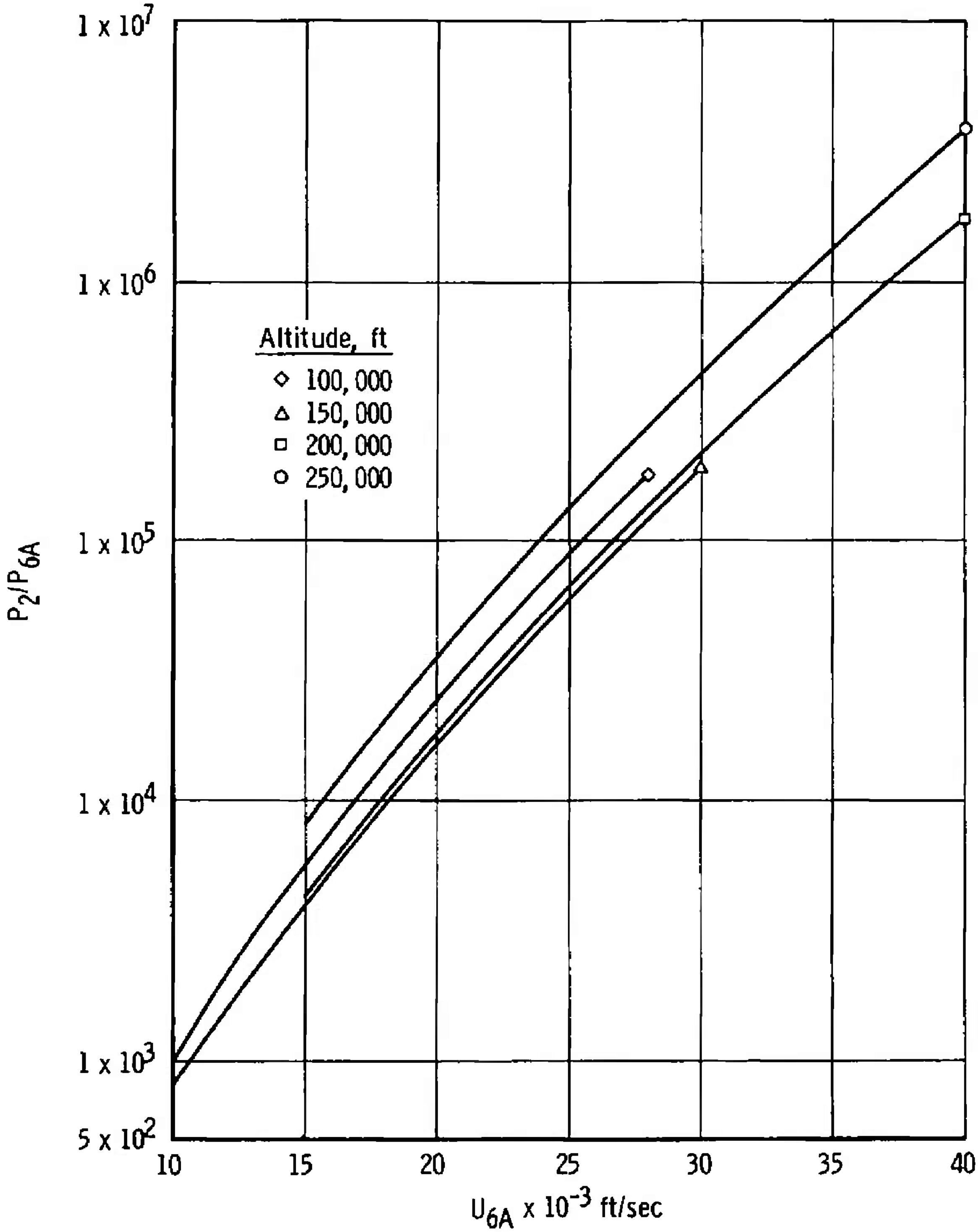


b. $A_{6A}/A_6 = 1000$ and $A_{6A}/A_6 = 100$

Fig. I-2 Concluded

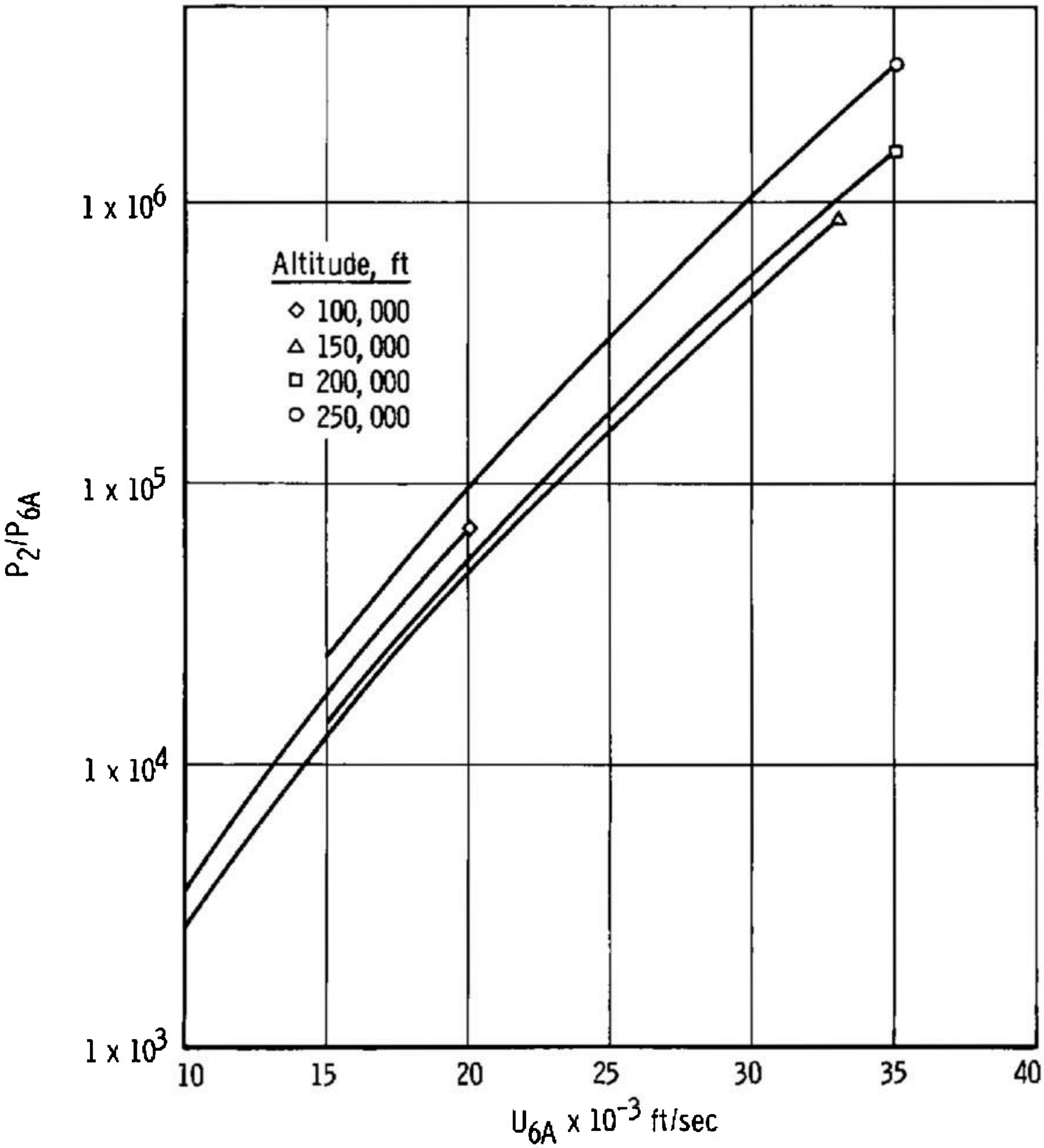


a. $A_{6A}/A_6 = 1.0$
Fig. I-3 Pressure behind Primary Shock in Driven Tube – P_2

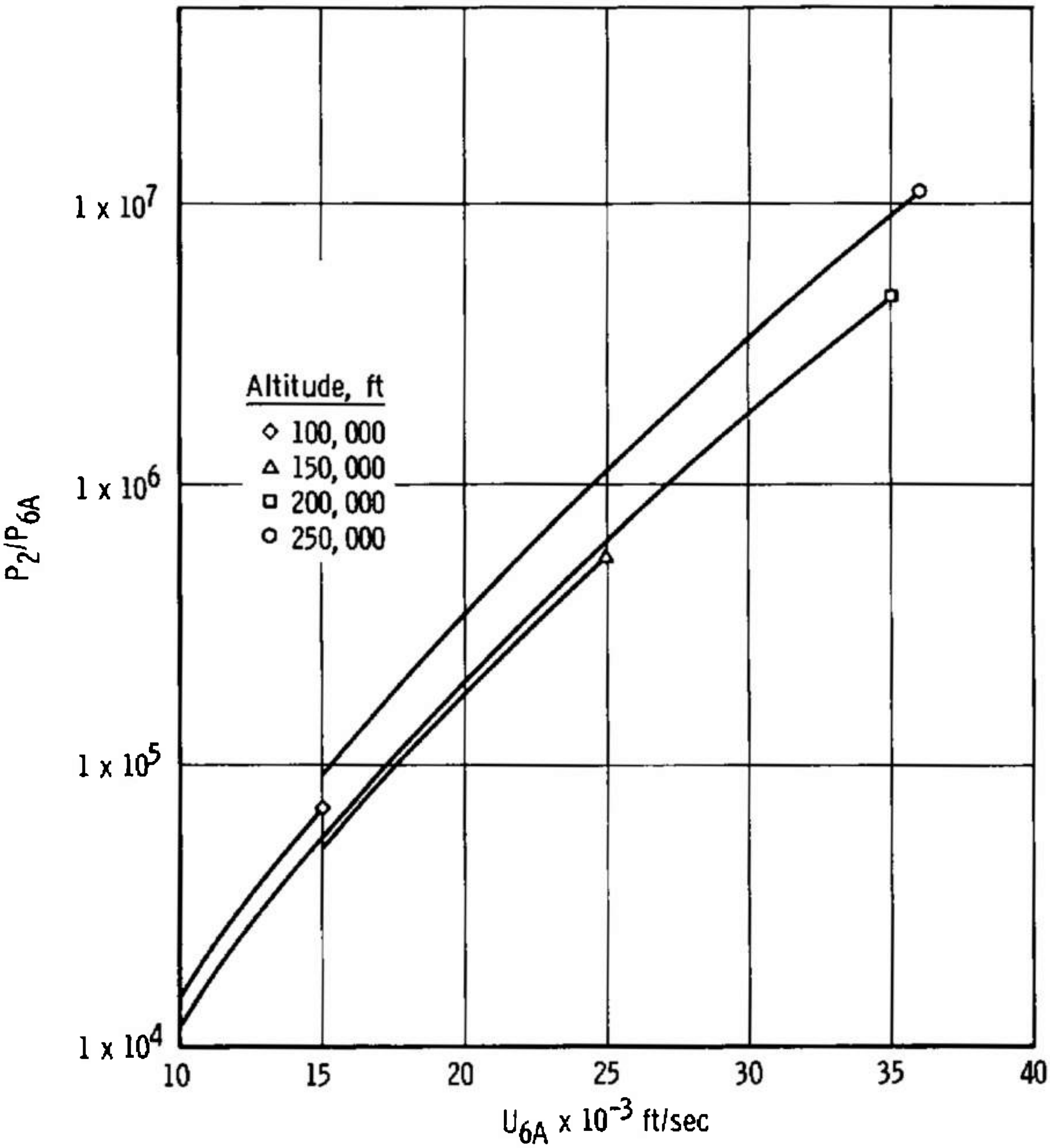


b. $A_{6A}/A_6 = 10$

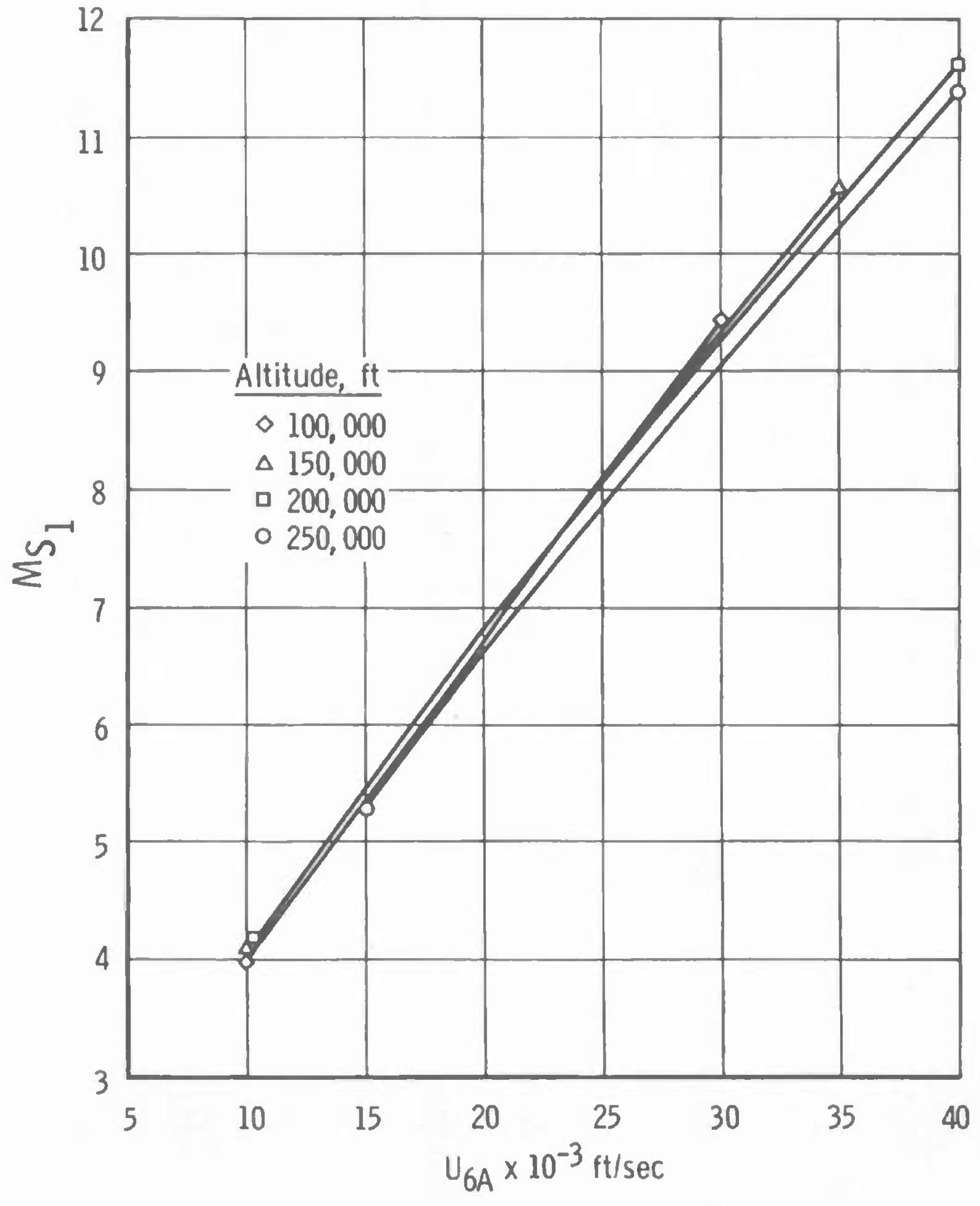
Fig. I-3 Continued



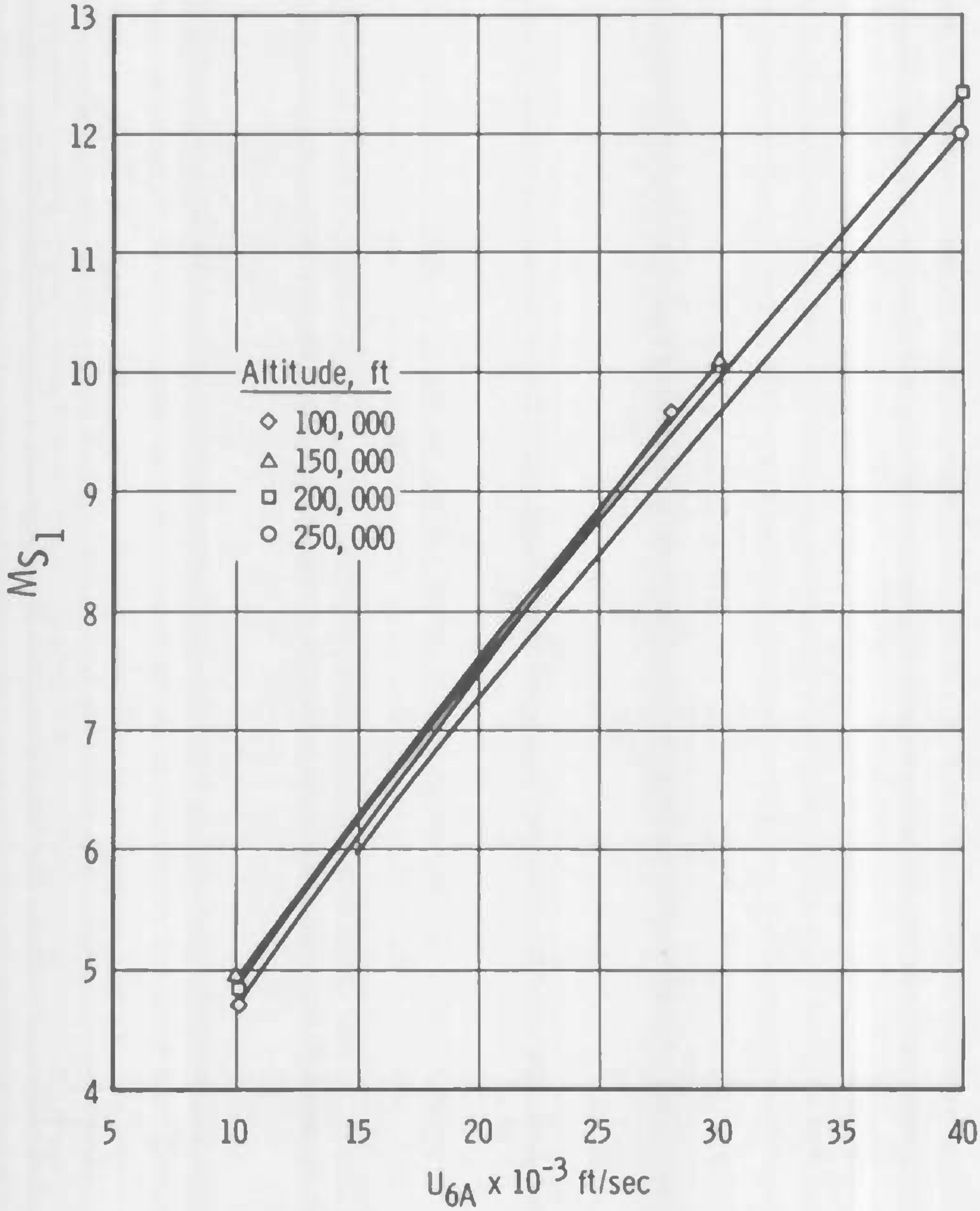
c. $A_{6A}/A_6 = 100$
Fig. I-3 Continued



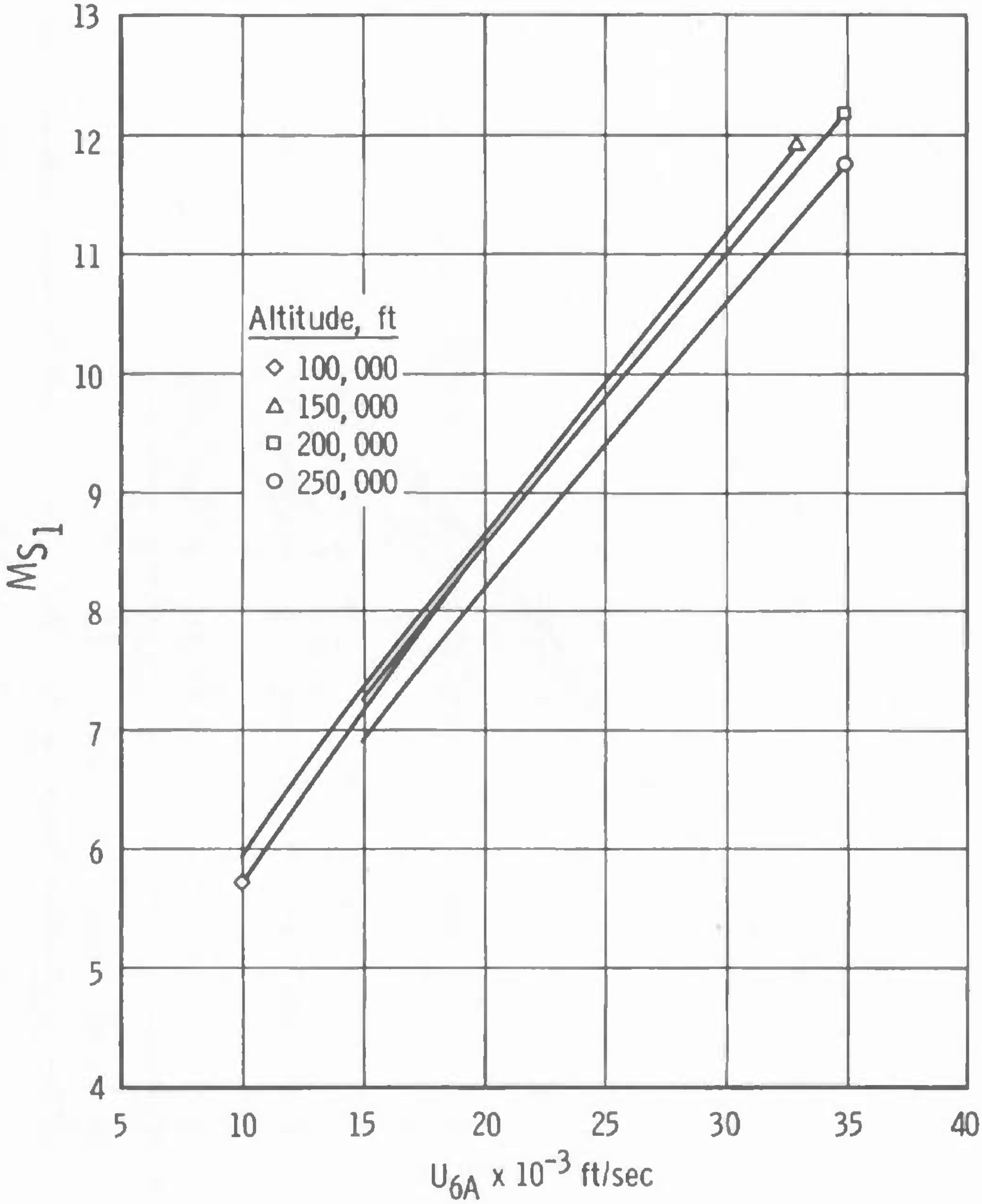
d. $A_{6A}/A_6 = 1000$
Fig. I-3 Concluded



a. $A_{6A}/A_6 = 1.0$
Fig. I-4 Primary Shock Strength Driven Tube – M_{S_1}

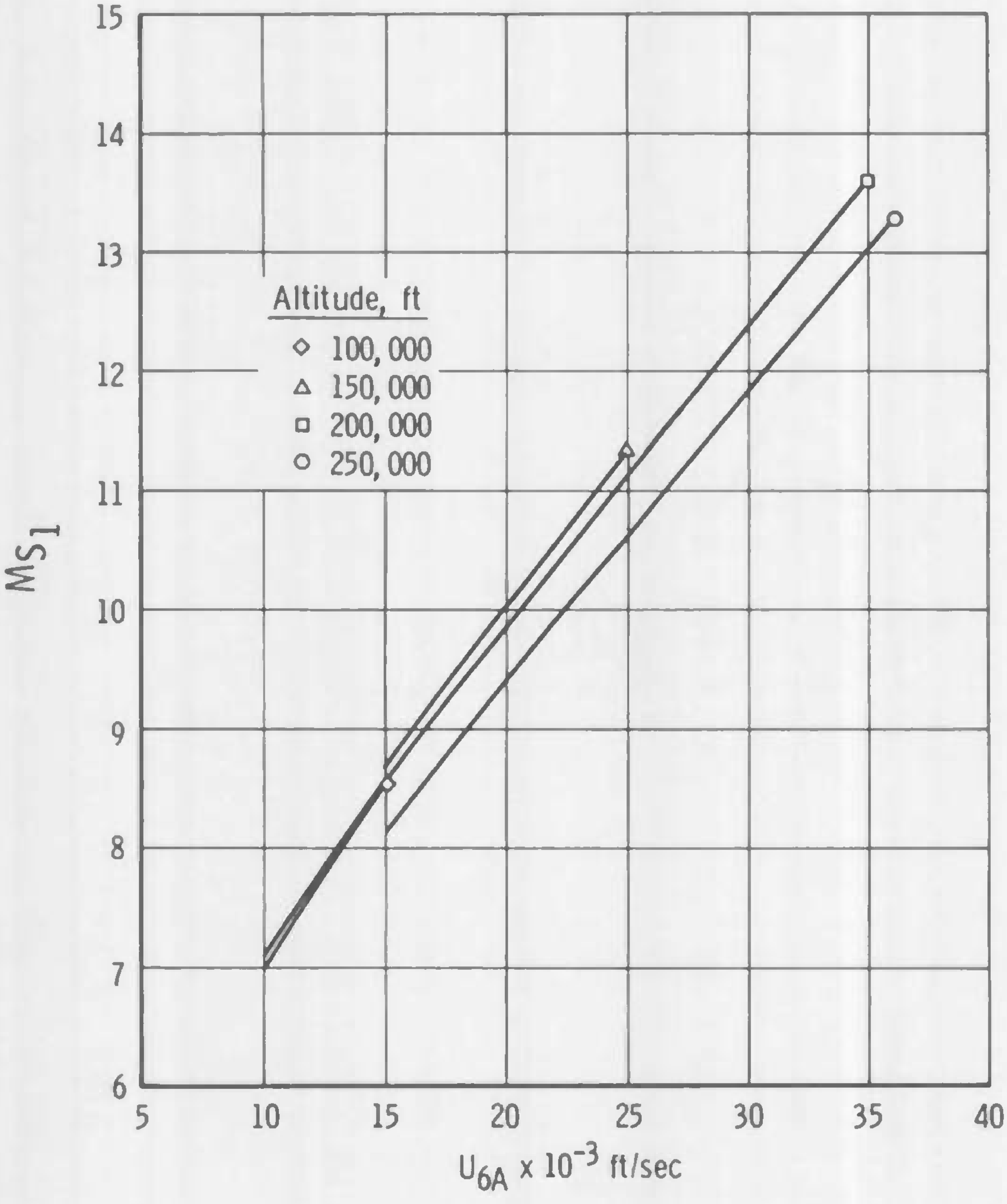


b. $A_{6A}/A_6 = 10$
Fig. I-4 Continued



c. $A_{6A}/A_6 = 100$

Fig. I-4 Continued



d. $A_{6A}/A_6 = 1000$

Fig. I-4 Concluded

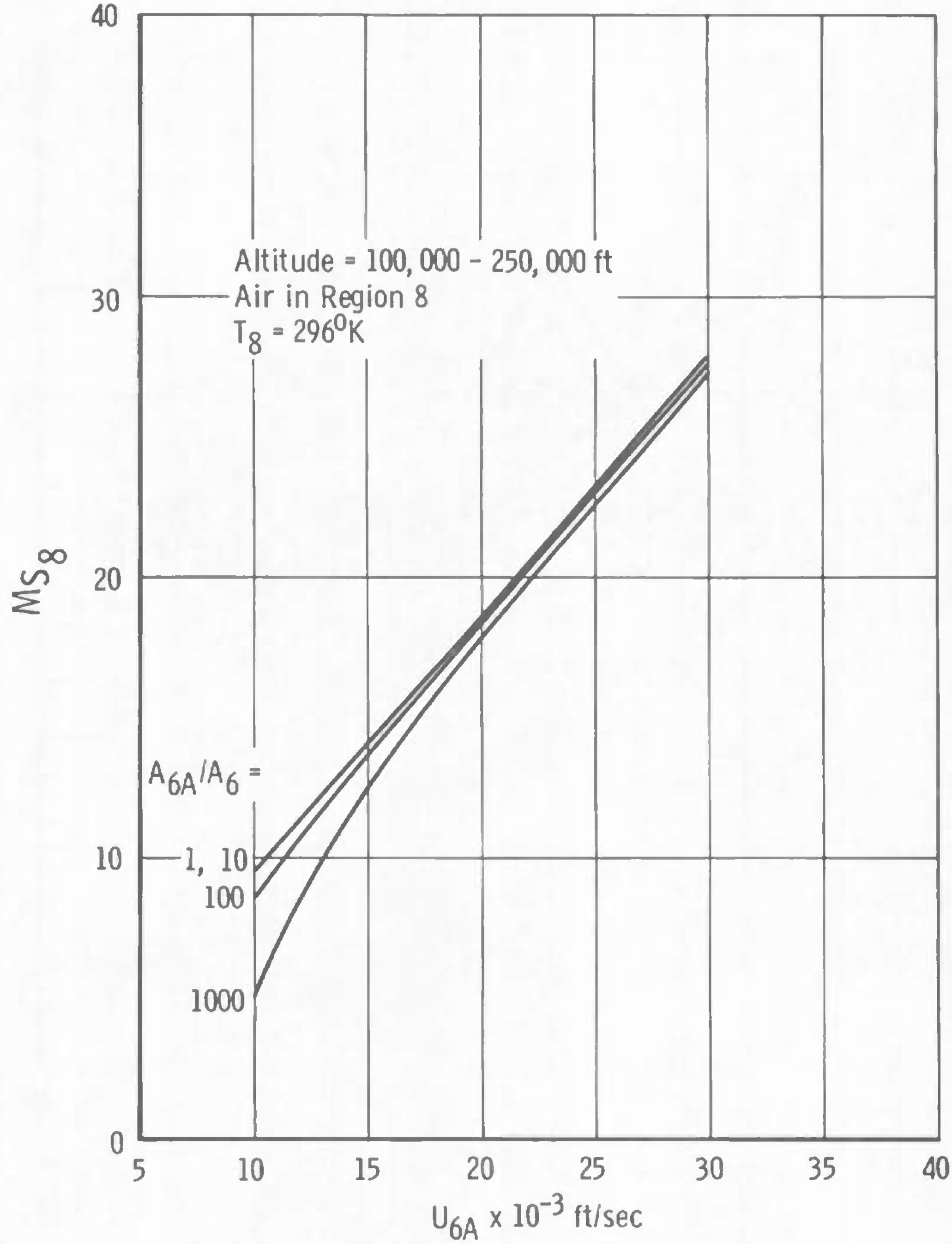


Fig. I-5 Primary Shock Strength – Accelerating Tube, M_{S_8}

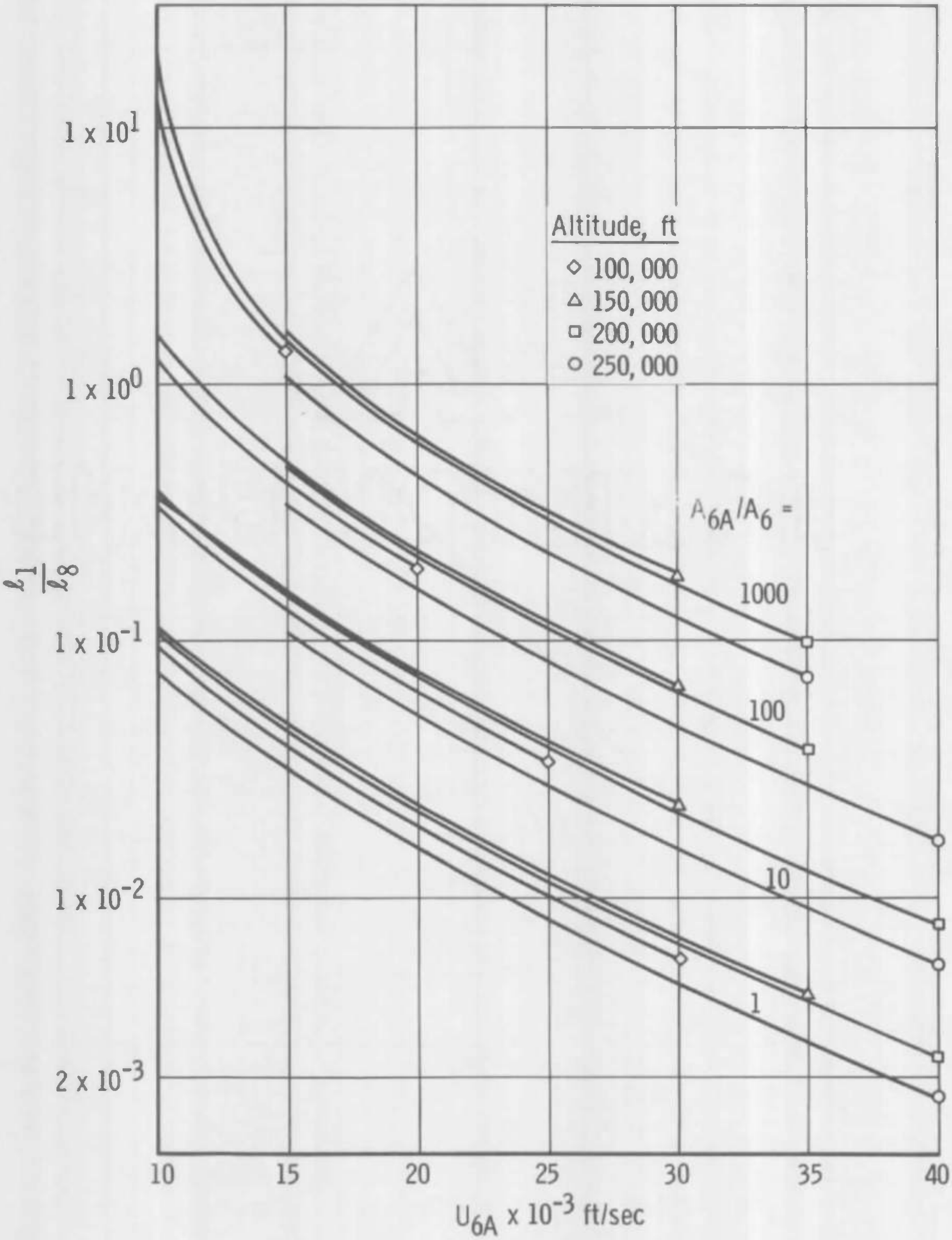


Fig. I-6 Driven Tube/Accelerating Tube Length Ratio

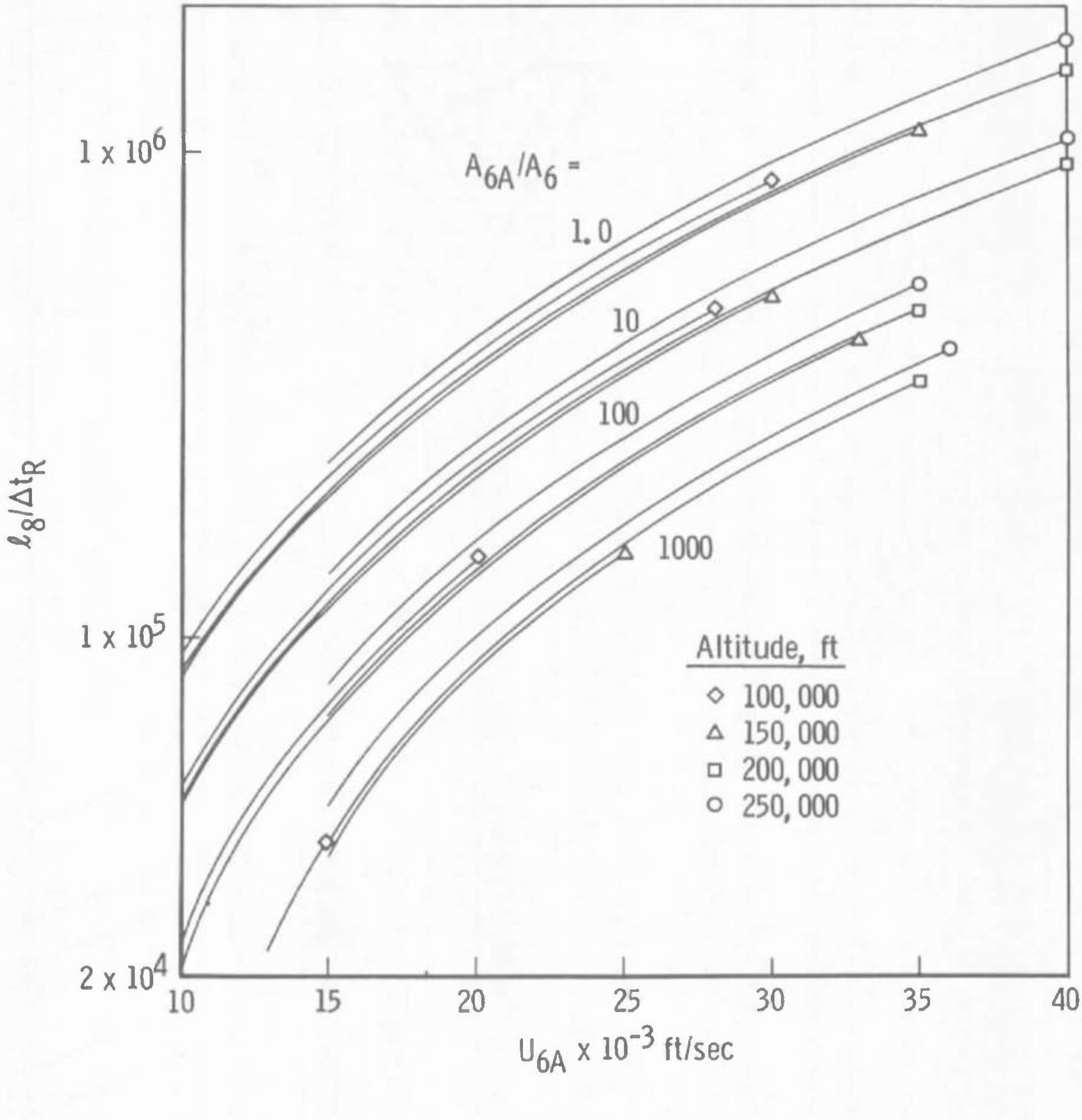


Fig. I-7 Accelerating Tube Length Per Unit Run Time

APPENDIX II
DERIVATION OF EQUATIONS USED IN THE COMPUTER PROGRAM

SHOCK CROSSING EQUATIONS

For a plane shock wave moving into a quiescent gas, the equations for the conservation of mass, momentum, and energy, and the equation of state are, respectively,

$$\rho_2 (U_{S_1} - U_2) = \rho_1 U_{S_1} \tag{II-1}$$

$$p_2 + \rho_2 (U_{S_1} - U_2)^2 = p_1 + \rho_1 U_{S_1}^2 \tag{II-2}$$

$$h_2 + 1/2\ (U_{S_1} - U_2)^2 = h_1 + 1/2\ U_{S_1}^2 \tag{II-3}$$

$$p_1 = \rho_1 RT_1 \tag{II-4}$$

These four equations will be used to determine ρ_1, U_{S_1}, p_1, and U_2.

Eliminating U_2 and $U_{S_1}^2$ from Eqs. (II-1), (II-2), and (II-3) gives[9]

$$(p_2/p_1 - 1)\ \frac{p_1 RT_a}{\rho_1} = \frac{(h_2/h_1 - 1)\ 2h_1}{1 + \rho_1/\rho_2} \tag{II-5}$$

Now, eliminating p_1 between Eqs. (II-4) and (II-5), one gets, after some manipulation,

$$\rho_1^2 + \rho_1 \left[\frac{2\rho_2 (h_2 - h_1)}{RT_1} + \rho_2 - \frac{p_2 T_a}{T_1}\right] - \frac{p_2 \rho_2 T_a}{T_1} = 0 \tag{II-6}$$

The positive sign in the quadratic formula corresponding to the above equation yields the desired value of ρ_1. Equations (II-3), (II-4), and (II-1) can be written

$$U_{S_1} = \left\{2(h_2 - h_1)/\left[1 - (\rho_1/\rho_2)^2\right]\right\}^{1/2} \tag{II-7}$$

---

[9] Introducing the nondimensional quantities of p in atm and ρ in amagats.

$$p_1 = \rho_1 T_1/T_a \tag{II-8}$$

$$U_2 = U_{S_1} (1 - \rho_1/\rho_2) \tag{II-9}$$

Use is made of Eqs. (II-6), (II-7), (II-8), and (II-9) in Appendix III.

LENGTH EQUATIONS

Equation (II-3), also appearing in Appendix III, will now be derived. Reference to Fig. II-1 will aid in the understanding of the following development. Hence, from Fig. II-1 it follows that

$$\ell_1/\Delta t_y = a_2 U_{S_1}/(U_{S_1} - U_2) \tag{II-10}$$

$$\ell_8/\Delta t_z = U_6 - a_6 \tag{II-11}$$

For the unsteady expansion between regions 2 and 6, the following equations are valid:

$$\frac{dt}{d\ell} = \frac{1}{U + a} \tag{II-12}$$

$$\frac{t - \Delta t_x}{\ell} = \frac{1}{U - a} \tag{II-13}$$

$$a dU = - dh \tag{II-14}$$

The parameter ℓ can be eliminated between Eqs. (II-12) and (II-13) by differentiating (Eq. II-13) and putting the result into Eq. (II-12).

$$(U - a) dt + (dU - da)(t - \Delta t_x) = (U + a) dt \tag{II-15}$$

Using Eq. (II-14) to remove dU from Eq. (II-15) and simplifying gives

$$\frac{2dt}{t - \Delta t_x} + \frac{da}{a} = - \frac{dh}{a^2} \tag{II-16}$$

Integrating Eq. (II-16) between regions 2 and 6 gives

$$\log \left| a_2 (t_2 - \Delta t_x)^2 \right| = - \int_{h_6}^{h_2} \frac{dh}{a^2} + \log \left| a_6 (t_6 - \Delta t_x)^2 \right| \tag{II-17}$$

Hence,

$$\log \left| \frac{a_2}{a_6} \left(\frac{\Delta t_y}{\Delta t_z} \right)^2 \right| = - \frac{\text{sum}}{a_s}$$

where

$$\text{sum} = \frac{a_a}{r_a\, T_a} \int_{h_6/R}^{h_2/R} \frac{d\,(h/R)}{(a/a_a)^2}$$

so that

$$\frac{\Delta t_y}{\Delta t_z} = \left(\frac{a_6}{a_2}\right)^{\frac{1}{2}} \exp\,(-\,0.5\ \text{sum}/a_a) \qquad \text{(II-18)}$$

Combining Eqs. (II-10), (II-11), and (II-18) gives

$$\frac{\ell_1}{\ell_8} = \frac{1}{(U_6 - a_6)\ \dfrac{U_{S_1} - U_2}{a_2\ \ U_{S_1}} \left(\dfrac{a_2}{a_6}\right)^{\frac{1}{2}} \exp\,(0.5\ \text{sum}/a_a)}$$

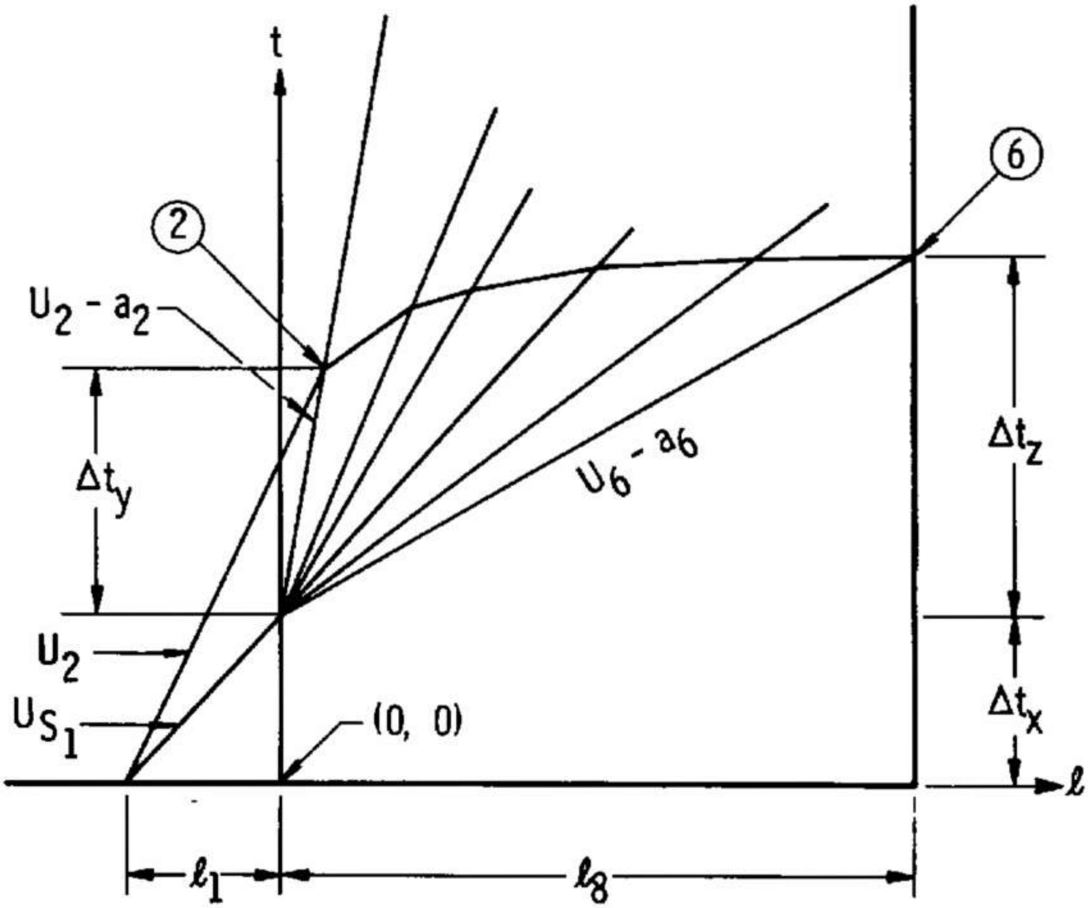
or, in the terminology of Appendix III,

$$\ell_1 = \frac{1}{(U_6 - a_6)\,y}$$

where

$$y = \frac{U_{S_1} - U_2}{a_2\ \ U_{S_1}} \left(\frac{a_2}{a_6}\right)^{\frac{1}{2}} \exp\,(0.5\ \text{sum}/a_a)$$

$$\ell_8 = 1$$



The symbols associated with the above lines represent the reciprocal of the slope of the lines.

Fig. II-1 Wave Diagram Illustrating Nomenclature Used in Calculation of Tube Length

APPENDIX III
COMPUTER PROGRAM

The purpose of this program is to compute certain quantities of interest associated with the unsteady expansion problem among which are the 6 conditions, the 2 conditions, and a characteristic length.

The method by which the above is accomplished basically reduces to solving two separate nonlinear equations by iterative schemes, and evaluating certain integrals by Gaussian mechanical quadrature. The gas properties are retrieved from magnetic tape using a double four-point interpolation.

Program flow is as follows (Figs. III-1 and 2, and Tables III-1, -2, -3, and -4):

A. SR, if not read in, is computed from T6A and P6A, T6A and P6A being computed as functions of altitude in subroutine ATP.

B. The remaining 6A conditions are computed from SR and P6A.

C. An iteration is performed to find ρ6. The initial guess is

$$\rho 6 = \rho 6A \frac{A6A}{A6}$$

Given a value of ρ6, H6 is computed as a function of SR and ρ6 (table look-up). The value of ρ6NEW is defined as

$$\rho 6NEW = \frac{\rho 6A \;\; U6A}{\sqrt{2(H06A - H6)}} \; \frac{A6A}{A6}$$

If ρ6 and ρ6NEW differ by not more than 0.01 percent, then the iteration is said to have converged. Otherwise, the iterative value of ρ6 is taken to be the average of ρ6 and ρ6NEW, and the process is continued.

D. The remaining 6 conditions are computed from SR and H6 by interpolation in the tables.

E. An iteration is performed to find H2. The initial guess on H2 is taken to be[10]

$$H2 = 0.6H1\,(1 + 0.195X^2)$$

---

[10]Developed empirically from the perfect gas results of Ref. 4, page 60.

where

$$X = 0.32 \frac{U6A}{A6A} + \left(\frac{A6A}{A6}\right)^{0.26} + 1$$

For known H2, U2 can be computed by two relations. The object of this iteration is to find the value of H such that these two values of U, U21 and U22, are equal. The two relations that U must satisfy are

1.

$$\rho 2 = \rho 2\,(SR, H2)\ \text{(from tape)} \tag{III-1a}$$

$$P2 = P2\,(SR, H2)\ \text{(from tape)} \tag{III-1b}$$

$$B = \frac{2\rho 2\,(H2 - H1)}{RT1} + \rho 2 - P2\left(\frac{TA}{T1}\right) \tag{III-1c}$$

$$C = -P2\rho 2\ TA/T1 \tag{III-1d}$$

$$\rho 1 = 0.5\left(-B + \sqrt{B^2 - 4C}\right) \tag{III-1e}$$

$$US1 = \left(2\,(H2 - H1)/\left(1 - \frac{\rho 1^2}{\rho 2^2}\right)\right)^{1/2} \tag{III-1f}$$

$$P1 = \rho 1\,(T1/TA) \tag{III-1g}$$

$$U21 = US1\,(1 - \rho 1/\rho 2) \tag{III-1h}$$

2.

$$U22 = U6 - \frac{aref}{rA\ TA}\int_{H6/R}^{H2/R} \frac{d\,(H/R)}{a/aref} \tag{III-2}$$

Equations III-1e through III-1h correspond to Eqs. II-6 through II-9, respectively. Notice that all the quantities necessary to compute U21 and U22 are known for an assumed H2. Newton's method with numerical first derivative is used to find the root of

$$f(H2) = U22 - U21 = 0$$

Hence

$$H2_{i+1} = H2_i - \frac{f(H2_i)}{g(H2_i)}$$

where

$$g(H2_i) = \frac{f(H2_i) - f(H2_{i-1})}{H2_i - H2_{i-1}}$$

As this technique requires two initial guesses, the second initial guess is taken to be 1.1 times the first initial guess. With the indicated initial guesses and iteration method, the root has converged in every case thus far. The iteration is said to have converged whenever $H2_{i+1}$ and $H2_i$ differ by not more than 0.01 percent.

F. The remaining region 2 conditions are computed in terms of SR and H2.

G. The characteristic length, L1, is obtained as follows:

$$\Delta t = \frac{US1 - U2}{a2 \quad US1} \tag{III-3a}$$

$$SUM = \frac{a_a}{r_a T_a} \int_{H6/R}^{H2/R} \frac{d(H/R)}{(a/aref)^2} \tag{III-3b}$$

$$Y = \Delta t \left(\frac{a2}{a6}\right)^{1/2} \exp(0.5\, SUM/aref) \tag{III-3c}$$

$$L1 = \frac{1}{(U6 - a6)Y} \tag{III-3d}$$

Input to the program is read from two different tapes.

A. Tape J1N2 (J1N2 = 10)

This tape contains the gas properties mentioned above. See Subroutine SLOW for the proper format.

B. Tape J1N1 (J1N1 = 5)

Two read statements are executed by this tape.

1. A title card, Format (72H...)
2. Input data, Format (6E12.0, I2)

   a. U6A (ft/sec)
   b. T1 (°K)
   c. A6AA
   d. SR
   e. P6A (atm)
   f. ALT (ft)
   g. MORED

All output from the program is on tape JOUT (JOUT = 6).

A. The title card

B. SR

C. Inputs and other constants

1. T1
2. H1
3. A6A/A6
4. RHOA
5. PA
6. R
7. SPEED REF

D. Values of the following at the 6-A, 6, and 2 conditions.

1. P
2. U
3. T
4. ρ
5. H
6. A
7. Z

E. Other output

1. L1
2. P1
3. US1
4. MS1
5. DT
6. L8/DTR (for unit L8)

Subroutine INTRP

The purpose of this routine is to do an N-point Lagrange interpolation where N-1 is a natural number. The argument list is:

(N, X, Y, XINT, YINT)

N is the number of points

X is the set of independent values[11]

Y is the set of dependent values[11]

XINT is the value of the independent variable at which the interpolation is to take place

YINT is the interpolated value of the dependent variable (the return argument)

---

[11]X and Y should be appropriately dimensioned in the calling routine.

Subroutine GAUSS

This subroutine defines constants b_i and x_i (i = 1, 16) such that

$$\int_p^q f(x)\,dx$$

can be approximated by

$$\frac{q-p}{2}\sum_{i=1}^{16} b_i\, f\left(x_i\,\frac{q-p}{2}+\frac{q+p}{2}\right)$$

The values of b_i and x_i were taken from Ref. 17.

The argument list for this subroutine is (b, x). Both b and x should be dimensioned sixteen in the calling program.

Subroutine SLOW

The purpose of this subroutine is to do a cross four-point central Lagrange interpolation of data which have been stored on tape as a function of two independent variables. The manner in which the input tape has been created should be equivalent to the following:

```
      DO 1 K = 1, N
    1 WRITE (IT) X(K), J, ((Y(K, I, L), I = 1, NV), L = 1, J)
```

where $4 \leq N$

$2 \leq NV \leq 9$, a constant defining the number of variables exclusive of X and J

$4 \leq J \leq 150$, a variable defining the number of points for a given K

For a given value of K, it is required that Y(K, I, L) be a strictly monotomic function of L for at least one I. It is also required that X(K) is a strictly monotonic (increasing or decreasing) function of K.

While X must always be one of the independent variables, the second independent variable and the dependent variable need not be specified until call time. Any Y that is a strictly monotonic function of K can be used as the second independent variable.

The meaning of the variables on the tape associated with this particular problem is as follows:

Fortran Name	Identification
X(K)	SR
J	variable
NV	9
Y(K, 1, L)	T
Y(K, 2, L)	$\log_{10} (\rho/\rho A)$
Y(K, 3, L)	$\log_{10}$ (P/PA)
Y(K, 4, L)	$\log_{10}$ (H/R)
Y(K, 5, L)	ye
Y(K, 6, L)	a/aref
Y(K, 7, L)	Z
Y(K, 8, L)	H/RT
Y(K, 9, L)	Z*

The data on this tape were taken from Refs. 6 and 7 primarily; however, certain unpublished extrapolations of the above are also present.

The argument list for the subroutine is

(XX, Z, I1, J1, IT, NV, NERR)

XX is a specified value of SR

Z is a subscripted variable dimensioned appropriately in the calling routine

I1 is a subscript indicating that Z(I1) is the second independent variable

J1 is a subscript indicating that Z(J1) is the dependent variable

IT indicates the channel and unit number on which the input gas tape is mounted

NV indicates the number of variables on the tape corresponding to a value of XX (NV is nine in this case)

NERR will be returned equal to one if and only if the interpolation failed for any reason.

Subroutine ATP

This subroutine was not written specifically for this program, and hence has options not used here. Use is made of the subroutine in this program to find temperature and pressure as a function of altitude. The data used by ATP were taken from Ref. 5.

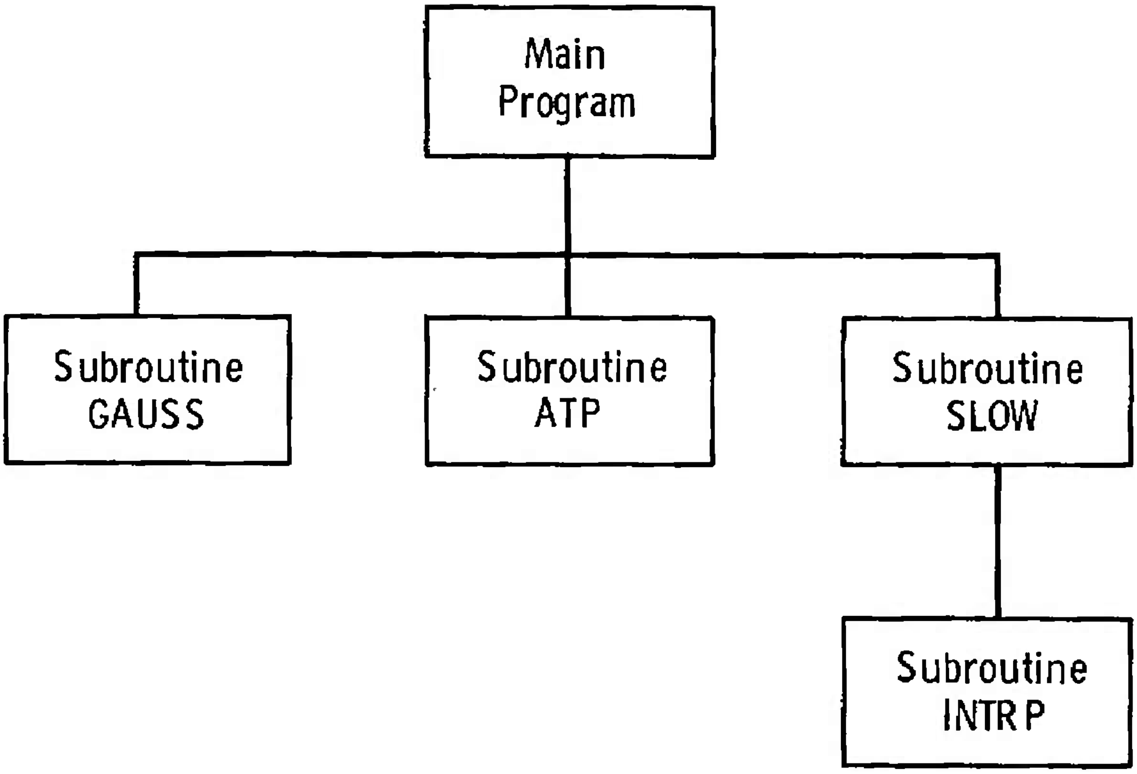


Fig. III-1 Tree Diagram

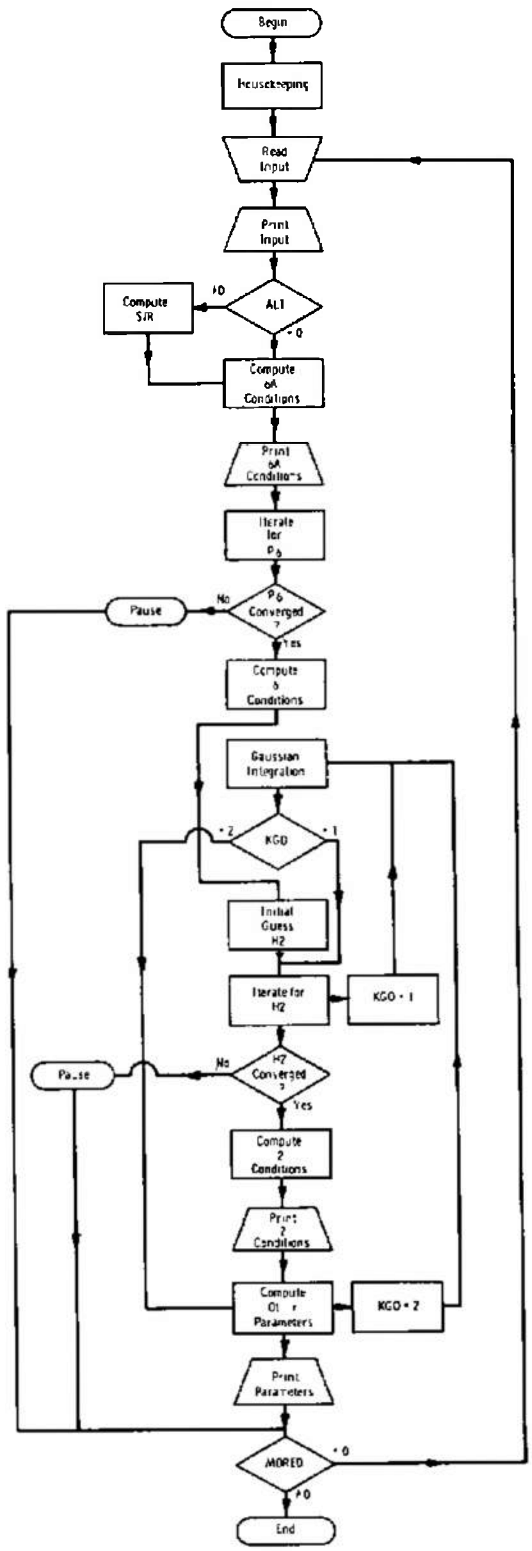


Fig. III-2 Flow Chart of Main Program

TABLE III-1
CROSS INDEX OF NOMENCLATURE

As Used in Appendix III	As Listed in Report Nomenclature
ALT	
SR	S/R
HO	h_o
HO6	h_{o6}
TA	T_a
γA	γ_a
aref	a_a
R	R
H1	h_1
T1	T_1
ρ1	ρ_1
P1	P_1
US1	U_{s1}
H2	h_2
T2	T_2
ρ2	ρ_2
P2	P_2
U2	U_2
H6	h_6
T6	T_6
ρ6	ρ_6
P6	P_6
U6	U_6
T6A	T_{6_a}
ρ6A	ρ_{6_a}
U6A	U_{6_a}
P6A	P_{6_a}
A6A	a_{6_a}
a	a

TABLE III-2
SAMPLE INPUT

Date Set 1

(A) Card 1 (Title card)

(B) Card 2

1. U6A = 20000.
2. T1 = 296.
3. A6AA = 10.
4. SR = (Not required)
5. P6A = (Not required)
6. ALT = 150,000.
7. MORED = 0 (indicates another set of data follows)

Data Set 2

(A) Card 1 (Title card)

(B) Card 2

1. U6A = 8020.
2. T1 = 296.
3. A6AA = 1.
4. SR = 26.62
5. P6A = .9
6. ALT = (Not required)
7. MORED = 1 (indicates end of job)

TABLE III-3
SAMPLE OUTPUT

```
SAMPLE INPUT SHOT ONE   UNSTEADY EXPANSION  (INPUT ALTITUDE)

S/R=0.30108087E 02

INPUT
        T1              H1             A6A/A6             RHOA               PA                 R             SPEED REF
 0.29600000E 03  0.31997999E 07  0.09999999E 02  0.09999999E 01  0.09999999E 01  0.30917000E 04  0.10873999E 04

6-A CONDITIONS
        P               U               T                RHO                H                 A                Z
 0.13428957E-02  0.20000000E 05  0.26564383E 03  0.13802770E-02  0.28657203E 07  0.10728073E 04  0.99999994E 00
6-CONDITIONS
        P               U               T                RHO                H                 A                Z
 0.33525464E-01  0.19784877E 05  0.65598062E 03  0.13952848E-01  0.71796305E 07  0.16668861E 04  0.99999993E 00
2-CONDITIONS
        P               U               T                RHO                H                 A                Z
 0.22414427E 02  0.73579178E 04  0.29314190E 04  0.20742384E 01  0.39264564E 08  0.33444888E 04  0.10069432E 01
L1..75029610E-01

P1=.32025871E-00

US1=.85804500E 04

MS1=.75801096E 01

DT=.73562634E-03

L8/DTR=.21504901E 06



SAMPLE INPUT SHOT TWO   UNSTEADY EXPANSION  (INPUT S/R,P/PA)

S/R=0.26620000E 02

INPUT
        T1              H1             A6A/A6             RHOA               PA                 R             SPEED REF
 0.29600000E 03  0.31997999E 07  0.09999999E 01  0.09999999E 01  0.09999999E 01  0.30917000E 04  0.10873999E 04

6-A CONDITIONS
        P               U               T                RHO                H                 A                Z
 0.90000000E 00  0.80200000E 04  0.62182069E 03  0.39493404E-00  0.67900911E 07  0.16260885E 04  0.10003126E 01
6-CONDITIONS
        P               U               T                RHO                H                 A                Z
 0.90006664E 00  0.80199999E 04  0.62184337E 03  0.39493404E-00  0.67901570E 07  0.16261183E 04  0.10003123E 01
2-CONDITIONS
        P               U               T                RHO                H                 A                Z
 0.14919058E 02  0.39505739E 04  0.12788315E 04  0.31728404E 01  0.14795274E 08  0.23004521E 04  0.10043706E 01
L1..54458258E 00

P1=.67210025E 00

US1=.49104284E 04

MS1=.43379525E 01

DT=.28719155E-03

L8/DTR=.31534562E 05
```

TABLE III-4
FORTRAN LISTING

```
$ID    LOPER   IBJOB      UNSTEADY EXPANSION
$JOBOPPMAP,LOGIC
$IBMAP UNITS
       ENTRY    .UNIO.
.UNIO. PZE      UNIT10
UNIT10 FILE     ,B(1),READY,INOUT,BLK=256,LOW,BIN
       END
$IBFTC MAINP    M94,XR7
C      FORTRAN 4 UNSTEADY EXPANSION PROGRAM
C      SUBROUTINES REQUIRED ARE GAUSS,ATP,SLOW,INTRP
       DIMENSION Z(7),B(16),W(16)
       COMMON IMFT
       CALL GAUSS (B,W)
       RHOA= 1.
       PA= 1.
       PAA= 14.695
       R= 3091.7
       ASPED= 1087.4
       GAMA= 1.4
       TA= 273.15
       CP1= 10810.135
C
C      TAPE ORDER FOR CONSTANT S/R
C1     J               ,NUMBER OF POINTS FOR THIS S/R
C2     T               ,TEMPERATURE
C3     ALOG(RHO/RHOA)
C4     ALOG(P/PA)
C5     ALOG(H/R)
C6     GAME            ,GAMMA SUB E
C7     A/AA             A/(A SUB A )
C8     Z
C9     H/RT
C10    Z*               Z STAR
C
     5 FORMAT(72H
      1                                                                    )
    16 FORMAT(  6H0 S/R=E14.8//7H0 INPUT/114H              T1                 H1
      1           A6A/A6              RHOA              PA                R
      2         SPEED REF         /1H 7E16.8 //17H0 6-A CONDITIONS  /114H
      3       P                 U                 T                 RHO
      4     H                 A                 Z                 /1H 7E16.8/)


    25 FORMAT (15H0 6-CONDITIONS  /114H          P                 U
      1         T                 RHO               H                 A
      2       Z                 /1H 7E16.8/ )
    64 FORMAT (15H0 2-CONDITIONS  /114H          P                 U
      1         T                 RHO               H                 A
      2       Z                 /1H 7E16.8/ )
    91 FORMAT(5H0 L1,E13.8/5H0 P1=E13.8/6H0 US1=E13.8/6H0 MS1=E13.8/5H0 O
      1T=E13.8/9H0 L8/OTR=E12.8 )
C      JIN1= INPUT DATA TAPE
       JIN1=5
C      JIN2= INPUT GAS PROPERTY TAPE
       JIN2=10
C      JOUT= OUTPUT DATA TAPE (THE ONLY ONE)
       JOUT=6
       NTIME=1
     1 CONTINUF
       IMFT=0
     4 READ (JIN1,5)
       WRITE(JOUT,5)
       READ (JIN1,2) U6A,T1,A6AA,SR,P6A,ALT,MORED
     2 FORMAT(6F12.0,I2)
       H1= CP1*T1
       IF(ALT)200,10,200
   200 CALL ATP (1,2,1,2,ALT,T6A,P6A,DUM,DUM)
       PAA=P6A/PAA
       SR= 23.586 + 3.5*ALOG(T6A/TA)-ALOG(P6A/PA)
    10 NERR=0
       Z(3)= ALOG10(P6A/PA)
       CALL SLOW (SR,Z,3,1,JIN2,9,NERR )
       IF(NERR-1)11,100,11
    11 T6A=Z(1)
       CALL SLOW (SR,Z,3,2,JIN2,9,NERR )
    12 RHO6A= RHOA*10.**Z(2)
       CALL SLOW (SR,Z,3,4,JIN2,9,NERR )
    13 H6A= R*10.**Z(4)
       CALL SLOW (SR,Z,3,6,JIN2,9,NERR )
    14 A6A= ASPED*Z(6)
       CALL SLOW (SR,Z,3,7,JIN2,9,NERR )
    15 Z6A= Z(7)
       HO6A= H6A+.5*U6A*U6A
       WRITE (JOUT,16)         SR,T1,H1,A6AA,RHOA,PA,R,ASPED,P6A,U6A,T6A,
      1RHO6A,H6A,A6A,Z6A
```

TABLE III-4 (Continued)

```
      RHO6=RHO6A*A6AA
      DO 18 I=1,500
      Z(2)= ALOG10(RHO6/RHOA)
      CALL SLOW (SR,Z,2,4,JIN2,9,NERR )
      IF(NERR-1)17,100,17
   17 H6 = R*10.**Z(4)
      TEMP= SQRT(2.*(HO6A-H6))
      TEMP=  RHO6A*U6A*A6AA/TEMP
      IF(ABS((TEMP-RHO6)/TEMP)*100.-.01)20,20,18
   18 RHO6=.5*(RHO6+TEMP)
   19 PAUSE 11111
      GO TO 100
   20 CALL SLOW (SR,Z,4,1,JIN2,9,NERR )
      U6= RHO6A*U6A*A6AA/RHO6
      IF(NERR-1)21,100,21
   21 T6=Z(1)
      CALL SLOW (SR,Z,4,3,JIN2,9,NERR )
   22 P6= PA*10.**Z(3)
      CALL SLOW (SR,Z,4,6,JIN2,9,NERR )
   23 A6= ASPED*Z(6)
      CALL SLOW (SR,Z,4,7,JIN2,9,NERR )
   24 Z6=Z(7)
      WRITE(JOUT,25) P6,U6,T6,RHO6,H6,A6,Z6
      GO TO 30
C     SUBROUTINE TO COMPUTE INTEGRAL
   27 SUM=0.
      I=0
   28 I=I+1
      Z(4)= .5*(W(I)*(XU-XL)+XU+XL)
      Z(4)= ALOG10(Z(4))
      CALL SLOW (SR,Z,4,6,JIN2,9,NERR )
      IF (NERR-1)29,100,29
   29 SUM= SUM +P(I)/(  Z(6)**KCO )
      IF(I-16)28,26,26
   26 CONTINUE
      SUM= SUM*(XU-XL)*.5*ASPEO/(GAMA*TA)
      GO TO (35,76),KGO
C     THE 2-CONDITIONS
   30 XX=  .32*U6A/A6A  +(A6AA)**.26+1.
      H21= H1*(1.+.195*XX*XX)*.6
      H2=H21
```

```
      DO 50 J=1,500
      Z(4)= ALOG10(H2/R)
      CALL SLOW (SR,Z,4,2,JIN2,9,NERR )
      IF(NERR-1)31,100,31
   31 RHO2= RHOA*10.**Z(2)
      CALL SLOW (SR,Z,4,3,JIN2,9,NERR )
   32 P2= PA*10.**Z(3)
      BB= (2.*RHO2*(H2-H1)/(R*T1))+RHO2 -P2*TA/T1
      CC= -P2*RHO2*TA/T1
      RHO1= .5*(-BB+SQRT(BB*BB-4.*CC))
      US1= SQRT(2.*(H2-H1)/(1.-RHO1*RHO1/(RHO2*RHO2)))
      P1=RHO1*T1/TA
      U22= US1*(1.-RHO1/RHO2)
      XU= H2/R
      XL= H6/R
      KGO=1
      GO TO 27
   35 U21= UA-SUM
      IF(J-1)40,36,40
   36 FX1= U21-U22
      H22= 1.1*H21
      GO TO 49
   40 FX2= U21-U22
      RATIO=(1.-H21/H22)/(1.-FX1/FX2)
      H23= H22*(1.-RATIO)
      IF(ABS((H23-H22)/H23)*100.-.01)60,60,45
   45 FX1=FX2
      H21=H22
      H22=H23
   49 H2= H22
   50 CONTINUE
      PAUSE 22222
      GO TO 100
   60 Z(4)= ALOG10(H23/R)
      CALL SLOW (SR,Z,4,1,JIN2,9,NERR )
      IF(NERR-1)61,100,61
   61 T2=Z(1)
      CALL SLOW (SR,Z,4,6,JIN2,9,NERR )
   62 A2=ASPED*Z(6)
      CALL SLOW (SR,Z,4,7,JIN2,9,NERR )
   63 Z2=Z(7)
      U2=U21
```

TABLE III-4 (Continued)

```
      WRITE(JOUT,64) P2,U2,T2,RHO2,H2,A2,Z2
C     CHARACTERISTIC LENGTH
   70 DELT= (US1-U2)/(A2*US1)
      Y= DELT
      XU= H2/R
      XL= H6/R
      KGO=2
      GO TO 27
   76 Y=Y*SQRT(A2/A6)*EXP(.5*SUM/ASPED)
      XL1=1./((U6-A6)*Y)
      XMS1= US1*SQRT(TA/T1)/ASPED
      XLBDT= U6*(U6-A6)/A5
      WRITE (JOUT,91)XL1,P1,US1,XMS1,Y,XLBDT
  100 CONTINUE
      IF(MORED)101,4,101
  101 RETURN
      END
$IBFTC ATP      M94,XR7
C     SUBROUTINE ATP - ALTITUDE TEMP AND PRESS  (01055/RAMSAY)          01055
      SUBROUTINE ATP(ITEST,JTEST,KTEST,LTEST,A,TA,PA,DA,CSA)
      DIMENSION HB(22),TMB(22),ELM(22),PB(22),EMB(22)
      DATA(HB(I),I=1,22)/0.,11000.,20000.,32000.,47000.,52000.,61000.,
     179000.,88743.,98451.,108129.,117776.,146541.,156071.,165571.,
     2184485.,221967.,286476.,376312.,463526.,548230.,630530./
      DATA(TMB(I),I=1,22)/288.15,216.65,216.65,228.65,270.65,270.65,
     1252.65,180.65,180.65,210.65,260.65,360.65,960.65,1110.65,1210.65,
     21350.65,1550.65,1830.65,2160.65,2420.65,2590.65,2700.65/
      DATA(ELM(I),I=1,22)/-.0065,0.,.001,.0028,0.,-.002,-.004,0.,
     1.00309023,.00516636,.01036592,.02085668,.01573977,.01052632,
     2.00740192,.00533589,.00434048,.00367336,.00298117,.00200699,
     3.00133657,.00133657/
      DATA(PB(I),I=1,22)/1013.25,226.32,54.7487,8.68014,1.10905,.590005,
     1.182799,.0103777,1.6438E-03,3.0075E-04,7.3544E-05,2.5217E-05,
     25.0617E-06,3.6943E-06,2.7926E-06,1.6852E-06,6.9604E-07,1.8838E-07,
     34.0304E-08,1.0957E-08,3.4502E-09,1.1918E-09/
      DATA(EMB(I),I=1,22)/28.9644,28.9644,28.9644,28.9644,28.9644,
     128.9644,28.9644,28.9644,28.9644,28.88,28.56,28.07,26.92,26.66,
     226.4,25.85,24.7,22.66,19.94,17.94,16.84,16.17/
      FAC1 = 0.72129
      FAC2 = 0.4788 2
      FAC3 = 1545.31
      FAC5 = 2781.558
      AR = 8314.32
      G = 9.80665
      FMO = 28.9644
      RE = 6356766.0
      IF(ITEST)217,216,217
  216 P1=PA*FAC2
      IF(KTEST-1 )218,218,219
  218 P1=P1*144.
  219 DO 220 I=2,22
      IF(PB(I)-P1)222,221,220
  220 CONTINUE
  221 H=HB(I)
      GO TO 223
  222 IF(ELM(I-1))235,236,235
  235 H=HB(I-1)+(TMB(I-1)/ELM(I-1))*((P1/PB(I-1))**((-AR*ELM(I-1))/
     1(G*FMO))-1.)
      GO TO 223
  236 PFAC=P1/PB(I-1)
      H=HB(I-1)-(AR*TMB(I-1)*ALOC(PFAC))/(G*FMO)
  223 Z=(RE*H)/(RE-H)
  225 A=Z/.3048
      GO TO 202
  217 Z=A*.3048
  200 H=(RE*Z)/(RE+Z)
  202 DO 100 J=2,22
      IF(H-HB(J))101,102,100
  100 CONTINUE
  101 J=J-1
  102 TA=TMB(J)+ELM(J)*(H-HB(J))
      IF(J-22)231,230,230
  230 EM=EMB(22)
      GO TO 232
  231 EM=EMB(J)-(EMB(J)-EMB(J+1))*((H-HB(J))/(HB(J+1)-HB(J)))
  232 TA=(EM/EMO)*TA
      CSA=FAC1*SORT (AR*TA)
      IF(ELM(J))103,104,103
  103 P=PB(J)*(TMB(J)/(TMB(J)+ELM(J)*(H-HB(J))))**((G*FMO)/(AR*ELM(J)))
      GO TO 105
  104 P=PB(J)*EXP ((-(G*FMO)*(H-HB( [illegible] AR*TMB(J)))
  105 GO TO (106,107),JTEST
  106 TA=1.8*TA
```

TABLE III-4 (Continued)

```
  107 IF(ITEST)210,210,215
  215 GO TO (108,109),KTEST
  108 PA=P*.014503766
      GO TO 210
  109 PA=P*2.0885438
  210 IF(JTEST-1 )211,211,212
  211 FAC35=FAC3
      GO TO 213
  212 FAC35=FAC5
  213 DA=(FM /FAC35)*(P*2.0885438/TA)
      GO TO (110,214,315),LTEST
  315 FAC2=0.
      AR=0.
      Q=0.
      FMO=0.
      RF=0.
      FAC1=0.
      FAC3=0.
      FAC5=0.
  214 DA=DA/32.174049
  110 RETURN
      END
$IBFTC SLOW     M94,XR7
      SUBROUTINE SLOW (XX,Z,I1,J1,IT,NV,NERR )
C     TAPE IS WRITTEN WITH LINES OF CONSTANT XX
C     Z(I1) AND XX ARE INDEPENDENT VARIABLES
C     Z(J1) IS THE DEPENDENT VARIABLE
C     AK= +1. IF XX INCREASES MONOTONICALLY ON TAPE
C     AK= -1. IF XX DECREASES MONOTONICALLY ON TAPE
C     IT= TAPE UNIT
C     NV= NO. OF VARIABLES ON TAPE FOR EACH XX .(NOT GREATER THAN 9)
C     NO. OF POINTS FOR EACH XX NOT GREATER THAN 150
C     BEGIN EXECUTION
      DIMENSION X(4),Y(4,9,150),Z(9),U(4),V(4),W(4),NP(4)
      COMMON IMET(20)
      IF(IMET(1)) 7,1,7
    1 BACK SPACE IT
      READ(IT) DUM
      REWIND IT
      DO 2 K=1,3
      READ(IT) X(K),J,((Y(K,I,L),I=1,NV),L=1,J )
    2 NP(K)=J
      XW=X(2)-X(1)
      AK= ABS(XW)/XW
      DIR1=1.
      IMET(1)=1
      XXX=XX
      NERR=0
      IM=3
      GO TO 70
    7 NERR=0
C     EXCEPT FOR FIRST TIME THROUGH
      IF((XX-X(M1))*(XX-X(M2)))100,100,10
   10 TEMP=(XX-XXX)*AK
      DIR2= ABS(TEMP)/TEMP
      GO= DIR1*DIR2
      XXX=XX
      DIR1=DIR2
      IF(DIR2)20,8,50
C
C     NEGATIVE DIRECTION
   20 IF(GO)30,8,40
   30 BACK SPACE IT
      BACK SPACE IT
      BACK SPACE IT
      GO TO 402
   40 IM=IM-1
      IF(IM  )401,401,402
  401 IM=4
  402 M1=IM+1
      BACK SPACE IT
      BACK SPACE IT
      IF(M1-4)404,404,403
  403 M1=1
  404 M2=M1+1
      IF(M2-4)406,406,405
  405 M2=1
  406 READ(IT) X(IM),J,((Y(IM,I,L),I=1,NV),L=1,J )
      NP(IM)=J
      IF((XX-X(M1))*(XX-X(M2)))100,100,42
   42 IF(X(M1)-X(M2))40,43,40
C     ERROR. VARIABLE OFF FRONT END OF TAPE
   43 CONTINUE
```

TABLE III-4 (Continued)

```
      NERR=1
      GO TO 200
C
C     POSITIVE DIRECTION
   50 IF(GO)60,8,70
   60 READ(IT) DUM
      READ(IT) DUM
      READ(IT) DUM
      GO TO 702
   70 IM=IM+1
      IF(IM-4)702,702,701
  701 IM=1
  702 M1=IM-1
      IF(M1)703,703,704
  703 M1=4
  704 M2=M1-1
      IF(M2)705,705,706
  705 M2=4
  706 READ(IT) X(IM),J,((Y(IM,I,L),I=1,NV),L=1,J )
      NP(IM)=J
      IF((XX-X(M1))*(XX-X(M2)))100,100,70
C
C     TAPE SEARCH COMPLETE , DO CROSS FOUR POINT
  100 DO 150 K=1,4
      NPK=NP(K)-1
      DO 115 I=1,NPK
      IF((Y(K,J1,I)-Z(J1))*(Y(K,J1,I+1)-Z(J1)))125,125,115
  115 CONTINUE
      NERR=1
      GO TO 200
  125 IF(I-1)127,126,127
  126 J=0
      GO TO 137
  127 IF(I-NPK)136,135,136
  135 J=NPK-3
      GO TO 137
  136 J=I-2
  137 DO 140 L=1,4
      MX=L+J
      U(L)= Y(K,I1,MX)
  140 V(L)= Y(K,J1,MX)




  150 CALL INTRP (4,U,V,Z(I1),W(K))
      CALL INTRP (4,X,W,XX,Z(J1))
  175 RETURN
    8 CONTINUE
  200 NERR=1
      IF(IMET(2))215,201,215
  201 IMET(2)=1
      DO 210 IM=1,4
      WRITE(6,202)X(IM)
  202 FORMAT(1H1E16.8)
  203 FORMAT(1H 7E16.8)
      NXXXX=NP(IM)
  210 WRITE(6,203)((Y(IM,I,L),I=1,NV),L=1,NXXXX)
  215 RETURN
      END
$IBFTC GAUSS   M94,XR7
      SUBROUTINE GAUSS (B,X)
C     GAUSS CONTAINS EIGHT PLACE,SIXTEEN POINT INTEGRATION CONSTANTS
      DIMENSION B(16),X(16)
      X(1)=.09501251D
      X(2)=.28160355
      X(3)=.45801678
      X(4)=.61787624
      X(5)=.75540441
      X(6)=.86563120
      X(7)=.94457502
      X(8)=.98940093
      B(1)=.18945061
      B(2)=.18260342
      B(3)=.16915652
      B(4)=.14959599
      B(5)=.12462897
      B(6)=.095158512
      B(7)=.062253524
      B(8)=.027152459
      DO 12345 I=9,16
      J=17-I
      X(I)=-X(J)
12345 B(I)= B(J)
      RETURN
      END
$IBFTC INTRP   M94,XR7
```

TABLE III-4 (Concluded)

```
C     THIS IS AN N-POINT LAGRANGE INTERPOLATION SUBROUTINE (N.GT.1)
      SUBROUTINE INTRP (N,X,Y,XINT,YINT )
      DIMENSION X(1),Y(1)
      YINT=0.
      DO 202 I=1,N
      SUMN=1.
      SUMD=1.
      DO 201 J=1,N
      IF(J-I) 200,201,200
  200 SUMN=SUMN*(XINT-X(J))
      SUMD=SUMD*(X(I)-X(J))
  201 CONTINUE
  202 YINT=YINT+Y(I)*SUMN/SUMD
      RETURN
      END
```

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1 ORIGINATING ACTIVITY (Corporate author) Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	2a REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP N/A

3 REPORT TITLE
A THEORETICAL REAL-GAS ANALYSIS OF THE EXPANSION TUNNEL

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
N/A

5 AUTHOR(S) (Last name, first name, initial)
Norfleet, Glenn D. and Loper, F. C., ARO, Inc.

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11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13 ABSTRACT

A theoretical real-gas analysis of the expansion tunnel is presented. A digital computer program, developed for this investigation, is discussed, and Fortran listings and flow charts are included. Tunnel performance, test gas slug length, and "working" parameters are given for several expansion area ratios. Driver temperature and energy requirements are given for specific cases.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
expansion tunnels real-gas analysis performance analysis test gas slug lengths design parameters						

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