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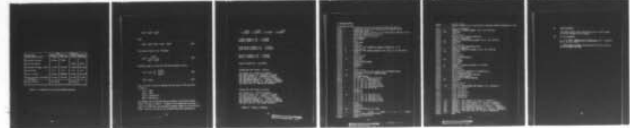
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Optimum Launch Vehicle Sizing- **LEVEL**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A FORTRAN program that computes the optimum sizing parameters of a multi-stage rocket in powered ascent has been developed. The computer program is based upon an optimization procedure, due to Ruppe, which maximized the payload weight to total launch vehicle weight. Based upon a simplified aerodynamic model, the optimization procedure is convenient to use and provides useful approximate values of launch vehicle sizing parameters for launch vehicle of n stages, where n = 0, 1, 2. . . A numerical example is given to illustrate the utility of the FORTRAN program.		

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OPTIMUM LAUNCH VEHICLE SIZING

I. INTRODUCTION

In launch vehicle sizing, it is often necessary to determine the relationships between the parameters of vehicle size and the parameters of mission requirements for multi-stage rockets in powered ascent. Relationships of this type are generally arrived at as a result of an optimization procedure based upon some reasonable criterion, such as maximizing the payload weight to launch weight ratio, or minimizing the total launch vehicle cost. In a particular situation, the mission may be to attain certain launch altitude and velocity. Then, if a set of preliminary design parameters are also known (such as the number of stages, the specific impulse of the stages and the structure ratios of each stage), the output of the optimization program will provide sizing parameters for each of the launch vehicle stages.

The major forces experienced by a multi-stage rocket in powered ascent are: a thrust force from the rocket motors, aerodynamic forces of drag and lift and a gravitational force of attraction towards the earth. Drag and lift forces are nonlinear functions of vehicle velocity, while the gravitation force depends upon vehicle altitude and is also a nonlinear function of altitude. Because of these facts, a general analytical optimization procedure for launch vehicle sizing taking into account the aerodynamic forces and the gravitational force, remains an unsolved problem. For cases where precise values of vehicle sizing are required, designers have resorted to large scale numerical computation programs which examines the value of each parameter individually while fixing the value of remaining parameters. While this numerical method does provide more accurate values, compared to those from an optimization procedure to be discussed, it is time consuming, tedious and does not provide a picture of the relationships between the parameters of launch vehicle size and the parameters of mission requirement. In addition, in a preliminary vehicle design effort an optimization approach based upon a simplified model often provides results of sufficient accuracy.

In this report, a brief description of an optimization procedure for launch vehicle sizing for multi-stage rockets in powered flight based upon a

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simplified model will be presented. This will be followed by an outline of the analytical relationships for a Fortran program which can be used to compute preliminary launch vehicle parameters.

II. OPTIMIZATION OF PAYLOAD WEIGHT TO TOTAL LAUNCH WEIGHT RATIO

In this section, we briefly describe an optimization procedure due to Ruppe¹ which can be used to compute the launch vehicle parameters for the case when the payload-to-launch weight ratio is optimized (maximized). The analytical procedure is developed by assuming the step rocket is in vertical ascent, in vacuum, under constant thrust per stage. Under these assumptions, the gravitational and aerodynamic forces are neglected so that the assumed model is not realistic. However, for initial vehicle sizing, the results obtained do provide useful information.

The optimum weight distribution for a multi-stage or step rocket in vertical ascent, under constant thrust (per stage), in vacuum will be outlined. First the following definitions are required:

$w_0(i)$ = weight of vehicle at ignition of step No. i

$w_c(i)$ = weight of vehicle at cutoff of step No. i

$w_1(i)$ = payload weight of step No. i

= weight of vehicle at ignition of step No. $i + 1$

$w_s(i)$ = weight of structure of step No. i

Figure 1 shows a 3-stage multi-stage rocket.

In a multi-stage rocket, the first stage accelerates to a burnout velocity V_1 , at which time the exhausted first stage structure is ejected and the second stage ignition starts. The second stage, which starts with initial velocity V_1 , accelerates the vehicle by a velocity increment of V_2 , so that at the end of stage two burn, the vehicle velocity is $V_1 + V_2$. This process continues for additional stages until the final burnout velocity of the payload is given by $V_1 + V_2 + \dots + V_N$, where N is total number of stages. To continue, the following definition will also be required:

MASS ratio of step No. i

$$r_i = \frac{w_0(i)}{w_c(i)} \quad (1)$$

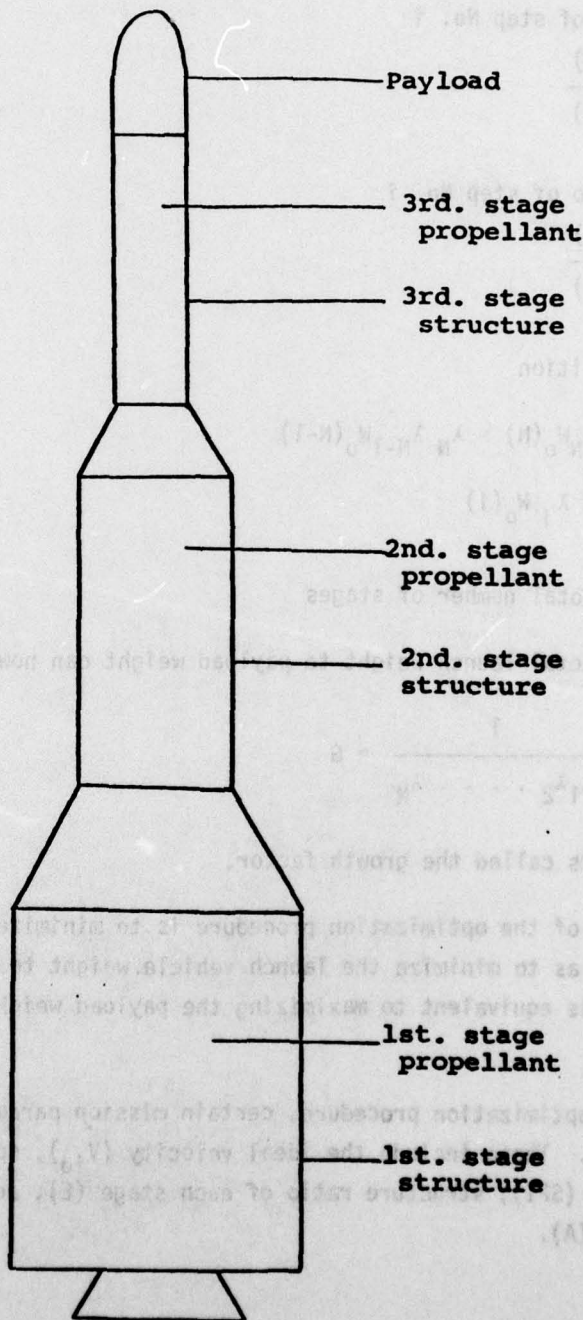


Fig. 1 - 3 Stage Rocket

Payload ratio of step No. i

$$\lambda_i = \frac{W_1(i)}{W_0(i)} \quad (2)$$

Structure ratio of step No. i

$$E_i = \frac{W_s(i)}{W_0(i)} \quad (3)$$

From the definition

$$\begin{aligned} W_1(N) &= \lambda_N W_0(N) = \lambda_N \lambda_{N-1} W_0(N-1) \\ &= \prod_1^N \lambda_i W_0(i) \end{aligned} \quad (4)$$

N = Total number of stages

The ratio of total launch weight to payload weight can now be written as

$$\frac{W_0(i)}{W_1(N)} = \frac{1}{\lambda_1 \lambda_2 \dots \lambda_N} = G \quad (5)$$

Where G is called the growth factor.

The objective of the optimization procedure is to minimize the growth factor, G, so as to minimize the launch vehicle weight to payload weight ratio. This is equivalent to maximizing the payload weight to launch weight ratio.

In the Ruppe optimization procedure, certain mission parameters are assumed known. These include the ideal velocity (V_{id}), specific impulse of each stage (SPI), structure ratio of each stage (E), and the initial load factors (A).

The ideal velocity is defined by:

$$V_{id} = V_m + V_w + V_{er} + V_{s1} + V_g + V_a \quad (6)$$

where V_m is the desired mission velocity, V_w is the velocity component allocated for launch windows capability, V_{er} is the velocity component due to earth rotation, V_{s1} is the velocity component for system losses (such as variations in motor efficiency), V_g is velocity component due to gravity loss and V_a is velocity component due to aerodynamic effects, such as drag and lift.

Then, the optimization procedure first solves for the unknown, λ_N from

$$\bar{R} = \frac{\prod_{i=1}^N \left(1 - \frac{C_N}{C_i} \frac{\lambda_N}{E_N + \lambda_N} \right) C_i / \bar{C}}{\prod_{i=1}^N E_i C_i / \bar{C}} \quad (7)$$

where \bar{R} is computed from

$$\bar{R} = \exp(V_{id} / \bar{C}) \quad (8)$$

With \bar{C} being the average exhaust velocity of the stages given by

$$\bar{C} = \frac{1}{N} \sum_{j=1}^N C_j \quad (9)$$

where C_j is the exhaust velocity of gas of j th. stage. Under our assumption of vacuum and constant gravitational acceleration,

$$C_j = SPI_{(j)} g_0 \quad (10)$$

where $SPI_{(j)}$ is the specific impulse of j th. stage and g_0 is the acceleration of gravity at earth's surface.

Since in Eq. 7, λ_N is the only unknown, the value of λ_N must be solved by an iterative procedure. Once this is accomplished, $\lambda_i, i = 1, 2 \dots N-1$, can be obtained from

$$\lambda_i = \frac{E_i}{1 - \frac{C_N}{C_i} \left(\frac{\lambda_N}{E_N + \lambda_N} \right)} - E_i. \quad (11)$$

With λ_i now known, the calculation can proceed to determine the parameters of vehicle sizing in the following:

Stage Weight (lbs)

$$W_0(1) = G \cdot \text{PAY}(N) \quad (12)$$

Fuel Weight (lbs)

$$W_f(i) = W_0(i) \left(\frac{r_i - 1}{r_i} \right)$$

$$r_i = \frac{1}{\lambda_i + E_i} \quad (13)$$

Structure Weight (lbs)

$$W_s(i) = W_0(i) \cdot E_i \quad (14)$$

Payload Weight of ith stage (lbs)

$$\text{PAY}(i) = W_0(i) - W_f(i) - W_s(i) \quad (15)$$

Exhaust Velocities (kilometer/sec)

$$C_i = \text{SPI}(i) \cdot g_0 \quad (16)$$

Thrust (lbs)

$$T(i) = A(i)W_0(i) \quad (17)$$

Burn time (sec)

$$T_b(i) = \frac{W_f(i)}{T(i)} \cdot SPI(i) \quad (18)$$

III. FORTRAN PROGRAM

Rally I (Section V) is a Fortran program which computes the launch parameters of a step rocket for the case when the payload weight to launch vehicle weight is maximized. The program is based upon the model which assumes the step rocket is in vertical ascent, in vacuum, and under constant thrust per stage. Although these assumptions may seem somewhat restrictive, the results obtained do provide first order approximations for launch vehicle design.

A list of the program INPUTS and OUTPUTS will now be provided:

INPUTS

- A. Structure ratios, E_1 , entered as data in step 200 under EPS for values corresponding to stages 1, 2, 3, . . . N, in order.
- B. Stage exhaust velocities (kilometer/sec), entered as DATA in step 200 under C for stages 1, 2, 3, . . . N in order.
- C. Specific impulses, entered as DATA in step 210 under SPI for stages 1, 2, 3, . . . N in order.
- D. Initial load factors (ratio of thrust to stage weight) entered as DATA in step 220 under AK for stages 1, 2, 3, . . . N in order.
- E. Payload weight, entered in step 400 under PAY in lbs.
- F. Number of stages, entered in step 500 under N. There is no restriction on the value of N, except the values in the DIMENSION size (steps 100, 110, 120) must be made equal to or greater than N.

G. Ideal velocity, V_{id} (kilometers/sec), entered in step 600 under VID.

OUTPUTS

The OUTPUTS of RALLY 1 are:

- A. The growth factor, G
- B. Thrust (lbs) per stage
- C. Stage weight (lbs) per stage
- D. Fuel weight (lbs) per stage
- E. Payload weight (lbs) per stage
- F. Structure weight (lbs) per stage
- G. Specific impulse (seconds) per stage
- H. Burn time (seconds) per stage

IV. NUMERICAL EXAMPLES

In this section, a sample calculation will be given to show the use of FORTRAN Program RALLY 1. For convenience, we consider a 2-stage rocket whose mission is to launch a payload into a circular orbit at an altitude of 100 nautical miles. The mission parameters for this example are given in a U. S. Air Force document titled: Space Planner's Guide², (SPG), page V-20. In this document, a graphic procedure for vehicle sizing, which maximizes the payload weight to launch vehicle weight, is given. The results of this graphic procedure will be compared to the values obtained from Rally 1.

A. Mission Parameter

The following mission parameters were given in SPG

Orbit	100 Nautical Miles, Circular	
Number of stages	2	
Payload Weight	81,324 lbs	
Ideal velocity	32,480 ft/sec	
Vacuum specific impulse	Stage 1 395 sec	Stage 2 419 sec
Thrust to weight ratio	1.3	1.0

TABLE 1 - Mission Parameters (SPG)

B. Rally 1 Parameters

In order to use Rally 1, the mission parameters of Table 1 are converted into appropriate units shown in Table 2.

Number of stages	2	
Payload Weight	81,324 lbs	
Ideal Velocity	9.885 km/sec	
	STAGE 1	STAGE 2
Exhaust velocity	3.871 km/sec	4.1062 km/sec
Load factors	1.3	1.0
Structure ratio	.0665	.0965
Specific impulse	395	419

TABLE 2 - Rally 1 Inputs

In Table 2, the ideal velocity was obtained simply by conversion of units into km/sec. The exhaust velocity was obtained by using Eq. 16.

$$c_j = \text{SPI}(j) \cdot g_0 \quad (18)$$

where c_j is the exhaust velocity of the j th stage, g_0 is the acceleration of gravity at earth's surface (km/sec), and $\text{SPI}(j)$ is the vacuum specific impulse. The values of "structure ratios", E , are computed from the values of "structure factor" and the values of stage weights shown in Table 3 for the SPG case. Since the definition of "structure factor" is

$$S_f(i) = \frac{W_s(i)}{W_0(i)} \quad (19)$$

where $S_f(i)$ is the structure factor of i th stage, $W_s(i)$ is the structure weight of i th stage and $W_0(i)$ is the stage weight of i th stage only (does not include weight of stages $i + 1, i + 2, \dots, N$); the relationship between $E(i)$ and $S_f(i)$ can be determined by noting

PARAMETERS	SPG		RALLY 1	
	STAGE 1	Stage 2	Stage 1	Stage 2
Stage weight (lbs)	1.854m	386,000	1.875m	360,045
Structure factor	0.0840	.0965		
Structure Ratio			.0665	.0965
Propellant Weight (lbs)	1.340m	275,000	1,389m	244,343
Load Factor	1.3	1.0	1.3	1.0
Thrust (lbs)	2.41m	286,000	2.44m	360,450
Stage Velocity Increment (ft/sec)	16,050	16,400	17,197	15,285
Growth factor	22.798		23.057	

Table 3 - Comparison of SPG and Rally Results

$$W_0'(1) = W_0'(1) + W_0'(2).$$

Since

$$W_0(2) = W_0'(2), W_0'(1) = W_0(1) - W_0'(2) \quad (20)$$

The structure factor of Eq. 19 becomes

$$S_f(1) = \frac{W_s(1)}{W_0(1) - W_0'(2)} \quad (21)$$

Dividing by $W_0(1)$, we note the relationship between E and S_f

$$E(1) = S_f(1) \left(1 - \frac{W_0(2)}{W_0(1)} \right) \quad (22)$$

$$E(2) = S_f(2) \quad (23)$$

Thus E (1) and E (2) can be computed from the values of SPG data given in Table 3.

$$S_f(1) = .0840$$

$$S_f(2) = .0965$$

$$W_0(1) = 1,854,000 \text{ lbs}$$

$$W_0(2) = 386,000 \text{ lbs}$$

The computed values of launch vehicle parameters using Fortran Program Rally 1 are shown in Table 4. A summary of the computations are shown in Table 3 for comparison, and reasonable agreement between the SPG values and Rally 1 values can be seen for the 2-stage rocket under consideration.

.....CBARRBARXLAMB
...3.98860 ...11.92114 ...0.70042 ...0.22562

LAMBDA NUMBER 1 IS ...0.19223
LAMBDA NUMBER 2 IS ...0.22562

LOAD RATIO NUMBER 1 IS ...3.86501
LOAD RATIO NUMBER 2 IS ...3.10446

DELTA V NUMBER 1 IS ...5.23345
DELTA V NUMBER 2 IS ...4.65166

GROWTH FACTOR IS ...23.05693

PARAMETERS FOR STAGE 1 FOLLOW

THE THRUST IS ...2437606.7 POUNDS
THE STAGE WEIGHT IS ...1875082.1 POUNDS
THE FUEL WEIGHT IS ...1389938.6 POUNDS
THE PAYLOAD WEIGHT IS ...360450.5 POUNDS
THE STRUCTURE WEIGHT IS ...124693.0 POUNDS
THE SPECIFIC IMPULSE IS ...395.00000 SECONDS
THE BURN TIME IS ...225.23147 SECONDS

PARAMETERS FOR STAGE 2 FOLLOW

THE THRUST IS ...360450.5 POUNDS
THE STAGE WEIGHT IS ...360450.5 POUNDS
THE FUEL WEIGHT IS ...244343.1 POUNDS
THE PAYLOAD WEIGHT IS ...81324.0 POUNDS
THE STRUCTURE WEIGHT IS ...34783.5 POUNDS
THE SPECIFIC IMPULSE IS ...419.00000 SECONDS
THE BURN TIME IS ...284.03271 SECONDS

TABLE 4 - Rally 1 OUTPUTS

V. PROGRAM LISTING

```

.TYPE PALLY1.FDR
00100 ..... DIMENSION EPS (5) ,C (5) ,ALAM (5) ,RATIO (5) ,DELY (5)
00110 ..... DIMENSION WF (5) ,WS (5) ,SW (5) ,SPI (5) ,THR (5) ,BT (5)
00120 ..... DIMENSION AK (5)
00200 ..... DATA EPS / .0665 , .0965 , 0. , 0. , 0. / , C / 3.871 , 4.1062 , 0. , 0. , 0. /
00210 ..... DATA SPI / 395. , 419. , 0. , 0. , 0. /
00220 ..... DATA AK / 1.3 , 1. , 0. , 0. , 0. /
00300 ..... E = 2.7182818
00400 ..... PAY = 81324.
00500 ..... N = 2
00600 ..... VID = 9.885
00700 ..... TYPE 9
00800 ..... TYPE 3 , N
00900 .. 3 ..... FORMAT ( ' THE NUMBER OF ROCKET STAGES IS ' , I1 )
01000 ..... TYPE 4 , VID
01100 .. 4 ..... FORMAT ( ' THE IDEAL VELOCITY IS ' , F5.1 , ' KM PER SEC. ' )
01200 ..... TYPE 9
01300 ..... CT = 0.0
01400 ..... DO 10 I = 1 , N
01500 ..... CT = CT + C ( I )
01600 .. 10 ..... CONTINUE
01700 ..... CBAR = CT / N .
01800 ..... RBAR = E ↔ ( VID / CBAR )
01900 ..... ANUM = 1.0
02000 ..... DENOM = 1.0
02100 ..... TRX = 0.1
02200 ..... K = 1
02300 .. 40 ..... DO 20 I = 1 , N
02400 ..... ANUM = ( ( 1. - ( C ( N ) / C ( I ) ) ↔ TRX ) ↔ ( C ( I ) / CBAR ) ) ↔ ANUM
02500 ..... DENOM = EPS ( I ) ↔ ( C ( I ) / CBAR ) ↔ DENOM
02600 .. 20 ..... CONTINUE
02700 ..... VAL = ANUM / DENOM
02800 ..... IF ( VAL .LT. RBAR ) GO TO 30
02900 ..... IF ( K .EQ. 1 ) TRX = TRX + 0.1
03000 ..... IF ( K .EQ. 2 ) TRX = TRX + 0.01
03100 ..... IF ( K .EQ. 3 ) TRX = TRX + 0.001
03110 ..... IF ( K .EQ. 4 ) TRX = TRX + 0.0001
03120 ..... IF ( K .EQ. 5 ) TRX = TRX + 0.00001
03200 ..... IF ( K .GT. 5 ) GO TO 32
03300 ..... ANUM = 1.0
03400 ..... DENOM = 1.0
03500 ..... GO TO 40
03510 .. 30 ..... IF ( K .EQ. 1 ) TRX = TRX - 0.1
03520 ..... IF ( K .EQ. 2 ) TRX = TRX - 0.01
03530 ..... IF ( K .EQ. 3 ) TRX = TRX - 0.001
03540 ..... IF ( K .EQ. 4 ) TRX = TRX - 0.0001
03550 ..... IF ( K .EQ. 5 ) TRX = TRX - 0.00001
03600 ..... K = K + 1
03700 ..... ANUM = 1.0
03800 ..... DENOM = 1.0
03900 ..... GO TO 40
04000 .. 32 ..... ALAMN = TRX ↔ EPS ( N ) / ( 1. - TRX )
04100 ..... TYPE 2
04200 .. 2 ..... FORMAT ( ' ..... CBAR ..... RBAR ..... X ..... LAMN ' )
04300 ..... TYPE 1 , CBAR , RBAR , TRX , ALAMN
04400 .. 1 ..... FORMAT ( 4 ( 1X , F10.5 ) )
04500 ..... TYPE 9

```

```

04600 ..... DD 50 I=1,N
04700 ..... ALAM(I) = (EPS(I) / (1 - (C(N) / C(I)) + (ALAMN / ((EPS(N) + ALAMN)))) - EPS
) ..... 1)
04800 ..... TYPE 5,I,ALAM(I)
04900 .. 5 ..... FORMAT(' LAMBDA NUMBER 'rI'r' IS 'rF10.5)
05000 .. 50 ..... CONTINUE
05100 ..... TYPE 9
05200 ..... DD 60 I=1,N
05300 ..... RATIO(I) = 1. / (ALAM(I) + EPS(I))
05400 ..... TYPE 6,I,RATIO(I)
05500 .. 6 ..... FORMAT(' LOAD RATIO NUMBER 'rI'r' IS 'rF10.5)
05600 .. 60 ..... CONTINUE
05700 ..... TYPE 9
05800 ..... DD 70 I=1,N
05900 ..... DELV(I) = C(I) * ALOG(RATIO(I))
06000 ..... TYPE 7,I,DELV(I)
06100 .. 7 ..... FORMAT(' DELTA V NUMBER 'rI'r' IS 'rF10.5)
06200 .. 70 ..... CONTINUE
06300 ..... TYPE 9
06400 ..... ALAMT = 1.0
06500 ..... DD 80 I=1,N
06600 ..... ALAMT = ALAMT + ALAM(I)
06700 .. 80 ..... CONTINUE
06800 ..... G = 1. / ALAMT
06900 ..... ALW = G * PAY
07000 ..... TYPE 8,G
07100 .. 8 ..... FORMAT(' GROWTH FACTOR IS 'rF10.5)
07200 .. 9 ..... FORMAT(' /)
07300 ..... SW(I) = ALW
07400 ..... DD 90 I=1,N
07500 ..... WF(I) = SW(I) * ((RATIO(I) - 1) / RATIO(I))
07600 ..... WS(I) = SW(I) * EPS(I)
07700 ..... SW(I+1) = SW(I) - (WF(I) + WS(I))
07800 ..... THR(I) = AK(I) * SW(I)
07900 ..... BT(I) = WF(I) / THR(I) * SPI(I)
08000 .. 90 ..... CONTINUE
08100 ..... TYPE 9
08200 ..... DD 100 I=1,N
08300 ..... TYPE 140,I
08400 .. 140 ..... FORMAT(' PARAMETERS FOR STAGE 'rI'r' FOLLOW')
08500 ..... TYPE 150,THR(I)
08600 ..... TYPE 160,SW(I)
08700 ..... TYPE 170,WF(I)
08800 ..... TYPE 180,SW(I+1)
08900 ..... TYPE 190,WS(I)
09000 ..... TYPE 200,SPI(I)
09100 ..... TYPE 210,BT(I)
09110 ..... TYPE 9
09200 .. 150 ..... FORMAT(' THE THRUST IS 'rF10.1r' POUNDS')
09300 .. 160 ..... FORMAT(' THE STAGE WEIGHT IS 'rF10.1r' POUNDS')
09400 .. 170 ..... FORMAT(' THE FUEL WEIGHT IS 'rF10.1r' POUNDS')
09500 .. 180 ..... FORMAT(' THE PAYLOAD WEIGHT IS 'rF10.1r' POUNDS')
09600 .. 190 ..... FORMAT(' THE STRUCTURE WEIGHT IS 'rF10.1r' POUNDS')
09700 .. 200 ..... FORMAT(' THE SPECIFIC IMPULSE IS 'rF10.5r' SECONDS')
09800 .. 210 ..... FORMAT(' THE BURN TIME IS 'rF10.5r' SECONDS')
09900 .. 100 ..... CONTINUE
10000 ..... END

```

VI. ACKNOWLEDGEMENTS

The authors express their appreciations to Dr. John N. Hayes for helpful comments on this report.

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2. Space Planner's Guide, United States Air Force, Air Force Systems Command, July 1965.