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GRADUATE ENGINEERING PRACTICE

IN MECHANICAL ENGINEERING

Final Report--Part III of III

SPACE SHUTTLE SEPARATION METHODS

Contract No. NAS9-10464

Louisiana State University
Mechanical, Aerospace & Industrial Engineering Department
Baton Rouge, Louisiana 70803

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MECHANICAL, AEROSPACE & INDUSTRIAL
ENGINEERING DEPARTMENT

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Manned Spacecraft Center
Houston, Texas 77058

ATTENTION: EX23/Charles Teixeira

SUBJECT: Contract NAS9-10464, Final Report--
Part III of III

Enclosed is the Final Report--Part III, "Space Shuttle Separation Techniques" by Jerry Rubli. The work was performed under contract NAS9-10464. Any questions may be forwarded to the program director.

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Enclosure

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FOREWARD

This report presents the results of work performed by Mr. Jerry J. Rubli at Louisiana State University under contract NAS9-10464. This is the final report for the work done on the separation of the booster and orbiter under the Graduate Engineering-Practice in Mechanical Engineering program and it covers the analysis performed during 1970. The faculty advisor was Dr. Mehdy Sabbaghian and the program director was Dr. L. R. Daniel, Jr. Associate Directors were Mr. Charles Teixeira (NASA-MSC) and Dr. R. W. Courter. The principal advisor was Dr. P. H. Miller.

SUMMARY

The analysis of the weight for four separational methods is presented. The computer program listing and results, which prove that it is feasible to design a pyrotechnic ram are enclosed. Finally, the energy versus weight curves for the four different techniques studied are presented.

LIST OF FIGURES

NOMENCLATURE

A	area, in^2
b	distance between the booster and orbiter center of gravities, ft.
C	isentropic pressure decay constant
C_p	constant pressure specific heat, BTU/lbm^{o}R
C_v	constant volume specific heat, BTU/lbm^{o}R
D	helical spring mean diameter, in.
d	helical spring wire diameter, in.
E	energy, ft-lbf
F	force, lbf
G	shear modulus, lbf/in^2
g	acceleration of gravity, 32.17 ft/s^2
g_c	gravitational constant, 32.17 lbm-ft/lbf-s^2
h	enthalpy, BTU/lbm
I_b	rotational inertia of the booster, lbm-ft^2
I_{sp}	specific impulse, lbf-s/lbm
I'_{sp}	theoretical specific impulse, lbf-s/lbm
I_{tot}	total impulse on booster, lbf-s
k	specific heat ratio
$\bar{m}$	molecular weight, lbm/lb mole
m_b	mass of the booster, lbm

m_o	mass of the orbiter, lbm
m	mass, lbm
n	number of spring coils
R	universal gas constant for a specific gas, ft-lbf/lbm^{o}R
$\bar{R}$	1545 ft-lbf/lb mole ^{o}R
R_{mf}	mass fraction
S_s	maximum yield strength for a helical compression spring, lbf
T	temperature, ^{o}R
t	time, sec.
u	internal energy, BTU/lbm
Vel	gas velocity, in/s
Vol	volume, in^3
v	specific volume, in^3/lbm
W	weight, lbf
X	relative separational displacement, ft
$\dot{X}$	relative separational velocity, ft/s
$\ddot{X}$	relative separational acceleration, ft/s^2
γ	specific weight, lbf/in^2
δ	spring deflection, ft
θ_b	booster rotation displacement, rad.
$\dot{\theta}_b$	booster rotational velocity, rad/s
$\ddot{\theta}_b$	booster rotational acceleration, rad/s^2

ρ	density, lbm/in^3
c.v.	control volume
M.S.C.	Manned Spacecraft Center

CHAPTER I

INTRODUCTION

Stage separation for space vehicles usually involves stages whose longitudinal axes are coaxial. The space shuttle envisioned by the NASA-Manned Spacecraft Center (MSC) in Houston, Texas, will involve two stages whose longitudinal axes will be parallel, but not coaxial.

The space shuttle is a reuseable, two stage, manned space ship. Some of the possible missions of the space shuttle include carrying men and supplies to an orbiting space station, satellite maintenance, and space rescue. The first stage of the shuttle, called the booster, will have a mass of 321,000 lbm at separation and will be 203 feet in length. The second stage of the shuttle, called the orbiter, will have a mass of 450,000 lbm at separation and will have an overall length of 123 feet. Both vehicles will have the ability to land at a conventional airport following mission completion. The orbiter is attached to the booster in a "piggyback" arrangement such that the center of gravity of the orbiter is forward of the center of gravity of the booster. The shuttle is launched in a verticle attitude with the booster engines supplying the thrust. The booster stage engines are operated at full thrust level from lift off until a longitudinal acceleration of 2.5 g's is obtained. The engines are then throttled to maintain the acceleration at a 2.5 g level.

Planned booster/orbiter separation occurs at 267,000 feet, at which time the shuttle will have obtained a velocity of Mach 11 and the dynamic pressure will be 1 lb/ft^2. Emergency abort before the shuttle has attained an altitude of 130,000 feet is nearly impossible. From 130,000 feet to 230,000 an abort at separation followed by down range land recovery is possible. At and above 230,000 feet abort to orbit is possible.

Since the overall weight of the shuttle influences the magnitude of the payload weight and the operational feasibility of the entire shuttle concept, the weight required for each separation technique is regarded as the main criterion in the selection of the separation method to be employed at staging.

As the translational velocity due to separation has not yet been specified, the energy required for separation is not known. Therefore, a logical approach to be followed involves determining the equation which relates hardware weight and its energy delivery capability. One difficulty which does arise, however, is the fact that this functional relationship can sometimes be expressed only implicitly.

The purpose of this analysis is to graphically express the energy capability versus hardware weight for the four separation techniques.

These techniques include:

1. separation rockets
2. spring loaded ram
3. non-ignitable gas ejectors
4. pyrotechnic ram

CHAPTER II

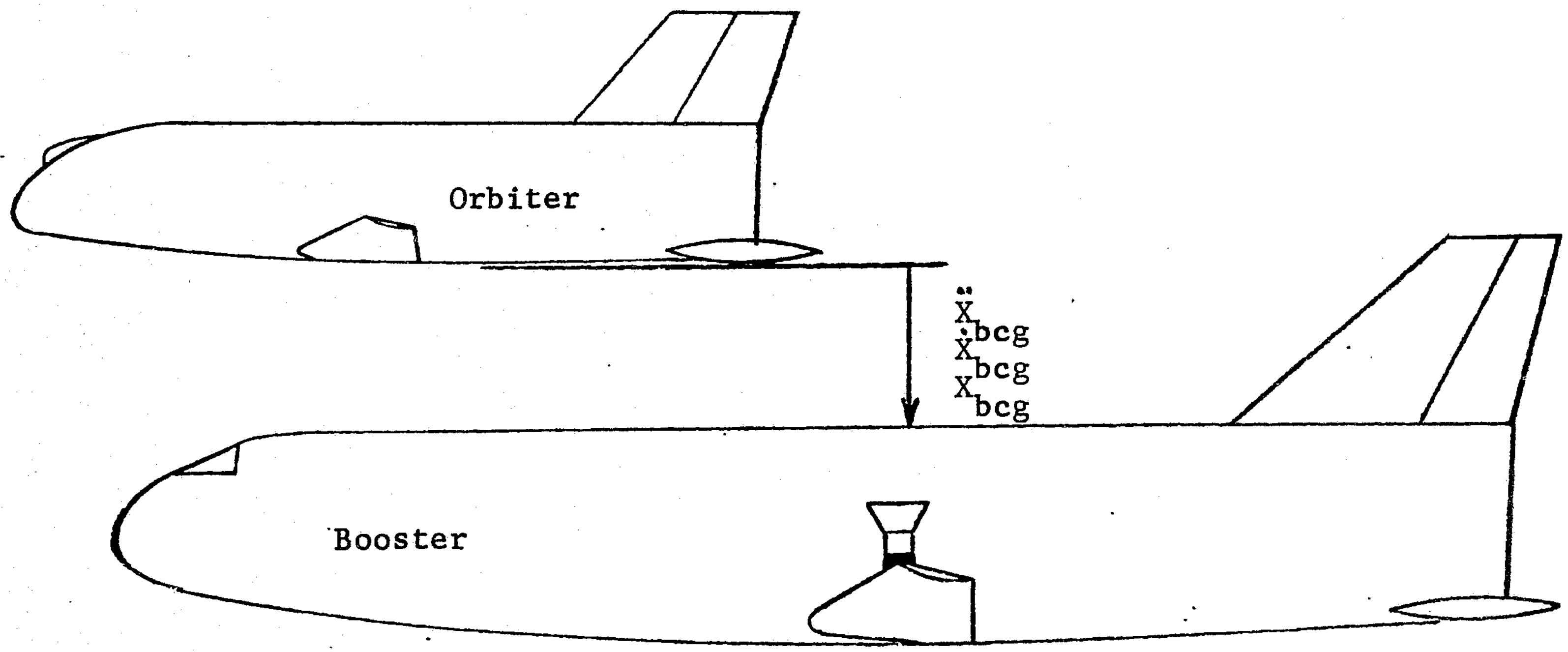
SEPARATION ROCKETS

The assumptions made are the following:

1. 2 rockets are located on the booster only, and the resultant force acts through its center of gravity.
2. The rocket thrust is instantaneously developed, remains constant, and is instantaneously stopped.
3. "State of the art" upper and lower values of the vacuum specific impulse for the propellant, I_{sp}, are 300 and 275 lbf-sec/lbm, respectively, (according to NASA personnel).
4. The range of values for the mass fraction R_{mf}, is from .85 to .90. The mass fraction is defined as the mass of the propellant divided by the total rocket mass.

Referring to Figure (II-1), the following dynamical relations govern the relative motion between the booster and orbiter during the operation interval.

$$\ddot{X}_{bcg} = \frac{F_b}{m_b} g_c \qquad \text{(II-1)}$$



ROCKET SEPARATION TERMINOLOGY

FIGURE II-1

$$\dot{X}_{bcg} = \frac{g_c}{m_b} \int F_b \, dt + c_1 \tag{II-2}$$

$$X_{bcg} = \int \left[\frac{g_c}{m_b} \int F_b \, dt + c_1 \right] dt + c_2 \tag{II-3}$$

where

c_1 and c_2 are integration constants

Since the force F_b is constant with time we can integrate Equations (II-1), (II-2), (II-3) from the initiation of separation until separation has been completed in order to obtain the final acceleration, velocity, and displacement

$$\ddot{X}_f = \frac{F_b}{m_b} g_c \tag{II-4}$$

$$\dot{X}_f = \frac{F_b t_f}{m_b} g_c \tag{II-5}$$

$$X_f = \frac{F_b t_f^2}{2m_b} g_c \tag{II-6}$$

The energy delivered to the booster/orbiter system is given as

$$E = \int F_b \, dx + c \qquad \text{(II-7)}$$

where

c is an integration constant.

Since F_b is not a function of displacement, one can evaluate Equation (II-7) from the beginning of separation until the final displacement is obtained. This provides

$$E = F_b X_f \qquad \text{(II-8)}$$

Substituting from Equation (II-6) into (II-8) yields

$$E = \frac{F_b^{\,2} \, t_f^{\,2}}{2m_b} \; g_c \qquad \text{(II-9)}$$

After rearrangement the above equation becomes

$$F_b t_f = \sqrt{\frac{2m_b \, E}{g_c}} \qquad \text{(II-10)}$$

The total impulse on the booster is defined as the product of the thrust acting on the booster and the time during which it acts on the booster. This may be expressed as

$$I_{tot} = F_b t_f \tag{II-11}$$

Since the product of the specific impulse and the rocket fuel mass is the impulse capability of one rocket engine, the total impulse capability of both rocket engines is

$$I_{tot} = 2\, I_{sp}\, m_{fuel} \tag{II-12}$$

Using Equations (II-10) and (II-11) the total impulse may be expressed as

$$I_{tot} = \sqrt{\frac{2m_b\ E}{g_c}} \tag{II-13}$$

Substituting this into Equation (II-12) and solving for m_{fuel} gives

$$m_{fuel} = \frac{\sqrt{\dfrac{2m_b\ E}{g_c}}}{2\ I_{sp}} \tag{II-14}$$

From the definition of R_{mf} as defined in assumption 4 at the beginning of this chapter, it can be shown that

$$m_{rocket} = \frac{m_{fuel}}{R_{mf}} \tag{II-15}$$

Substituting into Equation (II-15) the expression for m_{fuel} from Equation (II-14) yields

$$m_{rocket} = \frac{\sqrt{\dfrac{2m_b E}{g_c}}}{2I_{sp}R_{mf}} \tag{II-16}$$

Equation (II-16) indicates that the total rocket mass for a constant thrust engine is a function of the mass of the booster, the energy imparted to the booster, the specific impulse of the fuel, and the mass fraction. If it is desired to obtain the mass of tandem engines simply multiply by two to obtain

$$m_{2rockets} = \frac{\sqrt{\dfrac{2m_b E}{g_c}}}{I_{sp}R_{mf}} \tag{II-17}$$

In the English Engineering system of units

$$(\text{Force in lbf}) = (\text{mass in lbm}) \frac{g}{g_c} \tag{II-18}$$

Therefore,

$$W_{2rockets} = m_{2rockets} \frac{g}{g_c} \tag{II-19}$$

Substituting for $m_{2rockets}$ from Equation (II-17) into Equation (II-19) leaves

$$W_{2rockets} = \frac{\sqrt{\dfrac{2m_b E}{g_c}}}{I_{sp} R_{mf}} \frac{g}{g_c} \tag{II-20}$$

By using the lower values for the mass fraction, R_{mf}, and the specific impulse, I_{sp}, one can plot weight versus energy to obtain a lower bound for heavier and relatively inefficient rockets for the rocket engine design. Employing maximum values of these parameters will provide the upper bound for the lighter and more efficient engines. These curves are plotted in Figures (VI-1) and (VI-2).

CHAPTER III

SPRING LOADED RAM

The location of the spring loaded ram would be directly below the c.g. of the orbiter but forward of the booster c.g. The approach taken in the analysis of the required weight for this technique is to determine the relationship between weight and energy for the helical compression spring only. Since it will be demonstrated that the weight of the spring alone is excessive, the spring loaded ram hardware need not be considered.

The assumptions made in the analysis of the spring loaded ram technique are as follows:

1. A single spring device is located on the booster structure.
2. The spring is a helical spring. This assumption was made because for a helical spring the spring constant is constant. This will result in a much smaller initial force relative to final force than would be the case for a variable spring constant. NASA personnel have advised that the initial force relative to final force should be as small as is possible.

According to Reference (1), the deflection of a helical compression spring is given by

$$\delta = \frac{8Fc^3n}{Gd} \frac{1}{12} \qquad \text{(III-1)}$$

The elastic energy stored in a spring is

$$E = \frac{F\delta}{2} \qquad \text{(III-2)}$$

Substituting for δ from Equation (III-1) and solving for F results in

$$F = \sqrt{\frac{2EGd\ 12}{8c^3 n}} \qquad \text{(III-3)}$$

The maximum stress induced in a spring of this type is given by

$$S_s = \frac{8KFc}{\pi d^2} \qquad \text{(III-4)}$$

where

S_s = maximum shear stress lbf/in^2

K = Wahl factor = $\left[\frac{4c - 1}{4c - 4} + \frac{0.615}{c}\right]$

$c = \frac{D}{d}$

Replacing F by the expression given in Equation (III-3) yields

$$S_s = \frac{8K\sqrt{\frac{2EGd\ 12}{8cn}}}{\pi d^2} = \frac{4K}{\pi}\sqrt{EG\frac{12}{cd^3 n}} \qquad \text{(III-5)}$$

or

$$\left[cd^3n\right] = 192\ GE \left(\frac{K}{\pi S_s}\right)^2 \tag{III-6}$$

The weight of a helical spring is

$$W_{spring} = \gamma \frac{\pi d^2}{4} (\pi D)n \tag{III-7}$$

Substituting for D = cd in the above equation results in

$$W_{spring} = \frac{\gamma\pi^2}{4} \left[cd^3n\right] \tag{III-8}$$

From Equations (III-6) and (III-8) one would obtain

$$W_{spring} = \frac{48\gamma G}{S_s^2} K^2 E \tag{III-9}$$

Since it is desired to get the lightest spring possible, one needs to select the minimum values for K and $\gamma G/S_s^2$. As c becomes large, K approaches 1 asympototically. Therefore, K = 1 is used as an upper limit since no spring could be designed which would be lighter than one corresponding to this condition.

In order to minimize ($\gamma G/S_s^2$), one may notice that for most spring steels, γ = .285 lbf/in^3 . Also, G = 10.5 x 10^6 lbf/in^2 for hot wound springs and G = 11.5 x 10^6 lbf/in^2 for most cold drawn springs. The maximum allowable value for S_s is shown in Figure

(III-1) to be equal to 130,000 psi at d = .5 in. The spring material is hot wound SAE 6150 or SAE 9260. Using these values and a safety factor of 1.5 in Equation (III-9) yields

$$W_{spring} = \frac{48\left(.285\ \frac{lbf}{in^3}\right)\left(10.5 \times 10^6\ \frac{lbf}{in^2}\right)(1)^2(1.5)^2 E}{(130{,}000)^2\ \frac{lbf^2}{in^4}} \qquad \text{(III-10)}$$

Performing the indicated operations in Equation (III-10) leaves

$$W_{spring} = .0191\ E \qquad \text{(III-11)}$$

Equation (III-10) is the desired relation between energy capability and the design weight. As can be seen in Figure (VI-1), the excessive weight of the spring alone rules out the necessity for designing the hardware required to retain the spring.

Compression Springs
Maximum Allowable Stress

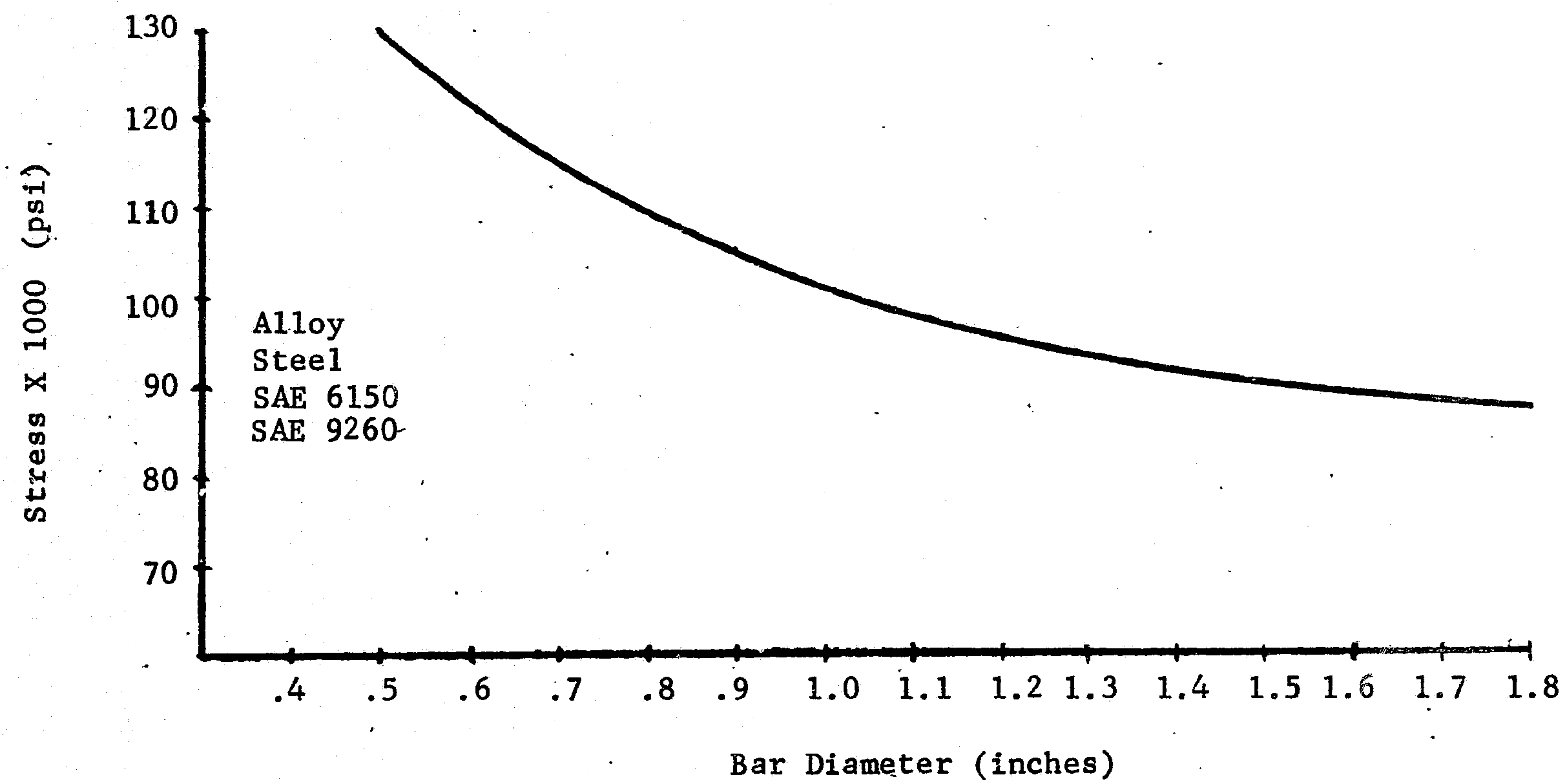


FIGURE III-1

CHAPTER IV

GAS EJECTOR

This device utilizes the thrust provided by the high speed ejection of a non-ignitable gas. Therefore, there is no impingement of high temperature gases on the orbiter. Because a one pound increase in the weight of the orbiter results in an overall shuttle weight increase of six pounds, it is more feasible to locate this device on the booster. Since a minimum of booster angular motion is desired at separation it is practical to locate the separational thrust through the booster c.g. If two ejectors are located on the booster wings, one on either side of the fuselage, the booster will experience no rotation during separation.

In analyzing this separation technique the following assumptions are made:

1. The thrust, stagnation pressure, and stagnation temperature are constant. Since it will be later demonstrated that even a constant pressure results in excessive weight, the actual device would be unfeasible.
2. The hydrogen or oxygen gas contained in the booster fuel tanks at normal tank pressure can be used as the high speed ejector gas, depending upon which one is more feasible. This assumption eliminates the weight associated with having separate tanks for the ejector.

3. An isentropic process occurs across the ejector exit nozzle. This assumption allows the use of Equation (IV-1) for the theoretical specific impulse.

4. The gases exit at the ambient pressure at separation altitude, i.e., complete expansion. This assumption was also necessary in order that Equation (IV-1) could be utilized.

These assumptions all result in a lighter weight for the gas being ejected. Since it will be later demonstrated that this technique results in an excessive weight, use of these simplifying assumptions is valid.

According to Reference (2), the theoretical specific impulse of a gas flowing through a nozzle is given as

$$I'_{sp} = \sqrt{\frac{\bar{R}}{g_c}} \sqrt{2\left(\frac{k}{k-1}\right) \frac{T_o}{\bar{m}} \left(1 - \left(\frac{P_2}{P_0}\right)^{\frac{k-1}{k}}\right)} \qquad \text{(IV-1)}$$

where

P_0 is the stagnation pressure

P_2 is the ambient pressure

T_o is the stagnation temperature

Using this theoretical value will result in a more conservative (lighter) value for the gas weight.

Substituting for $\bar{R}$ and g_c and evaluating gives

$$I'_{sp} = (6.94) \sqrt{2\left(\frac{k}{k-1}\right) \frac{T_o}{\bar{m}} \left(1 - \left(\frac{P_2}{P_0}\right)^{\frac{k-1}{k}}\right)} \qquad \text{(IV-2)}$$

Since the largest value for the terms in the last parentheses is 1.0 for $p_2 = 0$, a higher value for the theoretical specific impulse, I'_{sp}, will result if p_2 is set equal to zero. This will have the effect of decreasing the weight of required gas. Since it will be later shown that the gas ejector concept results in an excessive weight even with this assumption, it is valid to consider $p_2 = 0$.

Since the theoretical specific impulse is defined as the impulse divided by the mass of gas producing the thrust, we can obtain the required mass of gas for one ejector by dividing the impulse of one engine by the theoretical specific impulse. Since the impulse provided by one of the two gas ejectors is one half of the total impulse acting on the booster,

$$m_{gas} = \frac{I_{tot}}{2} \frac{1}{I'_{sp}} \tag{IV-3}$$

From assumption 1, since the thrust is considered constant, Equations (II-10) and (II-11) give for this condition

$$I_{tot} = \sqrt{\frac{2m_b E}{g_c}} \tag{IV-4}$$

Substituting I_{tot} from Equation (IV-4) into Equation (IV-3) leaves

$$m_{gas} = \frac{\sqrt{\dfrac{2m_b E}{g_c}}}{2I'_{sp}} \tag{IV-5}$$

The mass of gas required for both ejectors is twice that as expressed in Equation (IV-5). It is given as

$$m_{2\ gas} = \frac{\sqrt{\dfrac{2m_b E}{g_c}}}{I'_{sp}} \tag{IV-6}$$

Substituting for I'_{sp} from Equation (IV-2) into Equation (IV-6) leaves

$$m_{2\ gas} = .144 \sqrt{\left(\frac{k-1}{k}\right) \frac{\bar{m}}{T_o} \frac{m_b}{g_c} E} \tag{IV-7}$$

In deciding whether oxygen or hydrogen should be used as the ejecting gas, the gas which gives the minimum product of $\left(\frac{k-1}{k}\right)\frac{\bar{m}}{T_o}$ will result in less gas weight required, as can be seen in Equation (IV-7). For oxygen this product is equal to 4.42×10^{-2} $\frac{lbm}{lb\ mole\ ^oR}$. For hydrogen this product is equal to 1.39×10^{-2} $\frac{lbm}{lb\ mole\ ^oR}$. Therefore, hydrogen is the more feasible of the two gases.

If in Equation (IV-5) this value of 1.39×10^{-2} $\frac{lbm}{lb\ mole\ ^oR}$ is substituted for $\frac{k-1}{k}\ \frac{\bar{m}}{T_o}$, the mass of the booster, which is equal to 321,000 lbm, is substituted for m_b, and a safety factor of 1.5 is applied, the mass of gas required to supply two high speed non-ignitable gas ejectors becomes

$$m_{2\ gas} = 2.53 \sqrt{E} \qquad \text{(IV-8)}$$

Applying Equation (II-18) to Equation (IV-18), the weight for two ejectors can be expressed as

$$W_{2\ gas} = 2.53 \sqrt{E}\ \frac{g}{g_c} \qquad \text{(IV-9)}$$

This is the desired relationship between energy and weight. This equation is graphically displayed in Figure (VI-1). Since the gas weight for this device is excessive, the other components of such a system need not be considered.

CHAPTER V

PYROTECHNIC RAM

This chapter is divided into five sections. The first section deals with the description of this device and its operation. The second section is an analysis of the dynamics and energy involved in separating the two vehicles. The third section is concerned with the thermodynamics of the ram operation. The fourth section deals with the location and size of the inlet ports. Finally, the fifth and last section presents the method used to determine the ram weight.

The pyrotechnic ram device has been designed for normal operation (separation at 267,000 feet) and its use in an abort situation may be somewhat limited due to the excessive drag forces on the orbiter which the extended ram members must support. These drag forces are the result of the dynamic pressure on the orbiter which at nominal separation is only 1 psf. Moreover, during the ram operation either both vehicles must be coasting or the relative axial velocity of the vehicles must be zero so as to minimize the beam bending effect of the ram extension.

Several constraints were placed upon the physical dimensions of the ram and its operation by personnel at MSC. Among the most important constraints were the following:

1. The output force should vary as the fourth power of the elasped time following pyrotechnic ignition, for the greater portion of the ram operation. ($F = Kt^4$)
2. The maximum force should be no greater than 100,000 lbf.
3. The operation time should be greater than 1 second, but less than 2 seconds.
4. The stroke should be between 18 and 36 inches. The necessary clearance to perform a no recontact separation is not yet known. However, the required stroke to avoid recontact between the vehicles is probably within this range, according to NASA personnel.

1. Ram Description and Operation

One of the main advantages of the pyrotechnic ram over the other separational techniques investigated is that it could most easily be used as the main component of the shuttle mating system. Since this investigation is mainly concerned with the hardware required to perform vehicle separation, an analysis of the suitability of the ram for the mating function will not be performed. However, a ram cross section sufficient to withstand 3.5 times the weight of the orbiter (2.5g), excluding drag, has been specified. This is the maximum acceleration which the shuttle will experience.

In Figure (V-1), member 1 provides the ram piston constraint. However, it alone will not resist a moment which could rotate one vehicle with respect to the other and therefore supports must be placed aft to provide this restraint. Moreover, since the shuttle is designed for a nominal 2.5 g acceleration and the ram alone, as designed, can support only 2.5g, the back supports must take all of the longitudinal load caused by the drag on the orbiter.

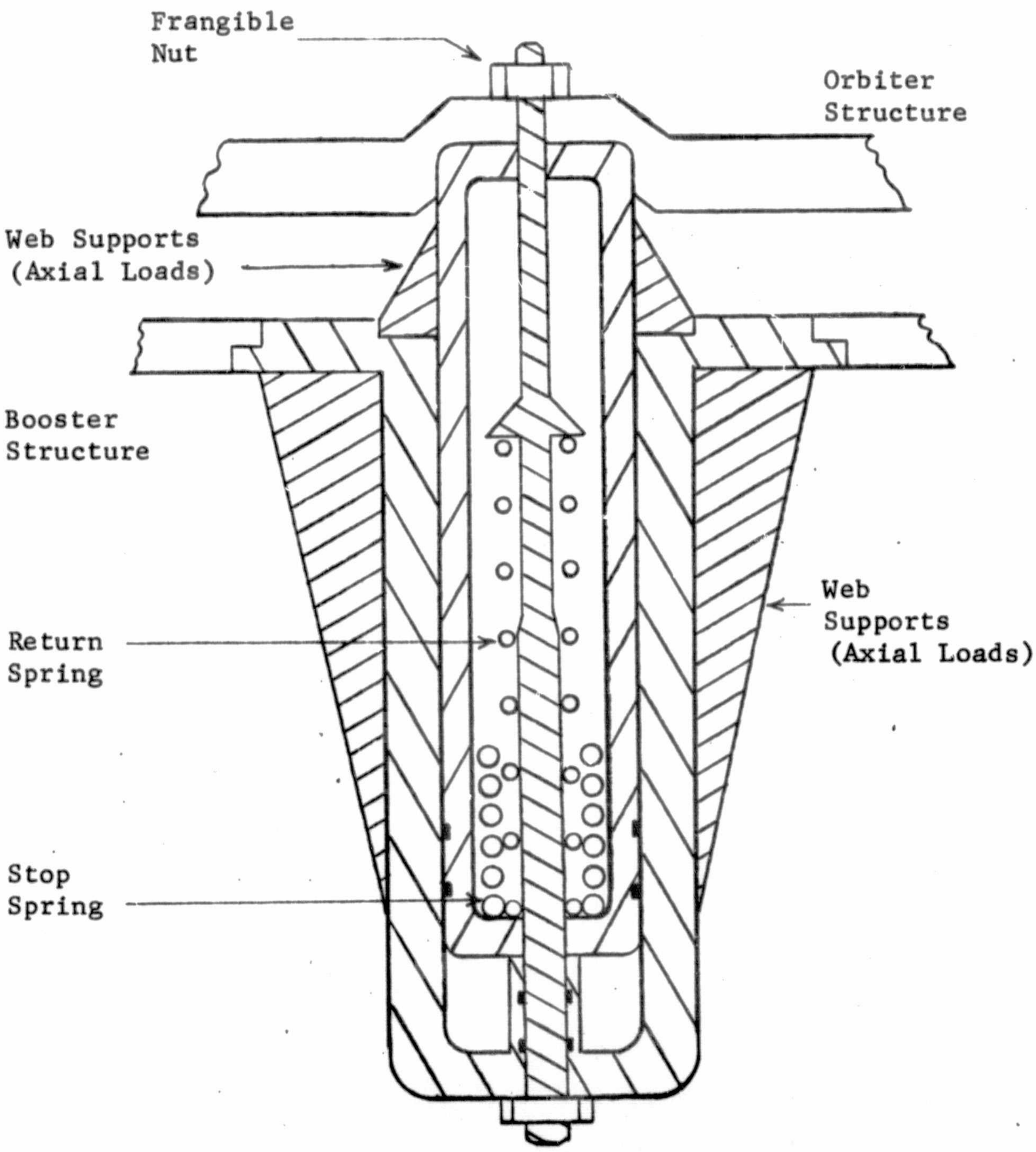
Member 2, the ram cylinder, is used to contain member 1 and it, along with the bottom section of member 1, serves as the ram chamber. The wall thickness of member 2 was determined by considering it as a pressure vessel. The maximum pressure it must withstand is equal to the output final force divided by the bottom cross section of member 1, upon which this pressure must act.

The magnitude of this pressure for the 6 inch diameter surface of member 1 is 3656 psi.

The function of member 3, the gas delivery chamber, is to serve as a manifold to deliver the high pressure gas to the ram chamber. Member 3 and member 4 comprise the stagnation chamber. This component is welded to member 2. Its wall size is determined by considering it as a pressure vessel with the initial pressure of 15,000 psi being the maximum that this member must withstand. Using this pressure will result in choked flow throughout the ram operation.

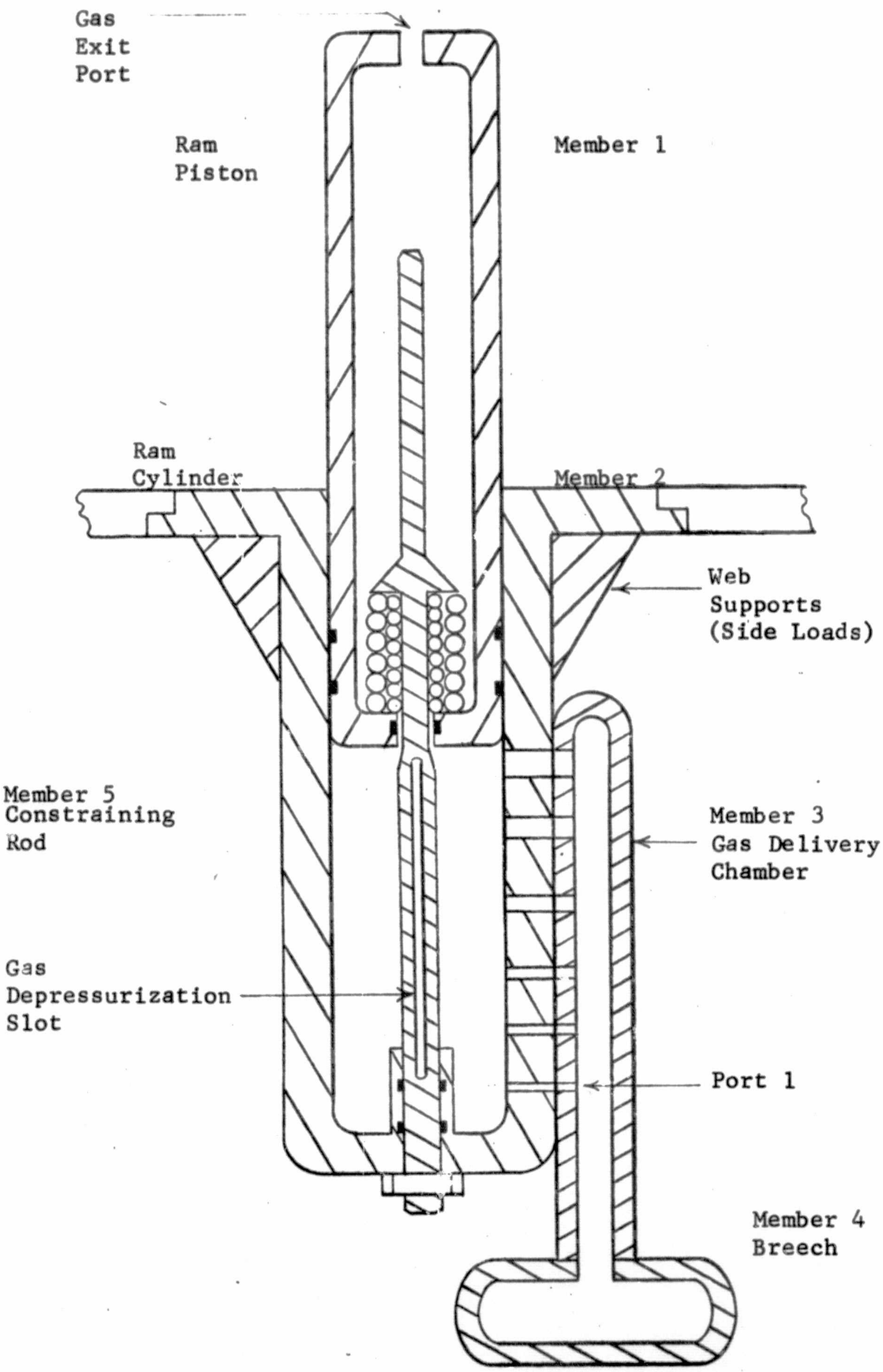
Member 4 is the breech where the pyrotechnic is ignited. The diameter and length of this vessel was determined by considering the density of the pyrotechnic before ignition.

Member 5, the constraining rod, provides upward transverse constraint for the two vehicles throughout the flight. It also stops the upward motion of member 1 and thereby concludes the ram operation. The frangible nut located on top of this member provides a reliable method of allowing the two vehicles to separate. The large spring located concentrically around member 5 is used to reduce the large tensile shock wave which this component must experience in stopping member 1. The smaller spring is used to return member 1 to its initial position following separation. The small slot and diameter reduction of member 5 are used to provide a means for gas depressurization during the ram retraction.



PYROTECHNIC RAM, SIDE VIEW, MATED POSITION

FIGURE V-1

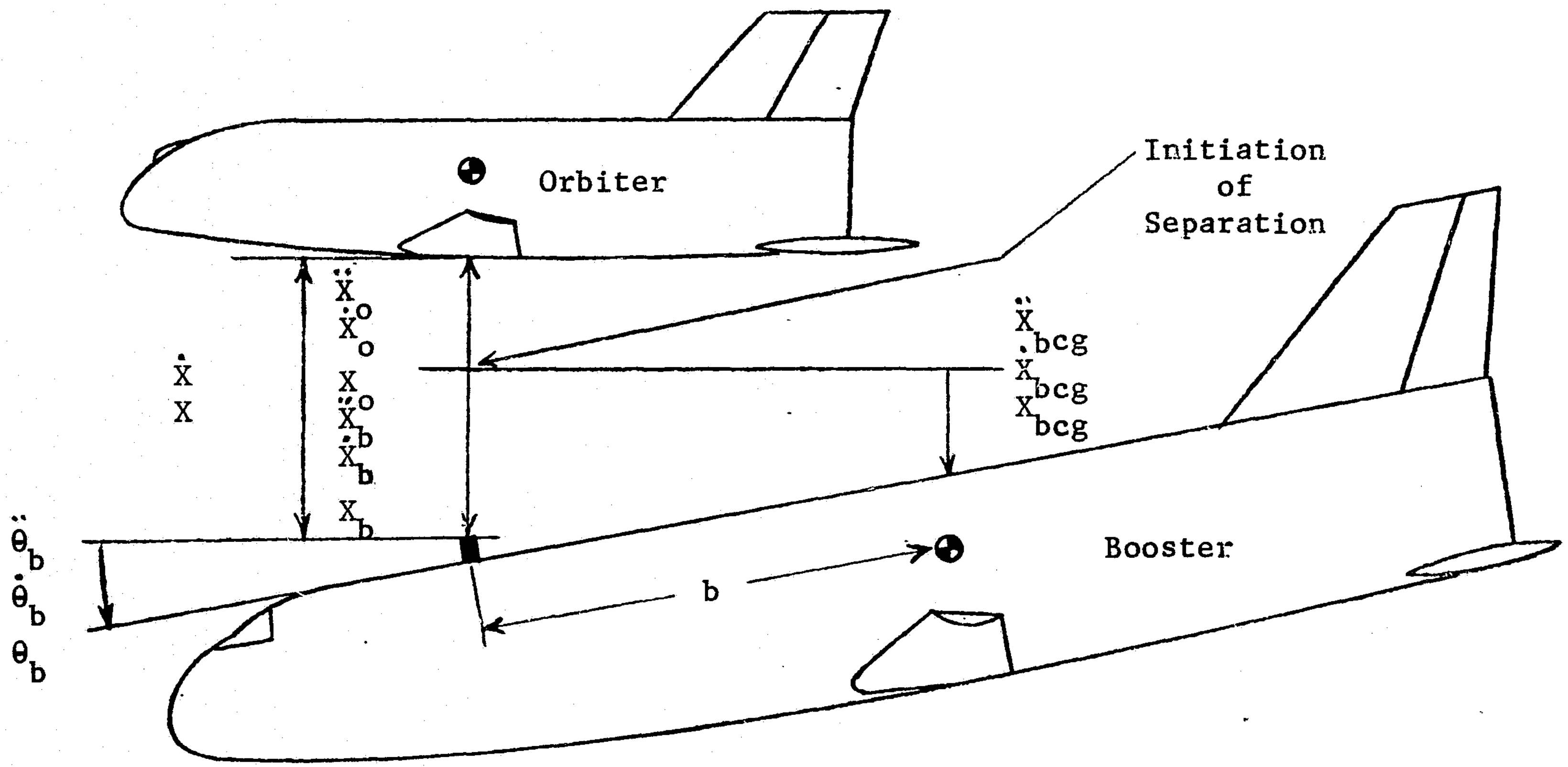


PYROTECHNIC RAM, FRONT VIEW, FIRED POSITION

FIGURE V-2

The material from which the main ram components are fabricated is Inconel 718. Its former use in a ram on the Apollo and its yield strength of 156,000 psi and ultimate tensile strength of 183,500 psi at $600^{\circ}F$ favor its use in this application. The pyrotechnic used in this analysis is Thiokol TP-Q-3027. It has a low flame temperature of $1883^{\circ}F$. The safety factor employed in this analysis was 1.5, the same as for the investigations of all four separational techniques. The final output force for which this was designed is 100,000 pounds.

In order to commence ram operation, the frangible nut is broken by means of two explosive caps contained within the nut. Simultaneously, the pyrotechnic material within the breech is ignited. The overall time required to reach the maximum pressure of 15,000 psi within the stagnation chamber is from 20 to 30 milleseconds. Initially, gas can enter the ram chamber only through the lowest port. As the pressure within this chamber builds up, friction is overcome and member 1 proceeds upward. As it does, additional inlet ports become available to admit the high pressure gas into the chamber. Member 1 is finally stopped by the large spring located around member 5. The gas is able to exit the ram through the large port at the top of member 1, and the smaller return spring returns member 1 to its initial position.



PYROTECHNIC RAM SEPARATION TERMINOLOGY

FIGURE V-3

2. Separation Dynamics and Calculation of Energy

Referring to Figure (V-3), the motion of the orbiter is described by the following equations.

$$\ddot{X}_o = \frac{Fg_c}{m_o} \tag{V-1}$$

$$\dot{X}_o = \int \frac{Fg_c}{m_o}\, dt + c_1 \tag{V-2}$$

$$X_o = \int\left(\int \frac{Fg_c}{m_o}\, dt + c_1\right) dt + c_2 \tag{V-3}$$

where c_1 and c_2 are integration constants. Since the separation force acts through the c.g. of the orbiter, the orbiter motion is completely defined by these equations.

The linear motion of the c.g. of the booster is given by Equations (II-1), (II-2), and (II-3). The angular motion of the booster can be derived as follows:

$$\ddot{\theta}_b = \frac{Fb}{I_b}\, g_c \tag{V-4}$$

$$\dot{\theta}_b = \int \frac{Fbg_c}{I_b}\,dt + c_3 \tag{V-5}$$

$$\theta_b = \int \left(\int \frac{Fbg_c}{I_b}\,dt + c_3 \right) dt + c_4 \tag{V-6}$$

where b is as shown in Figure (V-3)

and c_3 and c_4 are integration constants.

The relative velocity between the ram attach points on these vehicles is given by

$$\dot{X} = \dot{X}_o + \dot{X}_{bcg} + b\,\dot{\theta}_b \tag{V-7}$$

Substituting for $\dot{X}_o$, $\dot{X}_{bcg}$, and $\dot{\theta}_b$ from Equations (V-2), (II-2), and (V-5), respectively, into Equation (V-7), leaves

$$X = I_{fac} \int F\,dt + c_5 \tag{V-8}$$

where

$$I_{fac} = \left[\frac{1}{m_o} + \frac{1}{m_b} + \frac{b^2}{I_b} \right] g_c$$

and c_5 is a constant of integration.

The relative displacement between the two vehicles is given by

$$X = X_o + X_{bcg} + b\theta_b \qquad \text{(V-9)}$$

Substituting in Equation (V-9) from Equations (V-3), (II-3), and (V-6) for X_o, X_b, and θ_b, respectively, yields

$$X = I_{fac} \int \left(F \; dt \right) dt + \int c_5 \; dt + c_6 \qquad \text{(V-10)}$$

where c_6 is a constant of integration. In order to determine the energy output of this device reference is made to Figure (V-4). The output energy is given by

$$E_{out} = \int Fdx + c_7 \qquad \text{(V-11)}$$

where c_7 is an integration constant.

For the ramp force from t_1 to t_2,

$$F = K_1 \; t \qquad \text{(V-12)}$$

PYROTECHNIC RAM OUTPUT FORCE VS TIME

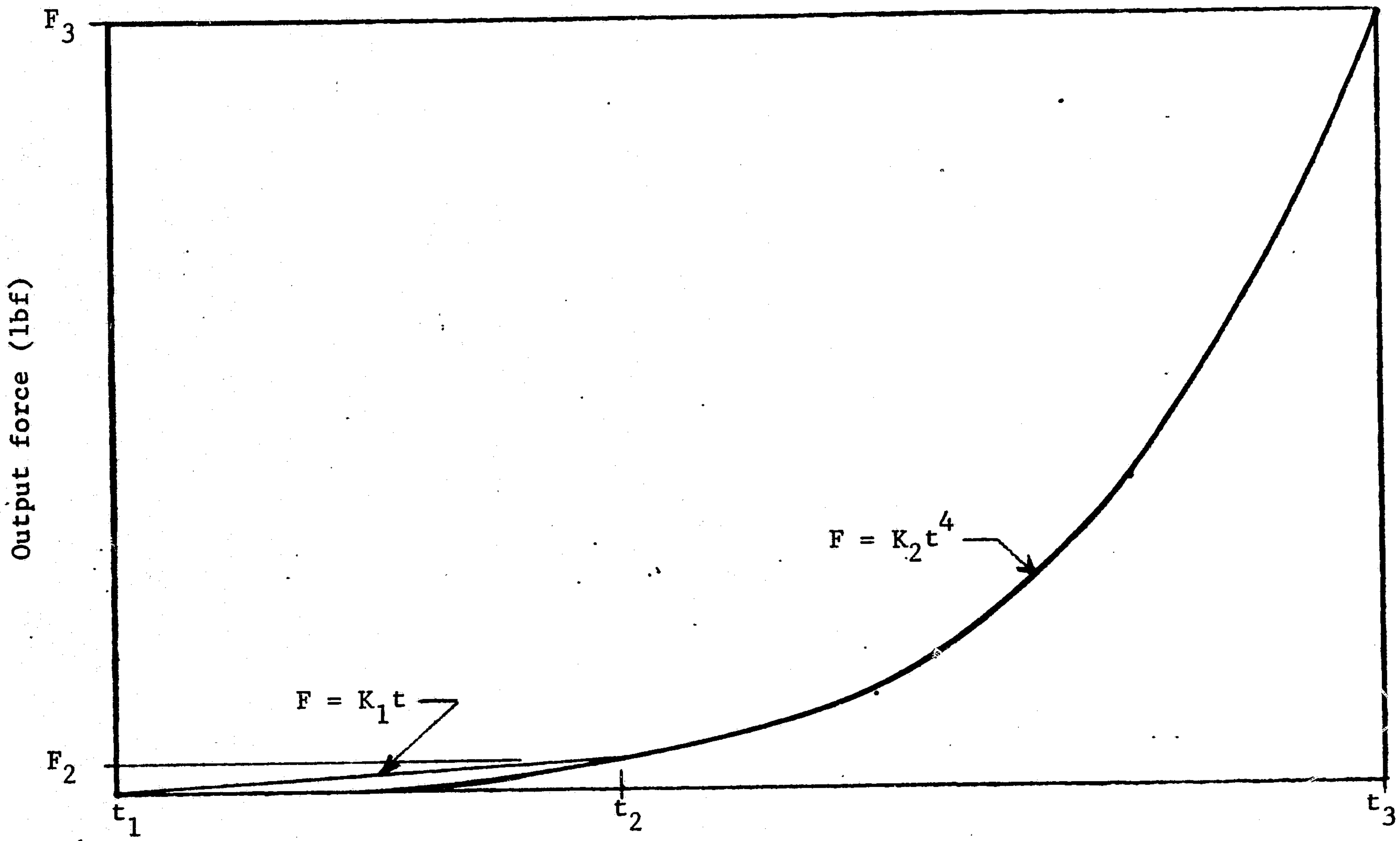


FIGURE V-4

where K_1 is a constant. Subsituting this into Equation (V-10) leaves

$$X = I_{fac} \int_o^t \left(\int_o^t K_1 \ t \ dt \right) dt \qquad \text{(V-13)}$$

where $t_1 < t \leq t_2$.

The integration constants c_5 and c_6 are both equal to zero because the separation velocity and displacement are zero at the beginning of motion, respectively.

Evaluating Equation (V-13) gives

$$X = I_{fac} \left. \frac{K_1 \ t^3}{6} \right|_o^t \qquad \text{(V-14)}$$

Substituting for F from Equation (V-12) into the above equation, yields

$$X = I_{fac} \frac{F \ t^2}{6} \qquad \text{(V-15)}$$

Therefore,

$$F = \frac{6X}{I_{fac} t^2} \qquad \text{(V-16)}$$

In order to determine the energy output during this interval, Equation (V-11) is used with F as expressed in Equation (V-16) to obtain

$$E_{out} = \frac{6}{I_{fac}t^2} \int_o^X X\,dx$$

$$E_{out} = \frac{3}{I_{fac}t^2} \; X^2 \Big|_o^X \tag{V-17}$$

At $t = t_2$, this becomes

$$E_{out} = \frac{3X_2^{\;2}}{I_{fac}t_2^{\;2}} \tag{V-18}$$

where X_2 is the displacement at $t = t_2$.

During the interval $t_2 < t \leq t_3$, the output force is given by

$$F = K_2 \; t^4 \tag{V-19}$$

where K_2 is a constant.

The displacement from the beginning of motion may be determined by substituting F into Equation (V-10). The integration constants, c_5 and c_6, are the velocity and displacement at $t = t_2$, respectively. For any time t, in this interval, X is obtained as

$$X = I_{fac} \int_{t_2}^{t} \left(\int_{t_2}^{t} K_2 \, t^4 \, dt \right) dt$$

$$+ \int_{t_2}^{t} \dot{X}_2 \, dt + X_2 \qquad \text{(V-20)}$$

Evaluating and substituting back for F yields

$$X = I_{fac} \frac{F \left(t^2 - t_2^2\right)}{30} + \dot{X}_2 \, (t - t_2) + X_2 \qquad \text{(V-21)}$$

from which F becomes

$$F = \frac{30}{I_{fac}\left(t^2 - t_2^2\right)} \left(X - \dot{X}_2 \, (t - t_2) - X_2\right) \qquad \text{(V-22)}$$

The energy which has gone into the separation at any time during this interval may be determined by using Equation (V-11). The integration constant c_7 is equal to E_2, the energy at $t = t_2$.

Therefore,

$$E_{out} = \int_{X_2}^{X} F \, dx + E_2$$

$$= \frac{30}{I_{fac}\left(t^2 - t_2^{\,2}\right)} \int_{X_2}^{X} \left[X - \dot{X}_2 \, (t - t_2) - X_2\right] dx + E_2$$

$$E_{out} = \frac{30}{I_{fac}\left(t^2 - t_2^{\,2}\right)} \left\{\frac{X^2 - X_2^2}{2} + \right. \tag{V-23}$$

$$\left. - \left[X - X_2\right]\left[\dot{X}_2 \, (t - t_2) + X_2\right]\right\} + E_2$$

Equation (V-23) gives the total work utilized for separating the booster and the orbiter. In order to determine the energy which must be used to compare the pyrotechnic ram to the other separational techniques we must determine the work done against friction. This frictional work is given by

$$E_{fr} = \int_{o}^{X_3} F_{fr} \, dx \tag{V-24}$$

This can be evaluated to yield

$$E_{fr} = F_{fr} X_3 \tag{V-25}$$

The energy capability of this device is given by

$$E = E_{fr} + E_{out} \tag{V-26}$$

In utilizing the preceding equations for the energy output and the vehicles' relative dynamics, the variables K_1 and K_2 are defined as

$$K_1 = \frac{F_2}{t_2} \tag{V-27}$$

$$K_2 = \frac{F_3}{t_3^4} \tag{V-28}$$

Another variable of use is the time factor, which specifies the ratio of the total amount of time during which the ram operates to the time during which the ramp portion is in operation.

$$t_{fac} = \frac{t_3}{t_2} \tag{V-29}$$

Finally, in order that the ramp function force and the fourth degree function force be equal at t_2, the following relation must hold:

$$K_1 \, t_2 = K_2 \, t_2^4 \qquad \text{(V-30)}$$

Among these four equations, (V-27), (V-28), (V-29), and (V-30), there are seven variables. If the quantities t_{fac}, K_1 and F_3 are specified, they may be solved simultaneously.

For the thermodynamics involved in the ram operation, the work involved in moving the ram piston from one point to the next must be determined. The differential work going to friction must also be calculated for each point.

Therefore, for the interval $t_1 < t < t_2$, the equation is

$$\Delta\text{Work}_j = \int_o^{X_j} F_j \, dx - \int_o^{X_{j-1}} F_{j-1} \, dx + \int_{X_{j-1}}^{X_j} F_{fr} \, dx \qquad \text{(V-31)}$$

where

j	refers to any iteration step,
$j-1$	refers to the preceding iteration step,
F_{fr}	is the frictional force,
F_j & F_{j-1}	must both be evaluated using Equation (V-16)

Substituting into Equation (V-31) for F_j and F_{j-1} from Equation (V-16), and integrating, leaves

$$\Delta Work_j = \frac{3}{I_{fac}}\left[\frac{X^2_j}{t^2_j} - \frac{X^2_{j-1}}{t^2_{j-1}}\right] + F_{fr}\,(X_j - X_{j-1}) \qquad (V\text{-}32)$$

During the interval $t_2 < t < t_3$, the differential work is given by

$$\Delta Work_j = \int_{X_2}^{X_j} F_j\,dx - \int_{X_2}^{X_{j-1}} F_{j-1}\,dx + \int_{X_{j-1}}^{X_j} F_{fr}\,dx \qquad (V\text{-}33)$$

Evaluating F_j and F_{j-1} by using Equation (V-22) and substituting, leaves

$$\Delta Work_j = \frac{30}{I_{fac}}\left\{\frac{1}{(t_j^{\,2} - t_2^2)}\int_{X_2}^{X_j}\left[X - \dot{X}_2\,(t_j - t_2) - X_2\right]dx\; + \right.$$

$$\left. - \frac{1}{(t^2_{j-1} - t_2^{\,2})}\int_{X_2}^{X_{j-1}}\left[X - \dot{X}_2\,(t_{j-1} - t_2) - X_2\right]dx\right\}$$

$$+ \int_{X_{j-1}}^{X_j} F_{fr}\,dx \qquad (V\text{-}34)$$

Integrating and evaluating Equation (V-34) leaves

$$\Delta Work_j = \frac{30}{I_{fac}} \left\{ \frac{1}{(t_j^2 - t_2^2)} \left[\left(\frac{X_j^2 - X_2^2}{2} \right) + \right. \right.$$

$$\left. - (X_j - X_2)(\dot{X}_2 (t_j - t_2) + X_2) \right] +$$

$$- \frac{1}{(t_{j-1}^2 - t_2^2)} \left[\left(\frac{X_{j-1}^2 - X_2^2}{2} \right) + \right.$$

$$\left. \left. -(X_{j-1} - X_2) (\dot{X}_2(t_{j-1} - t_2) + X_2) \right] \right\} + F_{fr} (X_j - X_{j-1}) \qquad \text{(V-35)}$$

3. Operational Thermodynamics

The method used to size and locate the inlet ports requires the calculation of the pressure, temperature, and mass of the pyrotechnic medium in the ram chamber as shown in Figure (V-5).

Several assumptions had to be made in order to analyze the thermodynamics. First, it was necessary to assume that the pryotechnic medium is an ideal gas. This assumption is approximately true for the majority of the constituent gases. It probably does not introduce too great of an error into the calculations.

This assumption implies that the Equation of State

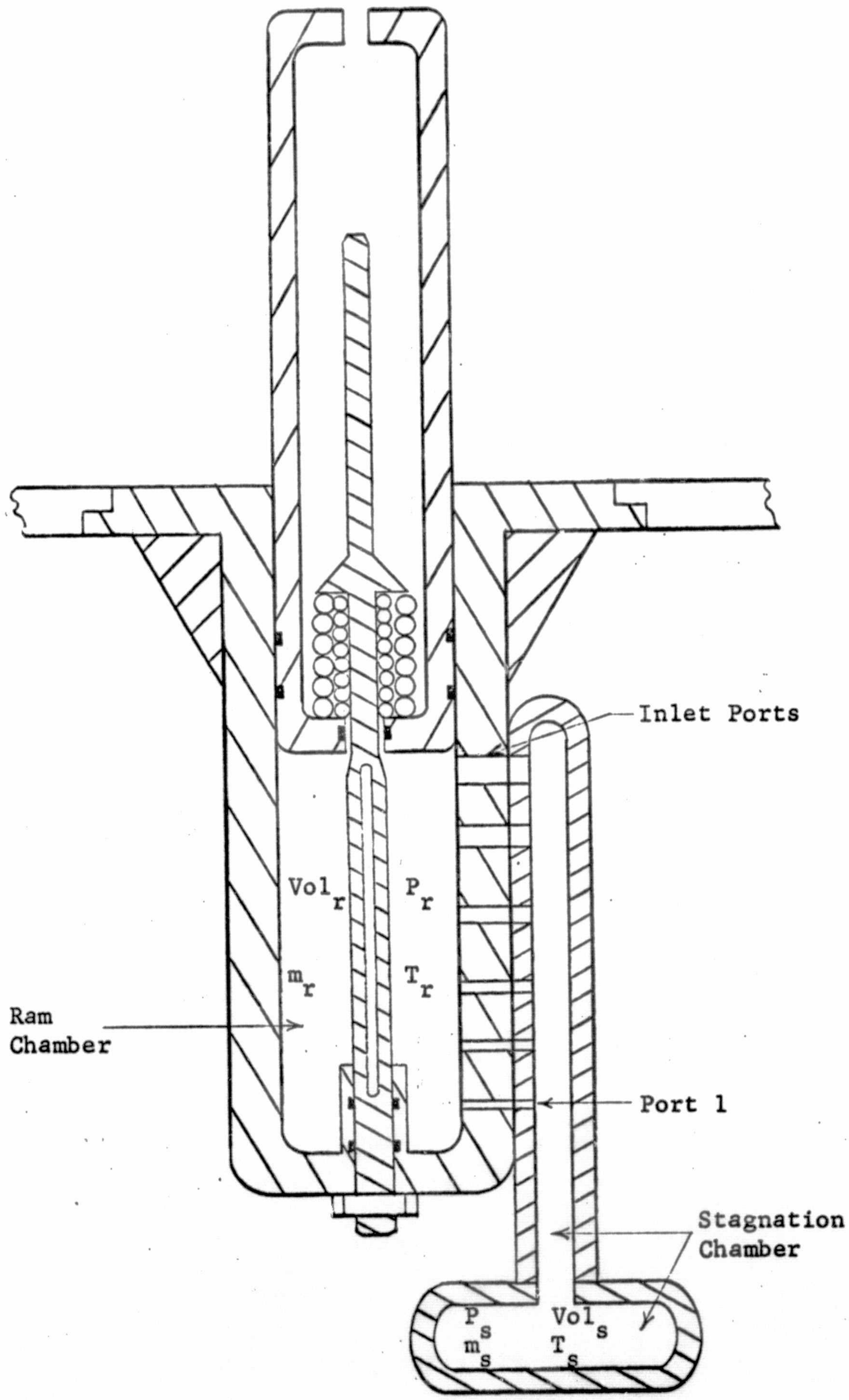
$$Pv = RT \tag{V-36}$$

can be applied. It also means that the internal energy and the enthalpy are functions of temperature only so that they are governed by the equations

$$u = C_v T$$

and (V-37)

$$h = C_p T$$



THERMODYNAMIC TERMINOLOGY

FIGURE V-5

Second, the process is essentially adiabatic. Since the only means of heat transfer from the control volume is by conduction through the ram walls and since the process occurs during a very short (1.0 - 2.0 sec) time interval this assumption is valid.

Third, the losses due to friction are essentially zero. This assumption is reasonable because the losses due to frictional flow are very small except for the first inlet port and the firctional energy loss due to the movement of the ram piston is only 1.0% of the total. This assumption, along with assumption two, imply that the process is isentropic so that the equation

$$Pv^k = C \tag{V-38}$$

where C is a constant, applies.

In addition to these assumptions the constraint is put on the process that only choked flow occurs across the inlet ports.

According to Reference (3), the First Law of Thermodynamics for an unsteady process occurring during a small time interval, Δt, is given by

$$Q_{c.v.} + \Sigma\, m_i \left(h_i + \frac{Vel_i^{\,2}}{2\, g_c} + Z_i \frac{g}{g_c}\right) = Work_{\,c.v.} +$$

$$+ \Sigma\, m_e \left(h_e + \frac{Vel_e^{\,2}}{2\, g_c} + Z_e \frac{g}{g_c}\right) + \left[m_1 \left(u_1 + \frac{Vel_1^{\,2}}{2\, g_c} + Z_1 \frac{g}{g_c}\right) +\right.$$

$$\left. - m_o \left(u_o + \frac{Vel_o^{\,2}}{2\, g_c} + Z_o \frac{g}{g_c}\right)\right]_{c.v.} \qquad \text{(V-39)}$$

where

the subscript i refers to quantities entering the control volume during Δt

e refers to quantities leaving the control volume during Δt

1 refers to quantities within the control volume after Δt

0 refers to quantities within the control volume before Δt

$Q_{c.v.}$ is the heat flowing out of the control volume,

$Work_{c.v.}$ is the work output of the process

Z's refer to the potential energy associated with changes of elevation.

In applying Equation (V-39) across the ram inlet ports, Figure (V-5), the following conditions are considered.

(a) $Q_{c.v.} = 0$ because of the adiabatic assumption,

(b) The change in elevation is negligible, $Z_i \doteq Z_e \doteq Z_o \doteq Z_1 \doteq 0.$,

(c) The mass exiting from the expanding ram chamber is zero, $\Sigma\, m_e = 0$. (until the ram motion is complete),

(d) The velocity of the gas within the ram chamber is negligible so that $Vel_1 = Vel_o = 0$.

With these considerations, Equation (V-39) reduces to

$$\Sigma\, m_i \left(h_i + \frac{Vel_i^{\,2}}{2\, g_c}\right) = Work_{c.v.} + \left[m_1\, u_1 - m_o\, u_o\right] \tag{V-40}$$

Substituting for h_1, u_2 and u_1 from Equation (V-38) gives

$$\Sigma\, m_i \left(C_p\, T_i + \frac{Vel_i^{\,2}}{2\, g_c}\right) = Work_{c.v.} + \left[m_1 C_v T_1 - m_o C_v T_o\right] \tag{V-41}$$

Equation (V-41) describes the general problem of gas entering an adiabatic system with movable boundaries, but with no gas escaping from this expandable control volume. Using Figure (V-5), Equation (V-41) may be rewritten as

$$\Sigma\, m_{t,1} \left(C_p\, T_{t,0} + \frac{Vel_{t,0}^{\,2}}{2\, g_c}\right) = \Delta Work_1 + \\ + \left[m_{r,1}\, C_v\, T_{r,1} - m_{r,0}\, C_v\, T_{r,0}\right] \tag{V-42}$$

where

$\Sigma\, m_{t,1}$ = summation of the mass of gas which has entered in the port throats at step number 1, lbm

$T_{t,o}$ = temperature of the gas in the port throats at step number 0, ^{o}R

$Vel_{t,0}$ = velocity of the gas in the port throats at step number 0, in/s

$\Delta Work_1$ = differential work in moving the ram piston, lbf-in

$m_{r,1}$ = the mass of gas in the ram chamber at step number 1, lbm

$T_{r,1}$ = the temperature of the gas in the ram chamber at step number 1, ^{o}R

$m_{r,0}$ = the mass of gas in the ram chamber at step number 0, lbm

$T_{r,0}$ = the temperature of the gas in the ram chamber at step number 0, ^{o}R

Step 0 corresponds to the time when no gas has yet entered the ram chamber. Step 1 corresponds to the time when the friction opposing the motion of the ram piston has just been overcome.

Since at step 0, no gas is in the ram chamber, $m_{r,0} = 0$. Because the ram piston has not moved, friction has not been overcome until right at Step 1, and therefore $\Delta Work_1 = 0$. Equation (V-42) therefore reduces to

$$\Sigma\, m_{t,1} \left(C_p T_{t,0} + \frac{Vel_{t,0}^{2}}{2\, g_c}\right) = m_{r,1}\, C_v T_{r,1} \qquad \text{(V-43)}$$

From the continuity equation, however,

$$\Sigma\, m_{t,1} = m_{r,1} \qquad \text{(V-44)}$$

This means that the summation of the mass of gas which has entered through the ports at Step 1 is equal to the mass of gas in the ram chamber at Step 1. Furthermore, since the temperature, $T_{t,0}$, and the velocity, $Vel_{t,0}$, in the throat of each of these ports is the same, we can obtain the following expression for the ram chamber gas temperature immediately preceding the onset of motion.

$$T_{r,1} = k\, T_{t,0} + \frac{Vel_{t,0}^{2}}{2 C_v g_c} \qquad \text{(V-45)}$$

where k is the specific heat ratio, C_p/C_v.

Since both $T_{t,0}$ and $Vel_{t,0}$ are decreasing with respect to time, Equation (V-45) is valid only for a small time interval

Δt. In order to determine $T_{t,0}$ and $Vel_{t,0}$, Reference (4) gives

$$T_{t,0} = (T_{fac})(T_{s,0}) \tag{V-46}$$

$$Vel_{t,0} = \sqrt{k\ g_c\ R\ T_{t,0}}$$

where T_{fac} is the ratio of choked temperature to stagnation temperature, commonly called the temperature factor.

After some gas has entered the ram chamber, Equation (V-42) may then be used to determine the gas properties. Writing it in a general form yields

$$\Sigma\, m_{t,j} \left(C_p\ T_{t,j-1} + \frac{Vel_{t,j-1}^{\ 2}}{2\ g_c}\right) = \Delta Work_j$$

$$+ \left[m_{r,j}\ C_v\ T_{r,j} - m_{r,j-1}\ C_v\ T_{r,j-1}\right] \tag{V-47}$$

where j is the step number.

In this equation there will, in general, be three unknowns, $\Sigma\, m_{t,j}$, $m_{r,j}$, and $T_{r,j}$. However, from the continuity equation one may conclude that

$$\Sigma\, m_{t,j} = m_{r,j} - m_{r,j-1} \tag{V-48}$$

Applying the Equation of State leaves

$$m_{r,j}\,T_{r,j} = \frac{P_{r,j}Vol_{r,j}}{R} \tag{V-49}$$

where $P_{r,j}$ and $Vol_{r,j}$ can be evaluated by knowing the force on the ram at step j and the relative displacement at j, respectively.

Substituting for $\Sigma\, m_{t,j}$, from Equation (V-48) and for $m_{r,j}$ from Equation (V-49) into Equation (V-47), one can obtain the mass within the ram chamber as

$$m_{r,j} = \frac{2g_c}{2g_cC_pT_{t,j-1} + Vel^2_{t,j-1}} \left\{\Delta Work_j + \frac{P_{r,j}Vol_{r,j}}{R}\,C_v + \right.$$

$$\left. + \, m_{r,j-1}\left(C_pT_{t,j-1} - C_vT_{r,j-1} + \frac{Vel^2_{t,j-1}}{2g_c}\right)\right\} \tag{V-50}$$

The gas temperature corresponding to this mass is

$$T_{r,j} = \frac{P_{r,j}\,Vol_{r,j}}{m_{r,j}R} \tag{V-51}$$

The mass of gas remaining in the stagnation chamber is given by the continuity equation.

$$m_{s,j} = m_{s,0} - m_{r,j} \tag{V-52}$$

where s refers to the stagnation chamber and $m_{s,0}$ is the mass of gas within the stagnation chamber at step 0. It may be determined by substituting the pressure, temperature, and specific volume of this gas at step 0 into the Equation at State.

The general equation for the pressure in the stagnation chamber is

$$P_{s,j} = C \left(\frac{Vol_s}{m_{s,j}}\right)^{-k} \tag{V-53}$$

where C is evaluated before any gas has entered the ram chamber.

The temperature in the stagnation chamber can be calculated from the Equation of State:

$$T_{s,j} = \frac{P_{s,j}\ Vol_s}{R\ m_{s,j}} \tag{V-54}$$

Finally, the throat temperature in the ports is given by

$$T_{t,j} = (T_{fac})(T_{s,j}) \tag{V-55}$$

and the gas velocity, which is at Mach 1, is given by

$$Vel_{t,j} = \sqrt{k\ g_c\ RT_{t,j}} \tag{V-56}$$

These two quantities $T_{s,j}$ and $Vel_{t,j}$ can be used in Equation (V-50) to determine the gas properties in the next iteration step.

The greatest source of error in the calculations for the ram operation centers around the assumptions made at the beginning of this section. Additionally, the small diameters of the first few ports causes the frictional losses accompanying flow through a narrow port to become dominant. For that reason the length to throat diameter ratio for the smallest size inlet port (port 1) was not allowed to be greater than 20. This produces about a 15% deviation between the calculated and actual pressure drop across this port and about a 12% deviation between the calculated and actual mass flow rate. By fabricating the ports in the form of converging-diverging nozzles, this error may be reduced since the length to throat diameter ratio is smaller. It is recommended that some experimental work be performed on this design in order to compensate for the slight discrepancies which exist between the actual gas and its flow characteristics and the idealized assumptions which had to be made in order to mathematically simulate the ram operation.

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4. Port Sizes and Locations

The size of the first port is assumed because it is a free variable. If it is assumed too large the operation time will be less than 1 second. If it is assumed too small the operation time becomes greater than 2 seconds. These conditions are contrary to the time constraint explained at the beginning of this chapter. The location of the first port is as shown in Figure (V-5). The initial mass flow rate into the ram chamber is only through this point. According to Reference (5) it is given by

$$\dot{m}_{r,\,1} = A_1 \frac{P_{s,\,1}}{\sqrt{T_{s,\,1}}}\,\dot{m}_{fac}\,, \qquad \text{(V-57)}$$

where A_1 is the area of port 1 and

$$\dot{m}_{fac} = \sqrt{\frac{kg_c}{R}}\;\frac{1}{\left(\frac{k+1}{2}\right)^{(k+1)/2(k-1)}}$$

Since $m_{r,1}$ can be easily evaluated from the Equation of State, (V-49), the time required to build up enough pressure in the ram chamber in order to overcome friction is given by

$$t_1 = m_{r,1}/\dot{m}_{r,1} \qquad \text{(V-58)}$$

For any interval after interval 1, the general equation for the mass flowing into the ram chamber is given by

$$\dot{m}_{r,j} = \sum_{1}^{j} A_j \frac{P_{s,j}}{\sqrt{T_{s,j}}} \dot{m}_{fac} \tag{V-59}$$

Since

$$A_j = \sum_{1}^{j} A_j - \sum_{1}^{j-1} A_j \tag{V-60}$$

the increase in total port area which must occur in order that the force output function be maintained can be calculated. The mass flow rate of any step in the ram operation may be evaluated as

$$\dot{m}_{r,j} = \frac{m_{r,j+1} - m_{r,j-1}}{2\Delta t} \tag{V-61}$$

Substitution of Equation (V-60) into Equation (V-59) and rearranging gives

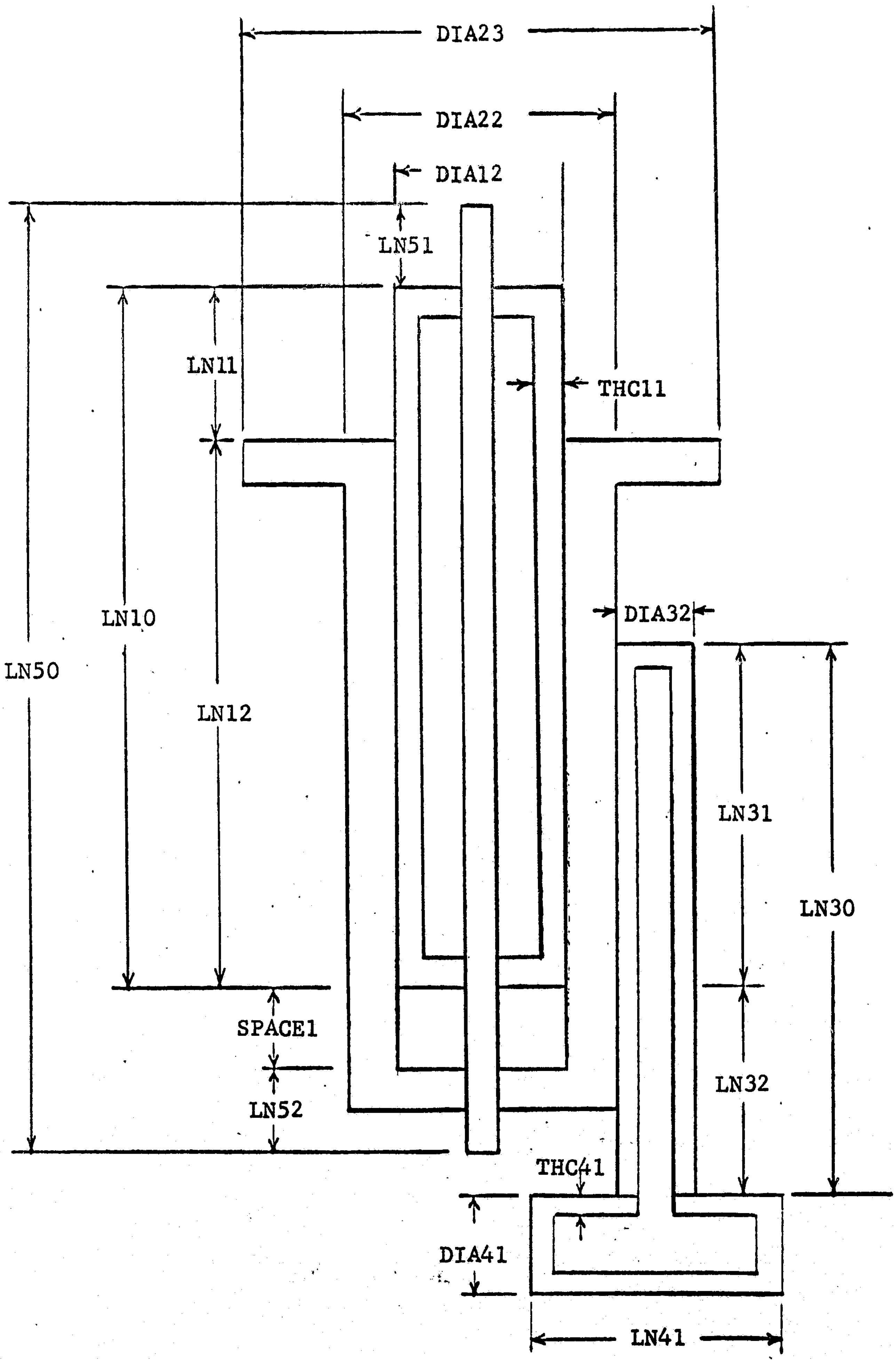
$$A_j = \frac{\dot{m}_{r,j}\sqrt{T_{s,j}}}{P_{s,j}\,\dot{m}_{fac}} - \sum_{1}^{j-1} A_j \tag{V-62}$$

The location of any port is at the displacement corresponding to $\dot{m}_{r,j}$, $T_{s,j}$, and $P_{s,j}$. At certain points during the ram operation, evaluation of Equation (V-62) will yield a negative value for A_t . This is because this position does not require the location of an inlet port. That is, more high pressure gas is not required to maintain the desired output force function. As can be seen from Appendix B, these points are only encountered during the time from t_1 until t_2 . It is felt that since the amount of energy which the ram puts into the system during this ramp portion is only a negligible portion of the total, the deviation from actual operation is not significant. Again, as explained at the end of the thermodynamic section of this chapter, the computed port sizes represent the lower limit of the actual sizes required . This is due to the assumptions of isentropic flow of an ideal gas.

5. Ram Weight

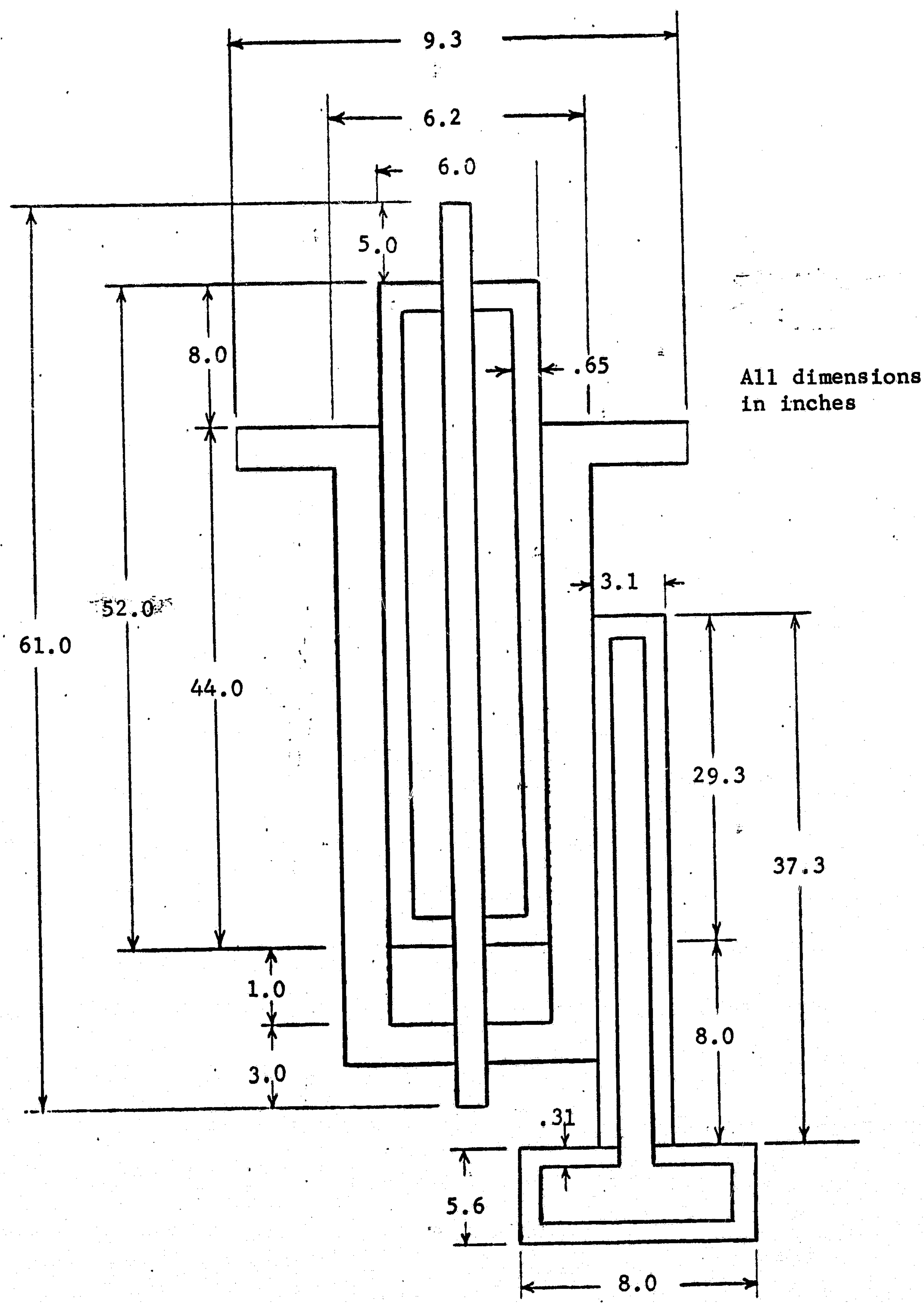
The method used in determining ram weight consisted in weighing the ram shown in Figure (V-6). This ram contains the predominant components of the ram shown in Figures (V-1) and (V-2). The terminology used in the computer program shown in Appendix A and Appendix B to determine the ram size and weight is illustrated in Figure (V-6). The resulting dimensions of a ram capable of supplying 130,207 ft-lbf to the booster and orbiter separation is shown in Figure (V-7). In this approach the weight of the stop spring, return spring, explosive nut, required washers, piston rings, seals, and weld material are compensated for by multiplying the resultant weight by an allowance factor of 1.20. It is felt that this 20% addition to the ram shown in Figure (V-6) is a conservative approximation because certain aspects of the model made it heavier, such as the reduction in member 5 area and the slight effect of the ports.

The ram weight was determined by knowing the ram stroke, either an inside or outside diameter for each member, the design pressures, the safety factor, and the metal tensile strength and density. The ram stroke determined the lengths of each member and the thicknesses of the pressure vessels could be determined from knowing the inside radius, pressure, and the tensile strength. The volume of each member was computed and multiplied by the density to obtain the weight.



RAM DIMENSION TERMINOLOGY

FIGURE V-6



Ram Dimensions for E = 130207 ft-lbf

FIGURE V-7

CHAPTER VI

RESULTS

The purpose of this study was to determine the minimum weight separation technique among the four investigated. Since the energy required for separation is a function of the final translational velocities of both vehicles and since these will not be known until the shuttle design is further refined, it is much more useful to show the graphical relationship between weight and energy than it would be to assume final specific translation velocities. Figures (VI-1) and (VI-2) are the results of this study. Figure (VI-1) shows all four separation systems and Figure (VI-2) decreases the range of the abscissa in order to better display the two least weight techniques. A safety factor of 1.5 is used for each technique because the safety factor employed in the design of the rocket engine cases used in the analysis of the rocket separational scheme was 1.5. The excessive weights of the spring for the spring loaded ram and the ejector gas in the case of the high speed, non-ignitable gas ejectors rules out their further study. The data for the rocket engines follows a range of values depending upon which numbers are taken as the vacuum specific impulse and the mass fraction. The curve for the pyrotechnic ram reveals that it is only good for a range of values from 80,000 ft-lbf to 160,000 ft-lbf. This is due to the four constraints placed on the ram and its operation by MSC personnel, explained at the beginning of Chapter V.

Referring to Figure (VI-2) it may be noted that the use of rockets results in a lighter separation subsystem design but for the range of values for which the ram may be used, it would result in a lighter overall shuttle system design since it would be dual functional. Because the method used to constrain the vehicles together before separation will employ one forward constraint and a set of aft supports, the ram piston could be conveniently used for the forward constraint. The pyrotechnic ram technique is the only separation method investigated which has this capability. If it can be said that 45% or greater of the ram weight is the weight which would be required to mate these two vehicles, then it can be shown that the pyrotechnic ram would be the most feasible separation technique.

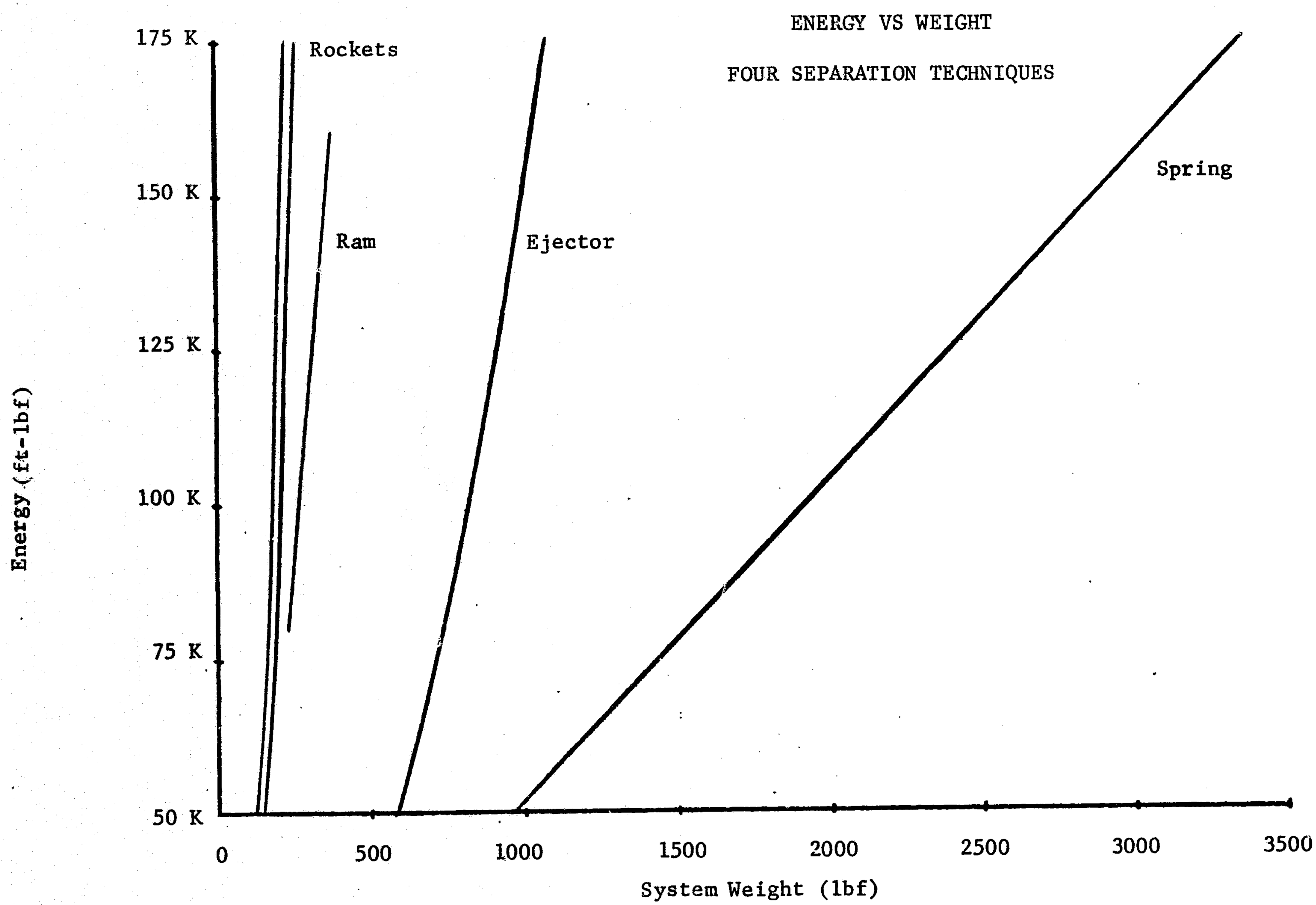

ENERGY VS WEIGHT
FOUR SEPARATION TECHNIQUES
Rockets
Ram
Ejector
Spring
175 K
150 K
125 K
100 K
75 K
50 K
Energy (ft-lbf)
0
500
1000
1500
2000
2500
3000
3500
System Weight (lbf)

FIGURE VI-1

ENERGY VS WEIGHT

ROCKETS AND PYRO RAM

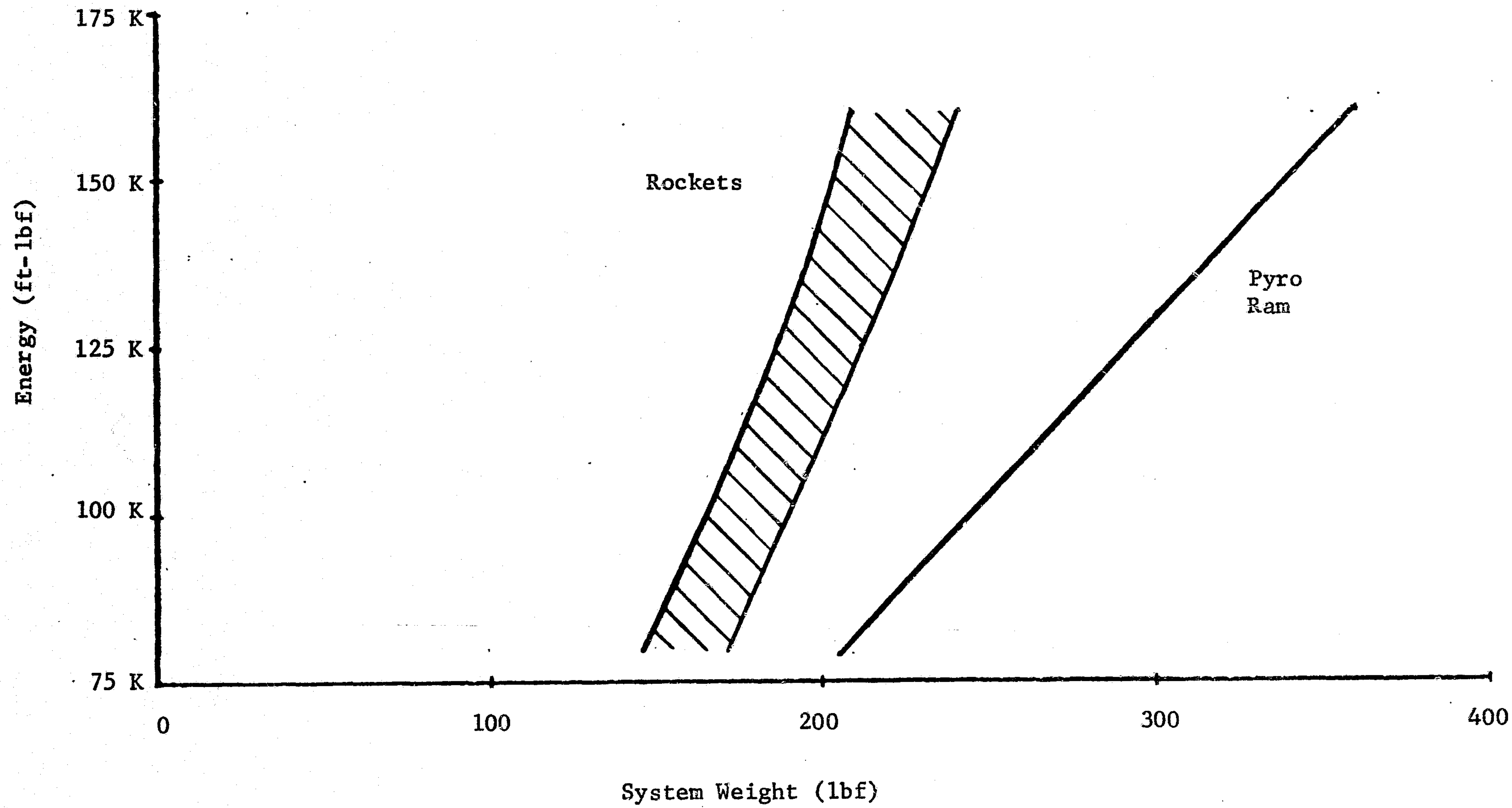


FIGURE VI-2

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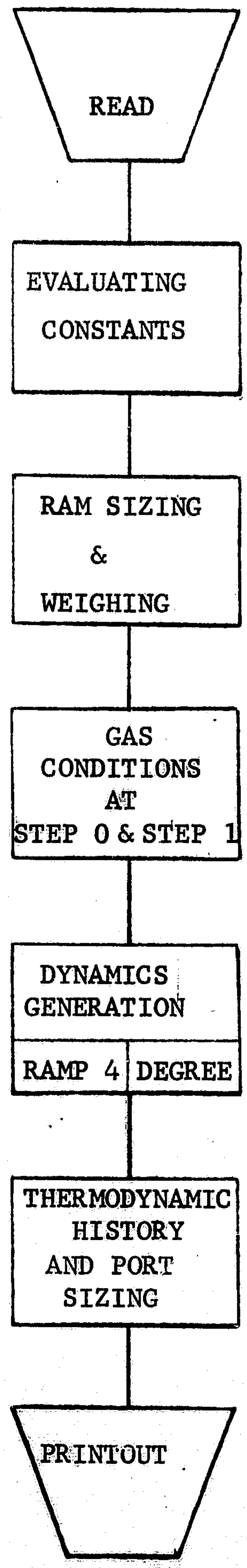
APPENDIX A

COMPUTER PROGRAM LISTING



COMPUTER FLOWCHART

```
COMMENT ********** PYROTECHNIC RAM PROGRAM **********

COMMENT ********** DATA INPUT **********

      IMPLICIT  REAL (L,M,K)
      REAL IB,INRFAC,INRSYS
      DIMENSION AREAC(25),AREAT(25),DIAT(25),FOUT(25),FRAM(25),
     1FRAMP(25),F4DEG(25),MASSDR(25),MASSR(25),MASSS(25),PRESR(25),
     2PRESS(25),RHOS(25),RHOT(25),TEMPR(25),TEMPS(25),TEMPT(25),
     3TIME(25),TIMEAM    (25),TIMEAA(25),TIMEFF(25),VOLR(25),
     4VELGT(25),WORKDL(25),X(25),XD(25),NUM(25)
      READ(5,1)KG,MOL,TEMFLM,SPHTPR,SPHTVL
      READ(5,1)CRAMP,FFR,FOUTF,TIMPER
      READ(5,1) THDFAC,VOLFAC
      READ(5,2) B,IB,MB,MO
      READ(5,3) NSTEPS
      READ(5,1) PRESSI,RHO,SFTFAC,STRSSU,STRSSY,WTEFAC
      READ(5,1)SPACE1
      READ(5,1)DIARM,LN11,LTSFAC,LT1FAC,THC11
      READ(5,1)D23FAC,LT2FAC
      READ(5,1)LN32,LT3FAC
      READ(5,1)DIA41,LN41,LT4FAC
      READ(5,1)DIA52,LN51,LN52
 1    FORMAT(8F10.3)
 2    FORMAT( F10.3,7F10.0)
 3    FORMAT(I10)
```

```
COMMENT ********** EVALUATING CONSTANTS **********

      PI=3.14159
      NSTEPM=NSTEPS-1
      ASTEPS=NSTEPS
      K1=1/KG
      K2=(KG-1.)*K1
      K3=1./K2
      K4=1./(1.-KG)
      K5=-K4
      TEMPSI=TEMFLM+460.
      R=1545.*12./MOL
      G2J144=32.17*2*778.*144.
      CRTKG1=SQRT(KG*32.17*12/R)
      CRTKG2=(KG+1.)/2.
      CRTKG3=(KG+1.)/(2*(KG-1.))
      MDFAC =CRTKG1*(1./((CRTKG2)**CRTKG3))
      RHOFAC=(2/(KG+1.))**K5
      PRSFAC=(2/(KG+1.))**K3
      TMPFAC=(2/(KG+1.))
      GC=32.17
      IB=IB*GC
      INRFAC=GC*12.*((1./MO)+(1./MB)+(B**2/IB))
      INRSYS=12./INRFAC
      TIMPER=TIMPER/100.
      TIMFAC=1./TIMPER
      FRAMPF=FOUTF/TIMFAC**4
      TIMEA=FRAMPF/CRAMP
      TIMEF=TIMEA/TIMPER
      TIMPER=TIMPER*100.
      TIMFAC=TIMFAC-.01
      AJA=((ASTEPS-1.)/TIMFAC)+1.
      TIMFAC=TIMFAC+.01
      JA=AJA
      C4DEG=FOUTF/TIMEF**4
```

```
      XA=INRFAC*CRAMP*TIMEA**3/6.
      XDA=INRFAC*CRAMP*TIMEA**2/2.
      ENERGA=3.*XA**2/(INRFAC*TIMEA**2*12.)
      XF=(INRFAC*C4DEG*(TIMEF**6-TIMEA**6)/30.)
     1+XDA*(TIMEF-TIMEA)+XA
```

```
COMMENT ********* RAM SIZING AND WEIGHING *********

      AREARM=(PI/4.)*(DIARM**2-DIA52**2)
      DIA12=DIARM
      VOLRI=SPACE1*AREARM/4.
      VOLRF=AREARM*XF+VOLRI
      VOLS=VOLRF*VOLFAC
      STRSSD=STRSSU/SFTFAC
      LN12=LTSFAC*XF
      LN31=XF
      LN30=LN31+LN32
      VOLS2=(PI*DIA41**2/4.)*LN41
      VOLS1=VOLS-VOLS2
      DIA31=SQRT(4.*VOLS1/(PI*LN30))
      PRESRF=(FOUTF+FFR)/AREARM
      DIA21=DIA12
      LN21=LN12+SPACE1
      THC21=(PRESRF*DIA21)/(2.*STRSSD)
      THC22=THC21*LT2FAC
      DIA22=DIA21+2.*THC21
      DIA23=DIA22*D23FAC
      THC31=(PRESSI*DIA31)/(2.*STRSSD)
      THC32=THC31*LT3FAC
      THC41=(PRESSI*DIA41)/(2.*STRSSD)
      THC42=THC41*LT4FAC
      DIA42=DIA41+2.*THC41
      DIA32=DIA31+2.*THC31
      THC12=THC11*LT1FAC
      LN10=LN11+LN12
      LN50=LN21+LN51+LN11+LN52
      DIA11=DIA12-2.*THC11
      VOL11=(PI*(DIA12**2-DIA11**2)/4.)*LN10
      VOL12=(PI*(DIA11**2-DIA52**2)/4.)*THC12*2.
      VOL1=VOL11+VOL12
      VOL21=(PI*(DIA22**2-DIA21**2)/4.)*LN21
```

```
      VOL22=(PI*(DIA23**2-DIA52**2)/4.)*THC22
      VOL2=VOL21+VOL22
      VOL31=(PI*(DIA32**2-DIA31**2)/4.)*LN30
      VOL3=VOL31
      VOL41=(PI*(DIA42**2-DIA41**2)/4.)*LN41
      VOL42=(PI*(DIA42**2)/4.)*THC42*2.
      VOL4=VOL41+VOL42
      VOL5=(PI*DIA52**2/4.)*LN50
      WT1=RHO*VOL1
      WT2=RHO*VOL2
      WT3=RHO*VOL3
      WT4=RHO*VOL4
      WT5=RHO*VOL5
      WTMEM=WT1+WT2+WT3+WT4+WT5
      WTERR=WTMEM*WTEFAC
      MASSSI=PRESSI*VOLS /(TEMPSI*R)
      WTGAS=MASSSI
      WEIGHT=WTMEM+WTGAS+WTERR
      DIAMIN=THC21/THDFAC
      ARAMIN=PI*DIAMIN**2/4.
      ENERGF=((30./(INRFAC*(TIMEF**2-TIMEA**2)))
     1*(((XF**2-XA**2)/2.)-(XF-XA)*(XDA*
     2(TIMEF-TIMEA)+XA)))/12.+ENERGA
```

```
COMMENT ********** GAS CONDITIONS AT 0 AND 1 **********

      CONGAS=PRESSI*(MASSSI/VOLS)**(-KG)
      PRESSF=PRESRF/PRSFAC
      TEMPTI=TMPFAC*TEMPSI
      VELGTI=SQRT(KG*32.17*12.*R*TEMPTI)
      TEMPR(1)=KG*TEMPTI+(VELGTI**2/(G2J144*SPHTVL))
      VOLR(1)=VOLRI
      PRESR(1)=FFR/AREARM
      MASSR(1)=PRESR(1)*VOLR(1)/(R*TEMPR(1))
      MASSS(1)=MASSSI-MASSR(1)
      PRESS(1)=CONGAS*(MASSS(1)/VOLS)**KG
      TEMPS(1)=PRESS(1)*VOLS/(R*MASSS(1))
      RHOS(1)=(PRESS(1)/CONGAS)**K1
      RHOT(1)=RHOS(1)*RHOFAC
      AREAT(1)=ARAMIN
      DIAT(1)=SQRT(ABS(AREAT(1)*4./PI))
      TEMPT(1)=TEMPS(1)*TMPFAC
      VELGT(1)=SQRT(KG*GC*12.*R*TEMPT(1))
      PSLSQT=PRESS(1)/SQRT(TEMPS(1))
      MASSDR(1)=AREAT(1)*(PSLSQT*MDFAC)
      TIMEBU=MASSR(1)/MASSDR(1)
      TIMOPR=TIMEF+TIMEBU
```

```
COMMENT ***** DYNAMICS,PRESSURE,VOLJME,AND DELTA WORK GENERATION *****

COMMENT ********** FORCE OUTPUT IS A RAMP FUNCTION **********

      TMINCR=TIMEF/(ASTEPS-1.)
      X(1)=0.
      XD(1)=0.
      FRAM(1)=FFR
      TIMEAA(1)=0.
      DO 400J=2,JA
      TIMEAA(J)=TIMEAA(J-1)+TMINCR
      TIMEAM(J)=TIMEAA(J)
      TIME(J)=TIMEAM(J)+TIMEBU
      FRAMP(J)=CRAMP*TIMEAA(J)
      FOUT(J)=FRAMP(J)
      FRAM(J)=FOUT(J)+FFR
      XD(J)=INRFAC*CRAMP*TIMEAA(J)**2/2.
      X(J)=INRFAC*CRAMP*TIMEAA(J)**3/6.
      PRESR(J)=FRAM(J)/AREARM
      VOLR(J)=(X(J)*AREARM)+VOLRI
      IF(J.NE.2) GO TO 402
      WORKDL(J)=(3./INRFAC)*((X(J)**2/TIMEAA(J)**2))
     1+FFR*X(J)
      GO TO 400
 402  WORKDL(J)=(3./INRFAC)*((X(J)**2/TIMEAA(J)**2)
     1-(X(J-1)**2/TIMEAA(J-1)**2))+FFR*(X(J)-X(J-1))
 400  CONTINUE
```

```
COMMENT ********** FORCE OUTPUT IS A 4 DEGREE FUNCTION **********

      JA1=JA+1
      TIMEFF(JA)=TIMEAA(JA)
      DO 401 J=JA1,NSTEPS
      AJ=J-1
      TIMEFF(J)=TIMEF*AJ/(ASTEPS-1.)
      TIMEAM(J)=TIMEFF(J)
      TIME(J)=TIMEAM(J)+TIMEBU
      F4DEG(J)=C4DEG*TIMEFF(J)**4
      XD(J)=(INRFAC*C4DEG*(TIMEFF(J)**5-TIMEA**5)/5.)
     1+XD(JA)
      X(J)=(INRFAC*C4DEG*(TIMEFF(J)**6-TIMEA**6)/30.)
     1+XD(JA)*(TIMEFF(J)-TIMEA)+X(JA)
      FOUT(J)=F4DEG(J)
      FRAM(J)=FOUT(J)+FFR
      PRESR(J)=FRAM(J)/AREARM
      VOLR(J)=X(J)*AREARM+VOLRI
      WORKDL(J)=(30./INRFAC)*((1./(TIMEFF(J)**2-TIMEA
     1**2))*(((X(J)**2-X(JA)**2)/2.)-(X(J)-X(JA))*
     2(XD(JA)*(TIMEFF(J)-TIMEA)+X(JA)))-(1./(TIMEFF(J-
     31)**2-TIMEA**2))*(((X(J-1)**2-X(JA)**2)/2.)
     4-(X(J-1)-X(JA))*(XD(JA)*(TIMEFF(J-1)-TIMEA)
     5+X(JA))))+FFR*(X(J)-X(J-1))
  401 CONTINUE
      TIME(1)=TIMEBU
      TIMEAM(1)=0.
      FOUT(1)=0.
```

```
COMMENT ********** THERMODYNAMICS GENERATION **********

      DO 500 J= 2,NSTEPS
      MSDUM1=SPHTVL*((PRESR(J)*VOLR(J)/R)-MASSR(J-1)*
     1TEMPR(J-1))
      MSDUM2=MASSR(J-1)*(SPHTPR*TEMPT(J-1)+(VELGT(J-1)
     1**2/G2J144))
      MSDUM3=MSDUM2/MASSR(J-1)
      MASSR(J)=((WORKDL(J)/(12.*778.))+MSDUM1+MSDJM2)/
     1MSDUM3
      TEMPR(J)=PRESR(J)*VOLR(J)/(MASSR(J)*R)
      MASSS(J)=MASSSI-MASSR(J)
      PRESS(J)=CONGAS*(MASSS(J)/VOLS)**KG
      TEMPS(J)=PRESS(J)*VOLS/(R*MASSS(J))
      RHOS(J)=(PRESS(J)/CONGAS)**K1
      RHOT(J)=RHOS(J)*RHOFAC
      TEMPT(J)=TEMPS(J)*TMPFAC
      VELGT(J)=SQRT(KG*32.17*12.*R*TEMPT(J))
  500 CONTINUE
```

```
COMMENT ********** PORT SIZES AND LOCATIONS **********

      AM1SUM=AREAT(1)
      NUM(1)=1
      NSUM=1
      AREAC(1)=AREAT(1)
      DO 501  J=2,NSTEPS
      PSLSQT=PRESS(J)/SQRT(TEMPS(J))
      IF(J-NSTEPM)503,503,504
  503 MASSDR(J)=(MASSR(J+1)-MASSR(J-1))/(2.*TMINCR)
      GO TO 505
  504 MASSDR(J)=(MASSR(J)-MASSR(J-1))/TMINCR
  505 AREAT(J)=(MASSDR(J)/(PSLSQT*MDFAC))-AM1SUM
      IF(AREAT(J))506,506,507
  506 AREAT(J)=0.000000
      DIAT(J)=0.000000
      AREAC(J)=AREAC(J-1)
      NUM(J)=0
      GO TO 501
  507 IF(AREAT(J)-ARAMIN)506,506,508
  508 AM1SUM=AM1SUM+AREAT(J)
      DIAT(J)=SQRT(4.*AREAT(J)/PI)
      NSUM=NSUM+1
      NUM(J)=NSUM
      AREAC(J)=AM1SUM
  501 CONTINUE
```

```
COMMENT *********PRINTOUT ********** PRINTOUT **********

COMMENT ********** PRINTOUT IMPORTANT PARAMETERS **********

      WRITE(6,10)
 10   FORMAT(1H1,5(/),T52,'PYROTECHNIC RAM ANALYSIS'/////)
      WRITE(6,11)ENERGF,WEIGHT
 11   FORMAT(T48,'DATA POINT-ENERGY VS WEIGHT CURVE'//
     1T49,'ENERGY(FT-LBF)',
     2T70,'WEIGHT(LB)'/ T50,F10.1,T67,F10.1 ////)
      WRITE(6,20)B,IB,MB,MO,INRSYS
 20   FORMAT( T53,'CONFIGURATION PARAMETERS'///T4 ,'DIST.B(FT)',
     1T24,'INER. BOOSTER(LBM-FT**2)',T56,'MASS BOOSTER(LBM)',
     2T83,'MASS ORBITER(LBM)',T108,'INER. SYS.(SLUG)'/
     3T2 ,F10.3,T26,F15.0,T53,F15.0,T80,F15.0,T104,F15.0////)
      WRITE(6,30)
 30   FORMAT( T50,'RAM OPERATIONAL CHARACTERISTICS'// )
      WRITE(6,31)TIMPER,TIMOPR,TMINCR,TIMEBU,TIMEA,TIMEF
 31   FORMAT( T7 ,'TIME PERC. RAMP',T27,'TIME OPER.(SEC)'
     1T47,'TIME INCR.(SEC)',T68,'TIME 1(SEC)',T89,'TIME 2(SEC)',
     2T109,'TIME 3(SEC)'/
     3T7,F10.2,T27,F10.4,T47,F10.4,T67,F10.4,T88,F10.4,T108,F10.4//)
      ENERG2=ENERGA+(FFR*XA/12.)
      WRITE(6,32)CRAMP,FRAMPF,XA,XDA,ENERG2
 32   FORMAT( T8,'K1 (LBF/SEC)',T33,'FORCE 2(LBF)',
     1T60,'DISP.2(IN)',T84,'VEL.2(IN/SEC)',T107,'ENERGY 2(LBF-FT)'/
     2T8,F10.2,T33,F10.2,T59,F10.5,T84,F10.5,T106,F12.2//)
      ENERG3=ENERGF+(FFR*XF/12.)
      WRITE(6,33)C4DEG,FOUTF,XF,XD(NSTEPS),ENERG3
 33   FORMAT( T6,'K2 (LBF/SEC**4)',T33,'FORCE 3(LBF)',
     1T60,'STROKE(IN)',T84,'VEL.3(IN/SEC)',T107,'ENERGY 3(LBF-FT)'/
     2T7,F10.2,T33,F10.2,T59,F10.5,T85,F10.5,T108,F10.2//)
      WRITE(6,34)FFR,NSTEPS
 34   FORMAT( T40,'FRIC. FORCE(LBF)',T68,'NUMBER OF STEPS ANALYZED'/
     1T40,F10.2, T76,I5////)
```

```
      WRITE(6,40)
40    FORMAT( 1H1,6(/),T46,'PYROTECHNIC GAS(TP-Q-3027)PROPERITIES'// )
      WRITE(6,41)MOL,TEMFLM,R,KG,SPHTPR,SPHTVL
41    FORMAT( T5 ,'MOL.WEIGHT',T22,'FLAME TEMP.(F)',T41,
     1'GAS CONST.-R(IN-LBF/LBM-R)',T72,'SP. HEAT RATIO' ,T91,
     2'CPO(BTU/LBM-R)',T110,'CVO(BTJ/LBM-R)'/
     3T4,F10.5,T21,F10.0,T47,F10.2,T74,F8.4,T93,F8.4,T112,F8.4//)
      WRITE(6,42)RHOFAC,PRSFAC,TMPFAC,CONGAS,MDFAC
42    FORMAT( T6 ,'DEN. FACTOR',T30,'PRES. FACTOR',T54,
     1'TEMP. FACTOR',T80,'STAG. PRES. FACTOR',T112,'FLOW FACTOR'/
     2T5,F10.4,T29,F10.4,T53,F10.4,T81,F12.0,T110,F10.4 ////)
      WRITE(6,50)
50    FORMAT( T55,'RAM DESIGN PARAMETERS'// )
      WRITE(6,51)PRESRF,PRESSI,SFTFAC
51    FORMAT(T16,'DESIGN PRES.-MEM.2(LBF/IN**2)',T81,
     1'DESIGN  PRES.-MEMS.3 AND 4(LBF/IN**2)', T58,'SAFETY FACTOR'/
     2T23,F10.1,T92,F10.1, T56,F10.2//)
      WRITE(6,52)STRSSU,STRSSY,RHO
52    FORMAT( T10,'RAM MATERIAL',T32,'ULTIMATE STRENGTH(LBF/IN**2)',T70,
     1'YIELD POINT(LBF/IN**2)',T103,'DENSITY(LBM/IN**3)'/
     2T10,'INCONEL 718',T40,F10.0,T74,F10.0,T104,F10.4////)
      WRITE(6,60)
60    FORMAT( T49,'RAM SIZING AND OPERATIONAL FACTORS'// )
      WRITE(6,61)VOLFAC,WTEFAC,THDFAC,INRFAC,TIMFAC
61    FORMAT( T9,'VOLFAC',T29,'ERROR FACTOR',T54,'THC/PORT DIA.'
     1T79,'INERTIA FACTOR',T107,'TIMEF/TIMEA'/
     2T9,F5.2,T32,F5.2,T58,F5.2,T80,F10.6,T105,F9.2 //  )
      WRITE(6,62)LT1FAC,LT2FAC,LT3FAC,LT4FAC,LTSFAC,D23FAC
62    FORMAT(T11,'LT1FAC',T31,'LT2FAC',T51,'LT3FAC',T71,'LT4FAC',
     1T91,'LTSFAC',T111,'D23FAC'/
     2T7,F9.2,T27,F9.2,T47,F9.2,T67,F9.2,T87,F9.2,T107,F9.2////)
      WRITE(6,70)
70    FORMAT( 1H1,9(/),T54,'RAM PHYSICAL DIMENSIONS'/T45,
     1'(INCHES EXCEPT WHERE OTHERWISE SPECIFIED)'// )
      WRITE(6,71)DIA11,DIA12,LN10,LN11,LN12,SPACE1,THC11,THC12,WT1
```

```
71   FORMAT( T62,'MEMBER 1'/T5,'DIA22',T20,'DIA12',T35,'LN10',T50,
    1'LN11',T64,'LN12',T76,'SPACE1',T90,'THC11',T104,'THC12',
    2T116,'WEIGHT(LB)'/ T4,F6.3,T19,F6.3,T34,F6.3,T49,F6.3,
    3T63,F6.3,T76,F6.3,T89,F6.3,T103,F6.3,T118,F7.3//)
     WRITE(6,72)DIA21,DIA22,DIA23,LN21,THC21,THC22,WT2
72   FORMAT( T62,'MEMBER 2'/T16,'DIA21',T32,'DIA22',T48,'DIA23',
    1T64,'LN21',T79,'THC21',T96,'THC22',T111,'WEIGHT(LB)'/
    2T15,F6.3,T31,F6.3,T47,F6.3,T63,F6.3,T78,F6.3,T95,F6.3,T113,F6.3//)
     WRITE(6,73)DIA31,DIA32,LN30,LN31,LN32,THC31,THC32,WT3
73   FORMAT( T62,'MEMBER 3'/T11,'DIA31',T26,'DIA32',T41,'LN30',
    1T56,'LN31',T71,'LN32',T86,'THC31'T101,'THC32',T113,'WEIGHT(LB)'/
    2T7,F9.3,T22,F9.3,T37,F9.3,T52,F9.3,T69,F6.3,T85,F6.3,T97,F9.3,
    3T115,F6.3//)
     WRITE(6,74)DIA41,DIA42,LN41,THC41,THC42,WT4
74   FORMAT( T62,'MEMBER 4' /T25,'DIA41',T40,'DIA42',T56,'LN41',
    1T70,'THC41',T85,'THC42', T99,'WEIGHT(LB)'/
    2T24,F6.3,T39,F6.3,T55,F6.3,T69,F6.3,T84,F6.3,T101,F6.3 //)
     WRITE(6,75)DIA52,LN50,LN51,LN52,WT5
75   FORMAT( T62,'MEMBER 5' /T33,'DIA52',T49,'LN50',T64,'LN51',
    1T78,'LN52', T90,'WEIGHT(LB)'/
    2T32,F6.3,T48,F6.3,T63,F6.3,T76,F6.3, T92,F6.3 //)
     WRITE(6,76)WTGAS,WTERR,WTMEM,WEIGHT
76   FORMAT( T56,'WEIGHT SUMMARY(LB)'/
    1T17,'GAS WEIGHT',T46,'WEIGHT-ERROR',T72,'WEIGHT-MEMBERS',
    2T102,'TOTAL WEIGHT' / T18,F6.1,T44,F10.1,T72,F10.1,T101,F10.1////)
     WRITE(6,80)
80   FORMAT(1H1,18(/), T54,'SPECIFIC GAS CONDITIONS'2(/))
     WRITE(6,81)MASSSI,PRESSI,TEMFLM,VOLS
81   FORMAT( T56,'STAG. CHAM.,TIME=0.'/ T27,'MASS(LBM)',T46,
    1'PRES.(LBF/IN**2)',T72,'TEMP.(F)',T93,'VOLUME(IN**3)'/
    2T28,F6.3,T47,F10.1,T69,F10.1,T92,F10.1////)
     TEMPS(NSTEPS)=TEMPS(NSTEPS)-460.
     WRITE(6,82)MASSS(NSTEPS),PRESSF,PRESS(NSTEPS),TEMPS(NSTEPS),VOLS
82   FORMAT( T53,'STAG. CHAM.,TIME=TFINAL'/T5,'MASS(LBM)',T20,
    1'MIN. PRES. FOR CHOKED FLOW (LBF/IN**2)',T65,'ACT. FINAL PRES(LBF/
```

```
      2IN**2)',T98,'TEMP.(F)',T113,'VOLUME(IN**3)'/
      3T6,F6.3,T33,F10.1,T71,F10.1,T95,F10.1,T112,F10.1//)
       TEMPS(NSTEPS)=TEMPS(NSTEPS)+460.
       TEMPR(NSTEPS)=TEMPR(NSTEPS)-460.
       WRITE(6,83)MASSR(NSTEPS),PRESRF,TEMPR(NSTEPS),VOLRF
 83    FORMAT( T55,'RAM CHAM.,TIME=TFINAL'/ T28,'MASS(LBM)'T46,
      1'PRES.(LBF/IN**2)'T72,'TEMP.(F)',T92,'VOLUME(IN**3)'/
      2T29,F6.3,T47,F10.1,T69,F10.1,T91,F10.1////)
       TEMPR(NSTEPS)=TEMPR(NSTEPS)+460.
```

```
COMMENT ********** PRINTOUT OPERATIONAL HISTORY **********
      WRITE(6,90)
 90   FORMAT(1H1,15(/),T59, 'HISTORY(DYNAMICS)' //
     1T7,'TIME FROM ZERO(SEC)',T30,'TIME BEG. MOT.(SEC)',
     2T55,'DISP.(IN)',T70,'VEL.(IN/SEC)',T87,'FORCE(BOTTOM,LBF)',
     3T110,'FORCE(OUTPUT,LBF)')
      DO 91 I=1,NSTEPS
 91   WRITE(6,92)TIME(I),TIMEAM(I),X(I),XD(I),FRAM(I),FOUT(I)
 92   FORMAT( T10,F8.4,T35,F8.4,T55,F8.4,T70,F8.4,T87,F12.2,T110,F12.2)
      WRITE(6,100)
 100  FORMAT(1H1,15(/),T55,'HISTORY(GAS IN RAM CHAM.)'//
     1T7,'TIME FROM ZERO(SEC)',T29,'MASS FLOW RATE(LBM/SEC)',T54,
     2'MASS(LBM)',T69,'PRES.(LBF/IN**2)',T94,'TEMP(F)',T111,
     3'VOLUME(IN**3)')
      DO 101 I=1,NSTEPS
      TEMPR(I)=TEMPR(I)-460.
 101  WRITE(6,102)TIME(I),MASSDR(I),MASSR(I),PRESR(I),TEMPR(I),VOLR(I)
 102  FORMAT( T12,F8.4,T35,F8.4,T53,F8.4,T69,F10.1,T91,F10.1,
     1T109,F10.1)
      WRITE(6,110)
 110  FORMAT( 1H1,15(/),T51,'HISTORY(GAS IN STAG. CHAMBER)'//
     1T5,'TIME FROM ZERO(SEC)',T35,'MASS(LBM)',T58,'PRES.(LBF/IN**2)',
     2T86,'TEMP.(F)',T106,'DENSITY(LBM/IN**2)')
      DO 111 I=1,NSTEPS
      TEMPS(I)=TEMPS(I)-460.
 111  WRITE(6,112)TIME(I),MASSS(I),PRESS(I),TEMPS(I),RHOS(I)
 112  FORMAT( T10,F8.4,T35,F8.4,T59,F10.1,T83,F10.1,T110,F8.4)
      WRITE(6,120)
 120  FORMAT( 1H1,15(/),T55,'HISTORY(GAS IN PORTS)'//
     1T11,'TIME FROM ZERO(SEC)',T70,'GAS VELOCITY(IN/SEC)',
     2T101,'DENSITY(LBM/IN**3)',T50,'TEMP(F)')
      DO 121 I=1,NSTEPS
      TEMPT(I)=TEMPT(I)-460.
 121  WRITE(6,122)TIME(I),TEMPT(I),VELGT(I),RHOT(I)
```

```
122   FORMAT( T13,F10.4,T47,F10.1,T74,F10.1,T104,F10.6)
      WRITE(6,130)
130   FORMAT( 1H1,15(/),T49,'PORTS AND APPROXIMATE LOCATIONS'//
     1T9,'PORT NUMBER',T29,'CUMULATIVE AREA(IN**2)',T59,
     2'AREA(IN**2)',T86,'DIA(IN)',T108,'LOCATION(IN)')
      DO 131 I=1,NSTEPM
131   WRITE(6,132)NUM(I),AREAC(I),AREAT(I),DIAT(I),X(I)
132   FORMAT(T10,I5,T33,F10.6,T59,F10.6,T84,F10.6,T108,F10.6)
      WRITE(6,140)
140   FORMAT(1H1)
      STOP
      END
```

APPENDIX B

COMPUTER PROGRAM RESULTS

PYROTECHNIC RAM ANALYSIS

DATA POINT-ENERGY VS WEIGHT CURVE

ENERGY(FT-LBF)	WEIGHT(LB)
130207.4	301.5

CONFIGURATION PARAMETERS

DIST.B(FT)	INER. BOOSTER(LBM-FT**2)	MASS BOOSTER(LBM)	MASS ORBITER(LBM)	INER. SYS.(SLUG)
83.300	963729152.	321000.	450000.	2479.

RAM OPERATIONAL CHARACTERISTICS

TIME PERC. RAMP	TIME OPER.(SEC)	TIME INCR.(SEC)	TIME 1(SEC)	TIME 2(SEC)	TIME 3(SEC)
40.00	1.3025	0.0640	0.0225	0.5120	1.2800

K1 (LBF/SEC)	FORCE 2(LBF)	DISP.2(IN)	VEL.2(IN/SEC)	ENERGY 2(LBF-FT)
5000.00	2560.00	0.54134	3.17193	80.30

K2 (LBF/SEC**4)	FORCE 3(LBF)	STROKE(IN)	VEL.3(IN/SEC)	ENERGY 3(LBF-FT)
37252.95	100000.00	29.30183	125.80605	130207.44

FRIC. FORCE(LBF)	NUMBER OF STEPS ANALYZED
500.00	21

PYROTECHNIC GAS(TP-Q-3027)PROPERITIES

MOL.WEIGHT	FLAME TEMP.(F)	GAS CONST.-R(IN-LBF/LBM-R)	SP. HEAT RATIO	CPO(BTU/LBM-R)	CVO(BTU/LBM-R)
21.81000	1883.	850.07	1.1950	0.2730	0.2280

DEN. FACTOR	PRES. FACTOR	TEMP. FACTOR	STAG. PRES. FACTOR	FLOW FACTOR
0.6206	0.5654	0.9112	5166983.	0.4364

RAM DESIGN PARAMETERS

DESIGN PRES.-MEM.2(LBF/IN**2)	SAFETY FACTOR	DESIGN PRES.-MEMS.3 AND 4(LBF/IN**2)
3656.0	1.50	15000.0

RAM MATERIAL	ULTIMATE STRENGTH(LBF/IN**2)	YIELD POINT(LBF/IN**2)	DENSITY(LBM/IN**3)
INCONEL 718	183500.	156000.	0.2970

RAM SIZING AND OPERATIONAL FACTORS

VOLFAC	ERROR FACTOR	THC/PORT DIA.	INERTIA FACTOR	TIMEF/TIMEA
0.47	0.20	20.00	0.004840	2.50

LT1FAC	LT2FAC	LT3FAC	LT4FAC	LTSFAC	D23FAC
1.10	1.10	1.10	1.10	1.50	1.50

RAM PHYSICAL DIMENSIONS
(INCHES EXCEPT WHERE OTHERWISE SPECIFIED)

MEMBER 1

DIA22	DIA12	LN10	LN11	LN12	SPACE1	THC11	THC12	WEIGHT(LB)
4.700	6.000	51.953	8.000	43.953	1.000	0.650	0.715	175.605

MEMBER 2

DIA21	DIA22	DIA23	LN21	THC21	THC22	WEIGHT(LB)
6.000	6.179	9.269	44.953	0.090	0.099	24.854

MEMBER 3

DIA31	DIA32	LN30	LN31	LN32	THC31	THC32	WEIGHT(LB)
2.749	3.087	37.302	29.302	8.000	0.169	0.185	17.120

MEMBER 4

DIA41	DIA42	LN41	THC41	THC42	WEIGHT(LB)
5.000	5.613	8.000	0.307	0.337	17.098

MEMBER 5

DIA52	LN50	LN51	LN52	WEIGHT(LB)
1.000	60.953	5.000	3.000	14.218

WEIGHT SUMMARY(LB)

GAS WEIGHT	WEIGHT-ERROR	WEIGHT-MEMBERS	TOTAL WEIGHT
2.9	49.8	248.9	301.5

SPECIFIC GAS CONDITIONS

STAG. CHAM.,TIME=0.

MASS(LBM)	PRES.(LBF/IN**2)	TEMP.(F)	VOLUME(IN**3)
2.851	15000.0	1883.0	378.6

STAG. CHAM.,TIME=TFINAL

MASS(LBM)	MIN. PRES. FOR CHOKED FLOW (LBF/IN**2)	ACT. FINAL PRES(LBF/IN**2)	TEMP.(F)	VOLUME(IN**3)
1.412	6465.7	6480.1	1583.1	378.6

RAM CHAM.,TIME=TFINAL

MASS(LBM)	PRES.(LBF/IN**2)	TEMP.(F)	VOLUME(IN**3)
1.439	3656.0	1968.7	812.3

HISTORY(DYNAMICS)

TIME FROM ZERO(SEC)	TIME BEG. MOT.(SEC)	DISP.(IN)	VEL.(IN/SEC)	FORCE(BOTTOM,LBF)	FORCE(OUTPUT,LBF)
0.0225	0.0	0.0	0.0	500.00	0.0
0.0865	0.0640	0.0011	0.0496	820.00	320.00
0.1505	0.1280	0.0085	0.1982	1140.00	640.00
0.2145	0.1920	0.0285	0.4461	1460.00	960.00
0.2785	0.2560	0.0677	0.7930	1780.00	1280.00
0.3425	0.3200	0.1322	1.2390	2100.00	1600.00
0.4065	0.3840	0.2284	1.7842	2420.00	1920.00
0.4705	0.4480	0.3627	2.4285	2740.00	2240.00
0.5345	0.5120	0.5413	3.1719	3060.00	2560.00
0.5985	0.5760	0.8556	4.1895	4600.62	4100.62
0.6625	0.6400	1.2521	5.7751	6750.00	6250.00
0.7265	0.7040	1.7738	8.1390	9650.62	9150.62
0.7905	0.7680	2.4783	11.5379	13460.00	12960.00
0.8545	0.8320	3.4416	16.2795	18350.57	17850.57
0.9185	0.8960	4.7609	22.7275	24509.93	24009.93
0.9825	0.9600	6.5585	31.3059	32140.54	31640.54
1.0465	1.0240	8.9862	42.5036	41459.82	40959.82
1.1105	1.0880	12.2292	56.8796	52700.55	52200.55
1.1745	1.1520	16.5105	75.0668	66109.88	65609.88
1.2385	1.2160	22.0966	97.7772	81950.56	81450.56
1.3025	1.2800	29.3017	125.8060	100499.63	99999.63

HISTORY(GAS IN RAM CHAM.)

TIME FROM ZERO(SEC)	MASS FLOW RATE(LBM/SEC)	MASS(LBM)	PRES.(LBF/IN**2)	TEMP(F)	VOLUME(IN**3)
0.0225	0.0021	0.0000	18.2	2600.6	6.9
0.0865	0.0005	0.0001	29.8	2598.4	6.9
0.1505	0.0006	0.0001	41.5	2574.9	7.1
0.2145	0.0009	0.0002	53.1	2522.2	7.7
0.2785	0.0014	0.0002	64.8	2446.2	8.7
0.3425	0.0021	0.0003	76.4	2363.5	10.5
0.4065	0.0031	0.0005	88.0	2288.9	13.2
0.4705	0.0045	0.0007	99.7	2229.3	16.8
0.5345	0.0093	0.0011	111.3	2185.0	21.8
0.5985	0.0218	0.0019	167.4	2645.0	30.4
0.6625	0.0457	0.0039	245.6	2628.8	41.3
0.7265	0.0891	0.0078	351.1	2495.3	55.6
0.7905	0.1672	0.0153	489.7	2368.7	75.0
0.8545	0.3048	0.0292	667.6	2271.7	101.5
0.9185	0.5422	0.0543	891.6	2201.7	137.7
0.9825	0.9431	0.0986	1169.2	2151.4	187.2
1.0465	1.6060	0.1750	1508.2	2114.1	253.9
1.1105	2.6826	0.3041	1917.2	2083.7	343.0
1.1745	4.4114	0.5184	2405.0	2054.5	460.7
1.2385	7.1888	0.8688	2981.2	2019.6	614.3
1.3025	8.9022	1.4385	3656.0	1968.7	812.3

HISTORY(GAS IN STAG. CHAMBER)

TIME FROM ZERO(SEC)	MASS(LBM)	PRES.(LBF/IN**2)	TEMP.(F)	DENSITY(LBM/IN**2)
0.0225	2.8509	14999.7	1883.0	0.0075
0.0865	2.8509	14999.5	1883.0	0.0075
0.1505	2.8509	14999.3	1883.0	0.0075
0.2145	2.8508	14999.0	1883.0	0.0075
0.2785	2.8507	14998.6	1883.0	0.0075
0.3425	2.8506	14997.9	1882.9	0.0075
0.4065	2.8505	14996.9	1882.9	0.0075
0.4705	2.8502	14995.4	1882.9	0.0075
0.5345	2.8499	14993.2	1882.8	0.0075
0.5985	2.8490	14987.9	1882.7	0.0075
0.6625	2.8471	14975.7	1882.4	0.0075
0.7265	2.8432	14951.1	1881.8	0.0075
0.7905	2.8357	14904.0	1880.5	0.0075
0.8545	2.8218	14816.8	1878.3	0.0075
0.9185	2.7967	14659.4	1874.2	0.0074
0.9825	2.7524	14382.3	1867.0	0.0073
1.0465	2.6760	13906.4	1854.2	0.0071
1.1105	2.5468	13108.2	1832.0	0.0067
1.1745	2.3326	11801.6	1793.1	0.0062
1.2385	1.9822	9715.4	1722.7	0.0052
1.3025	1.4124	6480.1	1583.1	0.0037

HISTORY(GAS IN PORTS)

TIME FROM ZERO(SEC)	TEMP(F)	GAS VELOCITY(IN/SEC)	DENSITY(LBM/IN**3)
0.0225	1674.8	28934.1	0.004674
0.0865	1674.8	28934.1	0.004674
0.1505	1674.8	28934.0	0.004674
0.2145	1674.8	28934.0	0.004673
0.2785	1674.8	28933.9	0.004673
0.3425	1674.8	28933.8	0.004673
0.4065	1674.8	28933.7	0.004673
0.4705	1674.7	28933.4	0.004673
0.5345	1674.7	28933.1	0.004672
0.5985	1674.6	28932.2	0.004671
0.6625	1674.3	28930.3	0.004667
0.7265	1673.7	28926.5	0.004661
0.7905	1672.6	28919.0	0.004649
0.8545	1670.6	28905.1	0.004626
0.9185	1666.9	28880.0	0.004585
0.9825	1660.3	28835.1	0.004512
1.0465	1648.6	28756.0	0.004387
1.1105	1628.4	28617.6	0.004175
1.1745	1592.9	28373.5	0.003824
1.2385	1528.8	27926.8	0.003249
1.3025	1401.6	27019.1	0.002315

PORTS AND APPROXIMATE LOCATIONS

PORT NUMBER	CUMULATIVE AREA(IN**2)	AREA(IN**2)	DIA(IN)	LOCATION(IN)
1	0.000016	0.000016	0.004483	0.0
0	0.000016	0.0	0.0	0.001057
0	0.000016	0.0	0.0	0.008458
0	0.000016	0.0	0.0	0.028547
0	0.000016	0.0	0.0	0.067668
0	0.000016	0.0	0.0	0.132163
0	0.000016	0.0	0.0	0.228378
2	0.000034	0.000018	0.004764	0.362656
3	0.000069	0.000035	0.006707	0.541341
4	0.000161	0.000092	0.010826	0.855567
5	0.000338	0.000177	0.015026	1.252090
6	0.000661	0.000323	0.020276	1.773756
7	0.001244	0.000582	0.027229	2.478330
8	0.002279	0.001036	0.036313	3.441604
9	0.004095	0.001816	0.048085	4.760860
10	0.007249	0.003154	0.063368	6.558531
11	0.012731	0.005482	0.083546	8.986238
12	0.022452	0.009721	0.111254	12.229156
13	0.040659	0.018207	0.152254	16.510498
14	0.079218	0.038559	0.221574	22.096558