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EXTENSION OF A SIMPLIFIED COMPUTER PROGRAM FOR ANALYSIS OF SOLID-PROPELLANT ROCKET MOTORS

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Final Report

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16. ABSTRACT This report presents the results of research performed at Auburn University during the period from December 15, 1972, to April 15, 1972, under Modifications Nos. 8, 9 and 10 to the Cooperative Agreement, dated October 6, 1969, between the NASA Marshall Space Flight Center and Auburn University. The research is an extension of that accomplished under Modification No. 6 to the same agreement which culminated in the development of a simplified computer program for preliminary design and performance analysis of solid-propellant rocket motors (SRMs) as reported in Reference 1.

The extension adds the following capabilities to the simplified program as program options.

1. Treatment of "wagon-wheel" cross-sectional propellant configurations alone or in combinations with circular perforated configurations.

2. Calculation of ignition transients with the igniter treated as a small rocket motor.

3. Accurate representation of spherical circular perforated grain ends as an alternative to the conical end surface approximation used in the original program.

4. Graphical presentation of program results using the "CalComp 663" digital plotter.

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ADDITIONAL NOMENCLATURE

See Reference 1 for the basic nomenclature. An asterisk before the symbol indicates an input variable. All input subscripted and non-subscripted variables are listed separately.

English Symbol	Definition	Units Used
A_{GS1}, A_{GS2}, A_{GS}	Cross-section area of a wagon-wheel grain associated with the first, second and both sets of grain points, respectively.	in^2
$*C^*_{ig}$	Characteristic exhaust velocity of the igniter propellant	ft/sec
$*h_1, *h_2$	The half width of the first and second set of points, respectively, of a wagon-wheel grain	in.
$*I_{go}$	Integer designating option of ignition transient calculation.	____
$*I_{po}$	Integer designating option of plotting results	____
$*I_{wo}$	Integer designating option of inert weight calculations	____
$*K_a, *K_b$	Empirical constants in the characteristic velocity versus chamber pressure linear relations (Eq. B4c) used for ignition transient calculations	ft/sec, ft/sec-psia
$*\ell_1, *\ell_2$	The length of the two parallel sides of the first and second set of points, respectively, of a wagon-wheel grain	in.
*N(jj)	Integer designating whether or not a specific output plot is desired	____
$*P_{big}$	Value of chamber pressure P_c at which a nozzle blowout plug in the main motor is ejected	psia

English Symbol	Definition	Units Used
$*P_{mig}$	Maximum chamber pressure attained in the igniter	psia
R_3	Distance from center of curvature of a spherical end of circular perforated grain to the burning surface associated with θ_G	in.
$*R_{ig}$	Average regression rate of the first half of the igniter pressure-time trace	psia/sec
S_{G1}, S_{G2}, S_G	Perimeter of a wagon-wheel grain associated with the first, second and both sets of grain points, respectively.	in.
$*t_{I1}, *t_{I2}$	Time for the igniter, pressure to reach maximum value and to decay to 10 percent of its maximum value, respectively	sec.
$*U_{fs}$	Flame spreading speed during ignition	in/sec
$*V_{ciT}$	Initial volume of chamber gases associated with tabular input	in^3
x_o', y_o'	Coordinates of tips of wagon-wheel grain	in.
x_1', y_1'	Coordinates of intersections of burning slant sides of wagon-wheel grain points with fillet arcs (origins at fillet centers)	in.
Greek Symbol		
$*\alpha_1, *\alpha_2$	The angle between the slant sides of a wagon-wheel grain point and the center line of the point for the first and second set of points, respectively	radians
$*\Delta t_{ig}$	Time increment for ignition transients	sec
θ_{fw}	Angular location of fillet centers with respect to radial centerline of wagon-wheel grain points	radians
λ	Volumetric loading density; i.e., initial volume occupied by propellant divided by empty case volume	____

Greek Symbol	Definition	Units Used
τ_{ww}	Web thickness of wagon-wheel grain.	in.

Subscript	
ig	ignition

I. INTRODUCTION AND SUMMARY

This report presents the results of research performed at Auburn University during the period from December 15, 1972, to April 15, 1972, under Modifications Nos. 8, 9 and 10 to the Cooperative Agreement, dated October 6, 1969, between the NASA Marshall Space Flight Center and Auburn University. The research is an extension of that accomplished under Modification No. 6 to the same agreement which culminated in the development of a simplified computer program for preliminary design and performance analysis of solid-propellant rocket motors (SRMs) as reported in Reference 1.

The extension adds the following capabilities to the simplified program as program options.

1. Treatment of "wagon-wheel" cross-sectional propellant configurations alone or in combinations with circular perforated configurations.

2. Calculation of ignition transients with the igniter treated as a small rocket motor.

3. Accurate representation of spherical circular perforated grain ends as an alternative to the conical end surface approximation used in the original program.

4. Graphical presentation of program results using the "CalComp 663" digital plotter.

In addition, inert weight calculations are made optional in the new program whereas they were required calculations in the original program necessitating specification of input values. Also, the initial and final gaseous chamber volumes are eliminated as input requirements in the new program. These values are now calculated from the other program inputs. Finally, the computer program has been modified in detail for the purpose of simplifying the program and minimizing the computation time. The net result of the extensions, however, is an increase in compilation time to a maximum of about 2 minutes and 20 seconds and an increase in execution time to about 20 seconds in the IBM 360 computer. Almost all of the increase is attributable to the ignition transient calculations. The new program uses approximately 19,000 words on the IBM 360.

The present report is prepared as an addendum to the original report. Familiarity of the reader with Reference 1 is assumed. Thus, the extensive notation of the original report is not repeated; only the new notation is given. The new input variables or deletions are discussed in Section II. The organization of the entire report follows that of the original report and equations are numbered consecutively with respect to the original report to provide for insertion at the appropriate locations in the original analysis. Figures and tables are numbered similarly according to whether they replace or supplement those of the basic report.

Flowcharts of the two new subroutines (ignition and graphical representation) are presented in Section IV but no attempt has been made to modify the flowcharts of the main program because the logic of the modifications is a straightforward extension of that of the original program and is made clear from the mathematical analyses presented in Section III. The new data card format is shown in Table IV-1 and the complete extended program is listed in Table IV-2. Program statements that must be removed in order to delete the CalComp plotter compilation requirements are indicated by check marks (▶) in Table IV-2. Removal of these statements is necessary if the computer is not equipped for "CalComp" plotting. However, if alternate plotters are available, generally only the plotting subroutine need be replaced.

Test cases are given in Section V to illustrate (1) ignition transient calculations, (2) spherical closure effects with circular perforated grains, (3) graphical representation of program result, and (4) computation for "wagon-wheel" cross-sectional grain configuration.

II. DISCUSSION OF INPUT AND OUTPUT

In this section each new input variable is defined in the order in which it is encountered in the program. Deletions or other changes in original variables are similarly treated. As in Reference 1, appropriate additional discussion of the variable and typical numerical values are given. New output variables of the program are also identified and defined.

Users Options

I_{go} (IGO)	0	For no ignition transient computations
	1	For ignition transient computations
I_{wo} (IWO)	0	For no inert weight computations
	1	For inert weight computations
I_{po} (IPO)	0	For no plots
	1	For plots of equilibrium burning only
	2	For plots of ignition transients only
	3	For plots of both ignition transients and equilibrium burning.
N(jj)(NUMPLT(JJ))		An integer designating whether or not a specific output plot is desired:
	0	If a specific plot is not desired
	1	If a specific plot is desired
		The order of specification of NUMPLT(JJ) is as follows:
	1	PHEAD versus T
	2	PONOZ versus T
	3	PHEAD and PONOZ versus T (superimposed)

4 RHEAD versus T

5 RNOZ versus T

6 RHEAD and RNOZ versus T (superimposed)

7 SUMAB versus T

8 SG versus T

9 SUMAB and SG versus T (superimposed)

10 F versus T

11 FVAC versus T

12 F and FVAC versus T (superimposed)

13 VC versus T

14 SUMAB versus Y

15 SG versus Y

16 SUMAB and SG versus Y (superimposed)

Primary Basic Motor Dimensions

V_{ci}, V_{cf} (VCI,VCF) — Initial and final volume of chamber gases, respectively. These are deleted as input variables in the new program except for volume associated with tabular input. See V_{ciT} below.

Ignition Characteristics. Not required if ignition calculations are not desired (IGO = 0)

K_a, K_b (KA,KB) — Empirical constants in the characteristic velocity versus chamber pressure relationship for the main motor (ft/sec, ft/sec-psia). A linear relationship is assumed. Data are obtained from thermochemical calculations.

U_{fs} (UFS) — Flame spreading speed (in/sec). Reference 2 cites a value of 3650 in/sec for one composite type propellant with ammonium perchlorate oxidizer and aluminum additives. Values will differ for various specific propellants.

C^*_{ig} (CSIG) — Characteristic velocity of the igniter propellant (ft/sec).

P_{mig} (PMIG) — Maximum chamber pressure of igniter when discharging into the atmosphere (psia). This pressure is usually established based upon minimization of the igniter weight. It will ordinarily range from 80 to 150 percent of the maximum operating pressure of the main motor.

t_{I1} (TI1) — Time for the igniter pressure to reach its maximum pressure (sec). Values range from 0.010 sec for a small igniter to 0.050 sec for a large igniter.

t_{I2} (TI2) — Time for the igniter pressure to decay to 10 percent of its maximum value when discharging into the atmosphere (psia/sec). Typical values range from 0.2 to 0.5 seconds in smaller igniters to 0.5 to 1.2 in very large igniters.

R_{ig} (RRIG) — Average regression rate of the first half of the igniter pressure time trace (psia/sec). Most igniter traces are generally regressive or two-level with the higher level occurring first. The analysis considers only the first half of the pressure time trace, because the contribution of the mass flow rate of the igniter to total mass flow rate is insignificant beyond this region during a normal ignition.

Δt_{ig} (DELTIG) — Time increment for calculation of ignition transients (sec). A value of 0.001 seconds is recommended for small motors and 0.005 seconds for very large motors.

P_{big} (PBIG) — Value of chamber pressure P_c at which a nozzle blowout plug in the main motor is ejected (psia). If no blowout plug is used, PBIG should be set equal to an estimate of the atmospheric pressure when ignition is initiated.

<u>Basic Properties of Weight Calculations</u>

These inputs as listed in the original program are no longer required if calculation of inert weight is not desired (IWO = 0)

Input to Establish the Program and Basic Grain Configuration and Arrangement

S_{op} (STAR) — Add: 3 for wagon-wheel (See Figure II-4)

C_{op} (COP) — For extreme ends of a circular perforated grain only:

0 If both ends are conical or flat.

1 If head end is conical or flat and aft end is spherical.

2 If both ends are spherical.

3 If head end is spherical and aft end is conical or flat.

If the end of a circular perforated grain is taken spherical, the corresponding angle THETACH or THETACH is not used in the program.

Tabular Burning Surface and Port Areas (Not required for INPUT=2)

V_{ciT} — Initial volume of chamber gases associated with tabular input (in^3)

Basic Geometry for Star Grains

In order to simplify the conversion from the original to the extended program, the wagon-wheel is considered a type of star grain and each variable in this group as listed in the original program must be specified for wagon-wheel as well as standard star or truncated star grains.

Special Geometry for Wagon-Wheel Grain (Not required for standard or truncated star grains (STAR = 1 or 2))

τ_{ww} — The web thickness of wagon-wheel grain (in.). The discussion under TAUWS for standard star grains is applicable.

ℓ_1, ℓ_2 (L1,L2) — The lengths of the pairs of parallel sides of the first and second set of grain points, respectively (in.) (See Figure II-4).

α_1, α_2 (ALPHA1,ALPHA2) — The angles between the slant sides and the center lines of the points of the first and second set of grain points, respectively (radians). The angles should not exceed $\pi/2$ radians.

h_w (HW) — The half-width of the star points (in.). HW must not exceed TAUWW (HW $\leq$ TAUWW).

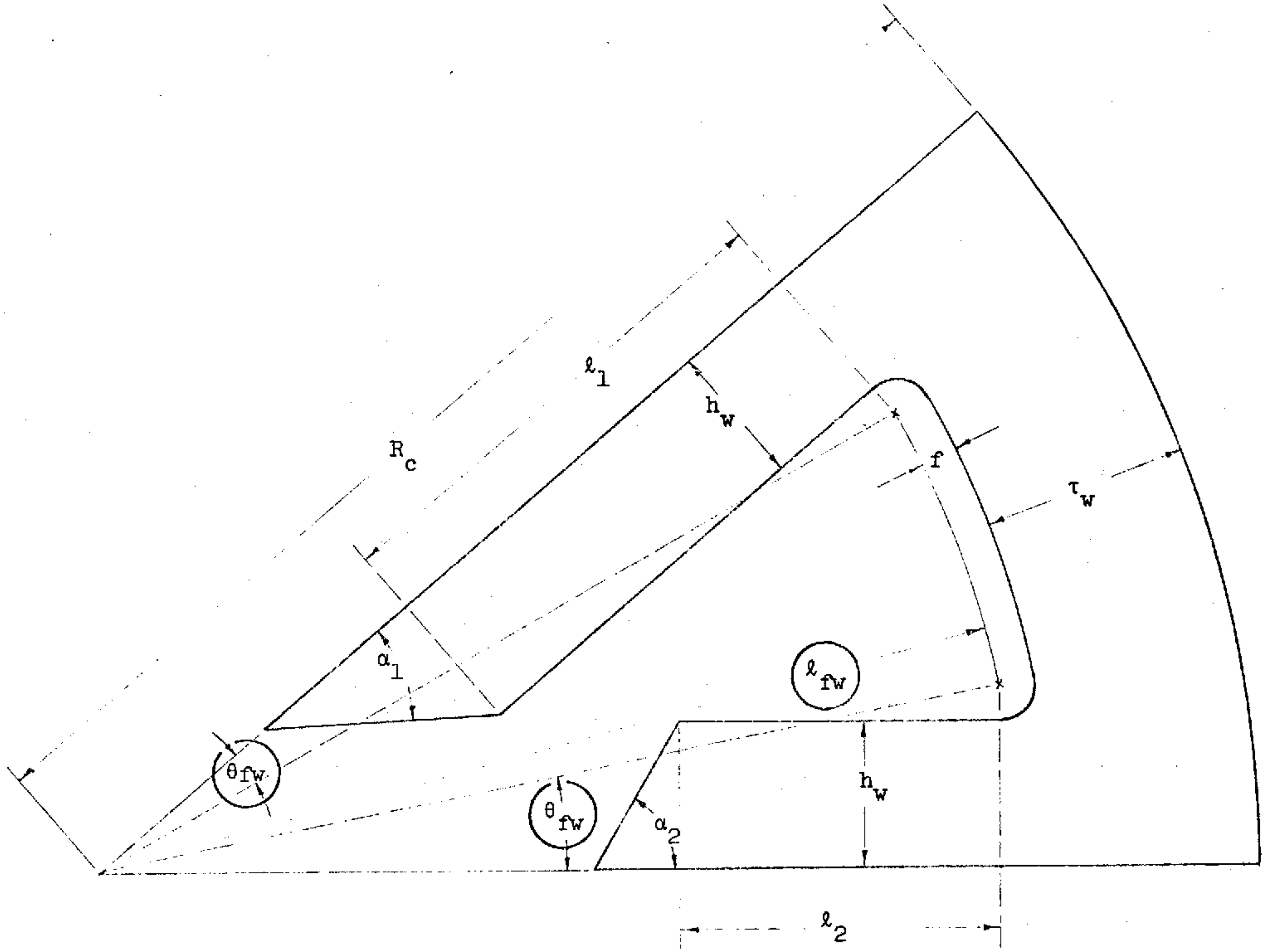

Figure II-4. Wagon-wheel grain cross-section. Calculated variables are circled.

Additional Program Outputs

The outputs listed below are in addition to those of the original program. However, those outputs related to the ignition transient calculations are only obtained when IGO = 1. It should be noted that values of pressure (PONOZ and PHEAD) are based upon the assumption of choked flow through the nozzle and values of delivered thrust (F) and related values (e.g., CF) are based upon the additional assumption of the nozzle flowing full (no separation). This introduces errors in the output parameters mentioned during the initial phase of the ignition.

Outputs as Functions of Time

t_{ig} (TIG)	Operating time during ignition (sec.). This is calculated from the time of initiation of flame spreading.
$P_{c(ig)}$(PCIG)	Chamber pressure within the igniter (psia). This is based on a piecewise linear pressure versus time relation before and after peak igniter pressure is encountered until the main motor pressure feeds back and controls the igniter pressure.

Non-Time Varying Quantities

A^*_{ig} (ASIG)	Required igniter throat cross-sectional area (in^2).
$\dot{m}_{ig(av)}$ (MIGAV)	Average mass flow rate of the igniter discharge over the first half of the igniter burning time excluding time prior to TI1 (slugs/sec).
$W_{ig(tot)}$(WIGTOT)	Estimated total weight of required igniter propellant (lbs.). This is based on the integral of $\dot{m}_{ig}$ over the time interval from TI1 to T12/2 plus a somewhat arbitrary allowance of two-thirds the stated integral to provide sustained heat transfer feedback during the final ignition phase and propellant for the pressure buildup phase within the igniter (see Eq. B9).
V_{ci},V_{cf}(VCI,VCF)	Initial and final volume of chamber gases, respectively (in^3)
λ (LAMBDA)	Volumetric loading density; i.e., initial volume occupied by the propellant divided by the empty case volume (1). Note discussion after Eq. 37d.

III. ANALYSIS

In this section the extensions to the mathematical analysis of the SRM design problem are presented in a step by step procedure following the method of the original report (Reference 1). The steps in the procedure are numbered consecutively with respect to those steps of the original report to permit insertion at the appropriate locations in the original analysis. In the few instances where one of the original analysis steps has been revised, the new analysis step bears the same number as the original step.

Burning Surfaces and Port Areas

End Geometry of Circular Perforated Grains

A0.h. Select an option for the circular perforated grain end configuration.

If both ends are conical or flat, set $C_{op} = 0$.

If head end is conical or flat and aft end spherical, set $C_{op} = 1$.

If head and aft ends are both spherical, set $C_{op} = 2$.

If head end is hemispherical and aft end conical or flat, $C_{op} = 3$.

A4.b. (revised) For the perforations.

If $2_y + D_i > D_o$, set $A_{bnc} = A_{bpc} = 0$, <u>Go to step A5</u>

If not and if $\theta_G \leq 5^\circ$ and

if $C_{op} = 0$, compute

$$L_{Gc} = L_{Gci} - y\ (\cot \theta_{cn} + \theta_{ch})$$

if $C_{op} = 1$ compute

$$L_{Gc} = L_{Gci} - \{[D_o{}^2 - (D_i + \Delta D_i)^2]^{\frac{1}{2}} - [D_o{}^2 - (D_i + \Delta D_i + 2y)^2]^{\frac{1}{2}}\}/2 - y \cot \theta_{ch}$$

if $C_{op} = 2$, compute

$$L_{GC} \approx L_{Gci} - \{[D_o{}^2 - D_i{}^2)^2]^{\frac{1}{2}} - [D_o{}^2 - (D_i + 2y)^2]^{\frac{1}{2}}\}$$

if $C_{op} = 3$, compute

$$L_{Gc} = L_{Gci} - \{[D_o{}^2 - D_i{}^2]^{1/2}$$

$$- [D_o{}^2 - (D_i + 2y)^2]^{1/2}\}/2 - y \cot \theta_{cn}$$

$$A_{bpc} = \pi(D_i + 2y)[L_{Gc} - T_\ell = S\ ] \quad \text{for } A_{bpc} > 0$$

$$A_{bpc} = 0 \text{ for } A_{bpc} \leq 0, \underline{\text{or}}$$

If $\theta_G > 5^\circ$ and

if $C_{op} = 0$ or 1, compute

$$A_{bpc} = \pi(D_i + 2y)\{L_{Gci} - y \cot \theta_{ch}$$

$$- T_\ell - [S + \tan(\theta_G/2)]y\} \quad \text{for } A_{bpc} > 0$$

if $C_{op} = 2$ or 3, compute

$$A_{bpc} = \pi(D_i + 2y) \quad \{L_{Gci} - \{[D_o{}^2 - D_i{}^2]^{1/2}$$

$$- [D_o{}^2 - (D_i + 2y)^2]^{1/2}\}/2 - T_\ell$$

$$- [S + \tan(\theta_G/2)]y\} \quad \text{for } A_{bpc} > 0$$

$$A_{bpc} = 0 \text{ for } A_{bpc} \leq 0.$$

A4.c. (revised) For the nozzle end surface.

If $\theta_G \leq 5^\circ$, set $A_{bnc} = 0$

If $\theta_G > 5^\circ$ and $C_{op} = 1$ or 2

$$R_3 = [(Di + \Delta Di)/2 + L_{Gni} \sin \theta_G] \cos \theta_G$$

$$- (\sin \theta_G) \quad \{(D_o/2)^2 - [(Di + \Delta Di)/2$$

$$+ L_{Gni} \sin \theta_G]^2\}^{1/2} \quad \text{and}$$

$$A_{bnc} = \pi[L_{Gni} - R_3 - y \tan(\theta_G/2)] \{(Di + \Delta Di)/2$$
$$+ y + (\sin\theta_G)[(D_o/2)^2 - (R_3 + y)^2]^{1/2}$$
$$+ (R_3 + y)\cos\theta_G\} \quad \text{for } A_{bnc} > 0$$

$$A_{bnc} = 0 \text{ for } A_{bnc} < 0$$

If $\theta_G > 5^\circ$ and $C_{op} = 0$ or 3

$$A_{bnc} = \pi[L_{Gni} - y\cot(\theta_G + \theta_{cn}) - y\tan(\theta_G/2)][Di+\Delta Di$$
$$+ y + L_{Gni}\sin\theta_G + y\csc(\theta_G + \theta_{cn})\sin\theta_{cn}] \quad \text{for } A_{bnc} > 0$$

$$A_{bnc} = 0 \text{ for } A_{bnc} \leq 0$$

Note: For $\theta_G > 5^\circ$, the entire burning end surface is treated as conical although a non-conical surface area evolves when $\theta_G + \theta_{cn} > \pi/2$ for $C_{op} = 0$ or 3 or when an analogous situation exists for $C_{op} = 1$ or 2.

Wagon-Wheel Cross-Sectional Geometry

A7.c. If $G_{op} = 2$ or 3 and $S_{op} = 3$ Go to step A17a

A17.a. Compute the radius of the fillet centers for a wagon-wheel grain.

$$\ell_{fw} = R_c - \tau_{ww} - f$$

b. Compute the angular location of the fillet centers

$$\theta_{fw} = \text{arc sin } [(h_w + f)/\ell_{fw}]$$

A.18. Compute the grain perimeters S_{G1} and S_{G2} and initial cross-secitonal areas A_{GS1} and A_{GS2} using $\ell = \ell_1$ and $\alpha = \alpha_1$ and then $\ell = \ell_2$ and $\alpha = \alpha_2$ in the following equations.

A18.a. If $y + f \leq \ell_{fw} \sin \theta_{fw}$ and $y \tan(\alpha/2) \leq \ell$,

$$S_G = n_p\,[\ell - 2y \tan(\alpha/2) + (\ell_{fw} \sin \theta_{fw} - f)/\sin \alpha - y \cot \alpha$$
$$+ (f+y)(\pi/2 + \theta_{fw}) + (\ell_{fw} + f + y)(\pi/n_p - \theta_{fw})]$$

<u>Go to step 18c</u>

If $y + f > \ell_{fw} \sin \theta_{fw}$, $y \tan(\alpha/2) \leq \ell$ and

if $y \leq \tau_{ww}$

$$S_G = n_p\,\{(y+f)[\pi/n_p + \arcsin(\frac{\ell_{fw}}{y+f} \sin \theta_{fw})]$$
$$+ \ell_{fw}(\pi/n_p - \theta_{fw})\}$$

<u>Go to step 18c</u>

<u>or</u> if $y > \tau_{ww}$

$$S_G = n_p\,(y+f)\{\theta_{fw} + \arcsin(\frac{\ell_{fw}}{f+y} \sin \theta_{fw})$$
$$- \arccos[\frac{R_c{}^2 - \ell_{fw} - (y+f)^2}{2\ell_{fw}(y+f)}]\} \quad \text{for } S_G > 0$$

$S_G = 0$ for $S_G \leq 0$

<u>Go to step 18c</u>

A18.b. If $y \tan(\alpha/2) > \ell$ compute the coordinates, x_1' and y_1', (origin at fillet center) of intersections of burning slant sides with fillet arcs:

If $\alpha \geq \pi/2$,

$$x_1' = -\ell + y \text{ and}$$
$$y_1' = -[(f+y)^2 - x_1'^2]^{1/2}$$

If $\alpha < \pi/2$

$$Q \equiv -f + \ell \tan \alpha - y/\cos \alpha$$
$$x_1' = -Q \tan \alpha - [-Q^2 + (f+y)^2 \sec^2\alpha]^{1/2} / \sec^2\alpha$$
$$y_1' = x_1' \tan \alpha + Q$$

and the coordinates of the tips of grain points,

$$y_o' = -\ell_{fw} \sin\theta_{fw} \text{ and}$$

$$x_o' = -\ell + y \quad \text{for } \alpha \geq \pi/2 \text{ or}$$

$$x_o' = (y_o' - Q)/\tan\alpha \quad \text{for } \alpha < \pi/2$$

Then compute burning perimeters:

If $y + f \leq [(\ell_{fw} \sin\theta_{fw})^2 + x_1'^2]^{1/2}$ and

if $y < \tau_{ww}$,

$$S_G = n_p\{[(x_1' - x_o')^2 + (y_1' - y_o')^2]^{1/2} + (f+y)[\pi/2 + \theta_{fw} - \arc\sin(\frac{x_1'}{f+y})] + (\ell_{fw} + f+y)(\pi/n_p - \theta_{fw})\}$$

Go to step 18c

or if $y \geq \tau_{ww}$,

$$S_G = n_p\{[(x_1' - x_o')^2 + (y_1' - y_o')^2]^{1/2} + (f+y)[\pi/2 - \arc\sin(\frac{x_1'}{f+y})] - \arc\cos(\frac{R_c^2 - \ell_{fw} - (y+f)^2}{2\ell_{fw}(y+f)})\} \text{ for } S_G > 0$$

$$S_G = 0 \quad \text{for } S_G \leq 0$$

Go to step 18c

If $y+f > [(\ell_{fw} \sin\theta_{fw})^2 + x_1^2]^{1/2}$ and

if $y \leq \tau_{ww}$,

$$S_G = n_p\{(y+f)[\pi/n_p + \arc\sin(\frac{\ell_{fw}}{y+f}\sin\theta_{fw})] + \ell_{fw}(\pi/n_p - \theta_{fw})\}$$

Go to step 18c

or if $y > \tau_{ww}$,

$$S_G = n_p\ (y+f)\ \{\theta_{fw} + \arc\sin\ (\frac{\ell_{fw}}{y+f}\ \sin\theta_{fw}$$

$$- \arc\cos\ [\frac{R_c^2 - \ell_{fw} - (y+f)^2}{2\ell_{fw}\ (y+f)}]\}\quad \text{for } S_G > 0$$

$S_G = 0$ for $S_G \leq 0$

A18.c. If $y \leq 0$, compute the (initial) cross-sectional area of the grain

$$A_{Gs} = (1/2)\{\pi R_c^2 - n_p \ell_{fw}^2 \sin\theta_{fw}[\cos\theta_{fw} - (\sin\theta_{fw})(\cot\alpha)$$

$$- 2\ (\ell + f\tan(\alpha/2))/\ell_{fw}] - (\pi - \theta_{fw} n_p)\ \ell_{fw}^2 - 2n_p f[\ell$$

$$+ \ell_{fw}\sin\theta_{fw})/\sin\alpha + \ell_{fw}(\pi/n_p - \theta_{fw}) + (\pi/n_p$$

$$+ \pi/2 - \csc\alpha)\ f/2]\}$$

A19.a. $S_G = S_{G1} + S_{G2}$

A19.b. $A_{Gs} = A_{G1} + A_{G2}$

Go to step A24

Initial Chamber Volumes

A37.a. If $y > 0$ Go to step 50

A37.b. If $G_{op} = 1$, set $L_{Gsi} = 0$ and $A_{Gs} = 0$

37.c. If $G_{op} = 2$, set $L_{Gci} = 0$ and $L_{Gni} = 0$

37.d. Compute the approximate initial gaseous volume of the chamber,

$$V_{ci} \simeq 1.10\ \{\pi D_i^2(L_{Gni} + L_{Gci})/4$$

$$+ (\pi D_o^2/4 - A_{Gs})L_{Gsi} + n_T \ell_{Tp}\ \pi D_{Tp}^2/4\} + V_{ciT}$$

Go to step 50

Note: The volume is approximate because an approximate relation is used for the volume of the thrust chamber passages and because an arbitrary ten percent additional allowance is made to account for slot volume, end volume and the effect of the convergent portion of the nozzle on the chamber pressure change characteristics. Any error thus introduced in the final volume and the volumetric loading density will be roughly one order of magnitude less than the error in initial volume.

Ignition Transients

This analysis is treated in the computer program as a major subroutine. The method used follows the general technique described by Sforzini and Fellows (Reference 2) for an igniter which is itself a small rocket motor. Features of the analysis include variation of the characteristic velocity of the main motor with chamber pressure. Chamber volume and surface area of the propellant grain are assumed constant during ignition, but the burning surface is established as a function of time in accord with the passage of the flame front which is assumed to spread at constant speed. Four changes are made in the referenced approach:

1. A simple piecewise linear approximation to the pressure-time trace of the igniter (assumed to be a small SRM) is used rather than the polynominal approximation used in the reference. Comparison shows there is very little difference between computations by the two methods, and the program input is greatly simplified.

2. The referenced analysis was modified to permit effects of erosive burning to be taken into account. This was accomplished by replacing the burning rate term Cp_c^n in equation 9 of Reference 2 with the average burning rate as calculated by the methods used in the basic program of Reference 1.

3. The igniter throat cross-sectional area is eliminated as an input variable by making use of an empirical criterion taken from Reference 3 for establishing the discharge mass flow rate of the igniter.

4. Provision is made for including, as a program option, calculations accounting for the effects of a main motor nozzle blowout plug.

BO. Set $t_{ig} = 0$

Bl.a. Compute the average mass flow rate of the igniter over the first half of the igniter burning time, excluding the pressure buildup phase (Time prior to t_{I1})

$$\dot{m}_{ig(av)} = 0.2A^*/g$$

This is an empirical relationship based upon Reference 3.

Bl.b. Calculate the required igniter throat cross-sectional area

$$A^*_{ig} = 2\,\dot{m}_{ig(av)}\,C^*_{ig}/[2\,P_{mig}-R_{rig}(t_{I2}-t_{I1})/2]$$

B2. Compute the chamber pressure of the igniter

B2.a. If $t_{ig} \leq t_{I1}$,

$$P_{cig} = P_{mig}\ t/t_{I1}$$

B2.b. If $t_{ig} > t_{I1}$ and $P_{cig} > P_c$

$$P_{cig} = P_{mig} - R_{rig}\ (t - t_{I1})$$

B2.c. If $t_{ig} > t_{I1}$ and $P_{cig} \leq P_c$

$$P_{cig} = P_c$$

B3. Compute the estimated instantaneous mass flow rate of the igniter

If $P_{cig} > P_c$

$$\dot{m}_{ig} = P_{cig}\ A^*_{ig}/C^*_{ig}$$

If $P_{cig} \leq P_c$ or $t_{ig} > t_{I2}/2$

$\dot{m}_{ig} = 0$ (See discussion after RRIG, Section II)

B4. Solve the following equations for the chamber pressure of the main motor P_c using a Runge-Kutta solution of the fourth order

B4.a. If $P_c < P_{big}$, set $\dot{m}_D = 0$

If $P_c \geq P_{big}$, set

$$\dot{m}_D = A^*P_c/(K_a + K_b\ P_c)$$

B4.b. $r_h = a\ [P_c(1 + \Gamma^2 J^2/2)]^n$

B4.c. $C^* = K_a + K_b P_c$

B4.d. $r_n = a\ [P_c(1-\Gamma^2 J^2/2)]^n$

$$+\ \alpha_{eb}\ (P_c A^* X/C^* A_{pn})^{0.8}(u_{fs} t_{ig})^{0.2}\ \exp\ (\beta r_n \rho_p A_{pn} C^*/P_c A^* X)$$

B5. Compute

$$P_h = P_c \; [1+\Gamma^2 J^2/2]$$

B6. Set $P_{on} = P_c$

B7. Calculate C_F, $C_{F\ vac}$, F, F_{vac}, $I_{sp\ vac}$, I_T, $I_{T\ vac}$ using equations 20 through 24 with $t_j = t_{ig}$.

B8. Set $T_{ig} = \sum_k \Delta t_{ig\ k}$ <u>Repeat step B2 through B7</u>

for $k = 1,2,3\ldots$

until $P_{c(k)} - P_{c(k-1)} < P_{c(k)}/1000$

B9. Calculate the estimated igniter propellant weight

$$W_{ig(tot)} = g\dot{m}_{ig(av)}[5(t_{12} - t_{11})/6]$$

IV. THE COMPUTER PROGRAM

This section contains the instructions for preparation and arrangement of the data cards for the extended program. A complete listing of the program statements is given followed by flow charts for the two new subroutines; the ignition and the plotting subroutine for the "CalComp 663" digital plotter.

Data Card Usage

The data formats have been established to allow the operator to look at the card and know which variables are represented on it. The format should be followed to insure correct reading of the inputs. The various data cards are as follows: (See Table IV-1 for the complete format)

I.	Number of configurations
II.	Initial zero values
III a&b.	User options (2 cards)
IV.	Propellant data
V a&b.	Motor geometry (2 cards)
VI a&b.	Performance data (2 cards)
VII.	Input, grain, etc.
VIII a&b.	Initial tabular inputs (2 cards)
IX a&b.	Tubular grain input (2 cards)
X.	General star data
XI.	Wagon wheel data
XII.	Truncated star data
XIII.	Standard star data
XIV.	Termination port data
XV a&b.	Data for ignition transient calculations (2 cards)
XVI a-e.	Data for weight calculations (5 cards)
XVII a&b.	Tabular inputs (2 cards)

NOTE: In the original report, tabular inputs and initial tabular inputs appeared under the same heading.

Cards II-VII must accompany each and every configuration even if only one parameter changes. If INPUT = 1 or 3, a number of sets of data cards XVII a&b are used. Consider a test run on four different configurations:

a. A combination grain with only tabular inputs (no ignition or termination ports, but with weight calculations).

b. A combination circular perforated and standard star grain with only equation inputs (No termination ports, no ignition, but with weight calculations).

c. A truncated star grain with two termination ports using both tabular and equation inputs (No ignition, but with weight calculations).

d. A combination circular perforated and wagon-wheel grain using both tabular and equation inputs (No weight calculations or termination ports, but with ignition calculations).

The correct order for the data cards is:

Configuration a

1. I
2. II
3. III a&b
4. IV
5. V a&b
6. VI a&b
7. VII
8. VIII a&b ($y=0$)
9. XVI a-e
10. XVII a&b ($y=y_1$)
11. XVII a&b ($y=y_2$)
12. XVII a&b ($y=y_3$)

Configuration b

13. II
14. III a&b
15. IV
16. V a&b
17. VI a&b
18. VII
19. IX a&b
20. X
21. XIII
22. XVI a-e

Configuration c

23. II
24. III a&b
25. IV
26. V a&b
27. VI a&b
28. VII
29. VIII a&b ($y=0$)
30. X
31. XII
32. XIV
33. XVI a-e
34. XVII a&b ($y=y_1$)
35. XVII a&b ($y=y_2$)
36. XVII a&b ($y=y_3$)

Configuration d

37. II
38. III a&b
39. IV
40. V a&b
41. VI a&b
42. VII
43. VIII a&b ($y=0$)
44. IX a&b
45. X
46. XI
47. XV a&b
48. XVII a&b ($y=y_1$)
49. XVII a&b ($y=y_2$)
50. XVII a&b ($y=y_3$)

Note that if a particular data card does not apply, no card is used. For example, XI is omitted for Configuration b. and XII for Configuration d.

Program Listing

A complete program listing is presented in Table IV-2.

Flowcharts

Flowcharts of the ignition and plotting subroutines for the extended program are presented in Figures IV-4 and IV-5.

TABLE IV-1

DATA CARD FORMATS

```
cc1     cc10      cc20      cc30      cc40      cc50      cc60      cc70      cc80

                                        I
  NUMBER OF CONFIGURATIONS TO BE TESTED =--

                                        II
0.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.0

                                       IIIa
IGO=-     IWO=-

                                       IIIb
IPO=-    NUMPLT(JJ)=-,-,-,-,-,-,-,-,-,-,-,-,-,-,-,-

                                        IV
RHO=-.------ A=-.---- N=-.--- ALPHA=--.- BETA=---.- MU=+-.----E+-- CSTAR=----.

                                        Va
L=----. TAU=--.-- DE=---.-- DTI=---.-- THETA=-.---- ALFAN=-.----

                                        Vb
    LTAP=---.-- XT=--.-- ZO=--.--

                                       VIa
DELTAY=-.--- ZOUT=----.-- DPOUT=----.-- ZETAF=.--- TB=---.- HB=------. GAM=-.---

                                       VIb
RADER=-.----

                                       VII
  INPUT=--    GRAIN=--    STAR=--   NT=---.    ORDER=--    COP=--
```

TABLE IV-1 (Cont'd)

```
ccl      cc10      cc20      cc30      cc40      cc50      cc60      cc70      cc80

                                       VIIIa
   Y=---.--    ABPORT=+-.----E+--   ABSLOT=+-.----E+--   ABNOZ=+-.----E+--

                                       VIIIb
               APHEAD=+-.----E+--   APNOZ=+-.----E+--    VCIT=+-.----E+--

                                       IXa
  DO=---.---    DI=---.---    DELDI=---.---     S=---.   THETAG=-.-----

                                       IXb
  LGCI=----.--   LGNI=---.--   THETCN=-.-----   THETCH=-.-----

                                        X
  NS=---.   LGSI=----.--   NP=---.   RC=---.---   FILLET=---.---   NN=---.

                                       XI
TAUWW=--.--    L1=--.--    L2=--.--   ALPHA1=-.-----    ALPHA2=-.-----    HW=--.--

                                       XII
  RP=---.---   TAUS=---.---

                                       XIII
  THETAF=-.-----   THETAP=-.-----   TAUWS=--.---

                                       XIV
   LTP=---.--    DTP=--.--    THETTP=-.-----    TAUEFF=-.---

                                       XVa
 KA=-----.-   KB=-.---   UFS=-----.-   CSIG=-----.-   PMIG=-----.-   TI1=-.---

                                       XVb
 TI2=--.--   RRIG=-----.-   DELTIG=-.---   PBIG=---.---
```

TABLE IV-1 (Cont'd)

```
cc1     cc10      cc20      cc30      cc40      cc50      cc60      cc70      cc80

                                      XVIa
 PIPK=.----   DTEMP=---.--   SIGMAP=-.---   SIGMAS=-.---   N1=--.--

                                      XVIb
 N2=--.--   SYCNOM=-------.--   DCC=---.--   PSIC=--.--   DELC=-.---

                                      XVIc
 LCC=----.--   NSEG=--.   HCN=--.-   SYNNOM=-------.--   PSIS=--.--

                                      XVId
 PSIA=--.--   K1=-.----   K2=-.----   PSIINS=--.--   DELINS=-.----

                                      XVIe
 KEH=-.----   KEN=-.----   DLINER=-.----   TAUL=-.----   WA=----.--

                                      XVIIa
   Y=---.--   ABPORT=+-.----E+--   ABSLOT=+-.----E+--   ABNOZ=+-.----E+--

                                      XVIIb
              APHEAD=+-.----E+--   APNOZ=+-.----E+--
```

TABLE IV-2

```
C     ********************************************************************
C     *              SRM DESIGN AND PERFORMANCE ANALYSIS                 *
C     *                PREPARED AT AUBURN UNIVERSITY                     *
C     *         UNDER MOD. NO.8 TO COOPERATIVE AGREEMENT WITH            *
C     *               NASA MARSHALL SPACE FLIGHT CENTER                  *
C     *                                                                  *
C     *                   ANALYSIS BY R.H. SFORZINI                      *
C     *            PROGRAMMING BY J.M. LYON AND J.E. MURPH               *
C     *               AEROSPACE ENGINEERING DEPARTMENT                   *
C     *                          APRIL 1973                              *
C     ********************************************************************
      INTEGER GRAIN
      REAL MGEN,MDIS,MNOZ,MN1,JROCK,N,L,ME1,ME,ISP,ITOT,MU,MASS,ISPVAC
      REAL N1,N2,NSEG,K1,K2,KEH,KEN,NS,LCC,LTAP
      REAL M2,MCBAR,ISP2,ITVAC,KA,KB,LAMBDA
      COMMON/CONST1/ZW,AE,AT,THETA,ALFAN
      COMMON/CONST2/CAPGAM,ME,BOT,ZETAF,TB,HB,GAM
      COMMON/CONST3/S,NS,GRAIN
      COMMON/VARIA1/Y,T,DELY,DELTAT,PONOZ,PHEAD,RNOZ,RHEAD,SUMAB,PHMAX
      COMMON/VARIA2/ABPORT,ABSLOT,ABNOZ,APHEAD,APNOZ,DADY,ABP2,ABN2,ABS2
      COMMON/VARIA3/ITOT,ITVAC,JROCK,ISP,ISPVAC,MDIS,MNOZ,SG,SUMMT
      COMMON/VARIA4/RNT,RHT,SUM2,R1,R2,R3,RHAVE,RNAVE,RBAR,YB,KOUNT,TL
      COMMON/VARIA5/ABMAIN,ABTO,SUMDY,VCI,VC
      COMMON/IGN1/KA,KB,UFS,RHO,A,N,L,PMIG,TI1,TI2,CSIG
      COMMON/IGN2/ALPHA,BETA,PBIG,RRIG,DELTIG,X,TOP,ZAP
▶     COMMON/PLOTT/NUMPLT(16),IPO,NDUM,IPT,IOP
      DATA PI,G/3.14159,32.1725/
      READ(5,500) NRUNS
C     ********************************************************************
C     *     READ IN THE NUMBER OF CONFIGURATIONS TO BE TESTED            *
C     ********************************************************************
  500 FORMAT(42X,I2)
      IOP=0
      DO 901 I=1,NRUNS
      WRITE(6,602) I
  602 FORMAT(1H1,42X,'CONFIGURATION NUMBER ',I2)
      READ(5,499) SUMDY,ANS,ZW,Y,T,DELTAT,RNOZ,RHEAD,SUMAB,PHMAX,SUM2,IT
     1OT,RHT,RNT,R1,R2,R3,RHAVE,RNAVE,RBAR,ITVAC,SUMMT
C     ********************************************************************
C     *     SET INITIAL VALUES OF SELECTED VARIABLES EQUAL TO ZERO       *
C     *     ***NOTE***  THESE VALUES MUST BE ZEROED AT THE BEGINNING OF  *
C     *     EACH CONFIGURATION RUN                                       *
C     ********************************************************************
  499 FORMAT(22F3.1)
      READ(5,491) IGC,IWO
▶     READ(5,493) IPC,(NUMPLT(JJ),JJ=1,16)
C     ********************************************************************
C     *     READ IN THE USER'S OPTIONS                                   *
```

TABLE IV-2. (Cont'd)

```
  C   *                                                                       *
  C   *     VALUES FOR IGO ARE                                                *
  C   *               0 FOR NO IGNITION TRANSIENT CALCULATIONS                *
  C   *               1 FOR IGNITION TRANSIENT CALCULATICNS                   *
  C   *     VALUES FOR IWO ARE                                                *
  C   *               0 FOR NO INERT WEIGHT CALCULATIONS                      *
  C   *               1 FOR INERT WEIGHT CALCULATIONS                         *
 ▶C   *     VALUES FOR IPO ARE                                                *
 ▶C   *               0 FOR NO PLOTS                                          *
 ▶C   *               1 FOR PLOTS OF EQUILIBRIUM BURNING ONLY                 *
 ▶C   *               2 FOR PLOTS OF IGNITION TRANSIENT ONLY                  *
 ▶C   *               3 FOR PLOTS OF BOTH IGNITION TRANSIENT AND              *
 ▶C   *                    EQUILIBRIUM BURNING                                *
 ▶C   *     VALUES FOR NUMPLT(JJ) ARE  (NOT REQUIRED FOR IPO=0)               *
 ▶C   *               0 IF SPECIFIC PLOT IS NOT DESIRED                       *
 ▶C   *               1 IF SPECIFIC PLOT IS DESIRED                           *
 ▶       CONTINUE
 ▶C   *          ORDER OF SPECIFICATION OF NUMPLT(JJ) IS                      *
 ▶C   *                          1  PHEAD VS TIME                             *
 ▶C   *                          2  PONOZ VS TIME                             *
 ▶C   *                          3  PHEAD AND PONOZ VS TIME                   *
 ▶C   *                          4  RHEAD VS TIME                             *
 ▶C   *                          5  RNOZ VS TIME                              *
 ▶C   *                          6  RHEAD AND RNOZ VS TIME                    *
 ▶C   *                          7  SUMAB VS TIME                             *
 ▶C   *                          8  SG VS TIME                                *
 ▶C   *                          9  SUMAB AND SG VS TIME                      *
 ▶C   *                          10 F VS TIME                                 *
 ▶C   *                          11 FVAC VS TIME                              *
 ▶C   *                          12 F AND FVAC VS TIME                        *
 ▶C   *                          13 VC VS TIME                                *
 ▶C   *                          14 SUMAB VS Y                                *
 ▶C   *                          15 SG VS Y                                   *
 ▶C   *                          16 SUMAB AND SG VS Y                         *
  C   *********************************************************************** 
    491 FORMAT(4X,I1,9X,I1)
 ▶  493 FORMAT(4X,I1,15X,16(I1,1X))
        WRITE(6,492) IGO,IWO
 ▶      WRITE(6,494) IPO,(NUMPLT(JJ),JJ=1,16)
    492 FORMAT(//,20X,'OPTIONS',/,13X,'IGO= ',I1,/,13X,'IWO= ',I1)
 ▶  494 FORMAT(13X,'IPO= ',I1,/,13X,'NUMPLT(JJ)= ',I1,15(',',I2))
        READ(5,501) RHO,A,N,ALPHA,BETA,MU,CSTAR
  C   ***********************************************************************
  C   *     READ IN BASIC PROPELLANT CHARACTERISTICS                          *
  C   *                                                                       *
  C   *     RHO IS THE DENSITY OF THE PROPELLANT IN SLUGS/IN**3               *
  C   *     A IS THE BURNING RATE COEFFICIENT                                 *
  C   *     N IS THE BURNING RATE EXPONENT                                    *
```

TABLE IV-2. (Cont'd)

```
C  *     ALPHA ANC BETA ARE THE CONSTANTS IN THE EROSIVE BURNING         *
C  *          RELATION OF ROBILLARD AND LENIOR                            *
C  *     MU IS THE VISCOSITY OF THE PROPELLANT GASES                      *
C  *     CSTAR IS THE CHARACTERISTIC EXHAUST VELOCITY IN FT/SEC           *
C  *********************************************************************
  501 FORMAT(4X,F8.6,3X,F6.4,3X,F5.3,7X,F4.1,6X,F5.1,4X,E11.4,7X,F5.0)
      WRITE(6,603) RHO,A,N,ALPHA,BETA,MU,CSTAR
  603 FORMAT( //,20X,'PROPELLANT CHARACTERISTICS',/,13X,'RHO= ',F8.6,/,1
     13X,'A= ',F6.4,/,13X,'N= ',F5.3,/,13X,'ALPHA= ',F4.1,/,13X,'BETA= '
     2,F5.1,/,13X,'MU= ',1PE11.4,/,13X,'CSTAR= ',1PE11.4)
      READ(5,502) L,TAU,DE,DTI,THETA,ALFAN,LTAP,XT,ZO
C  *********************************************************************
C  *     READ IN BASIC MOTOR DIMENSIONS                                   *
C  *                                                                      *
C  *     L IS THE TOTAL LENGTH OF THE GRAIN IN INCHES                     *
C  *     TAU IS THE AVERAGE WEB THICKNESS OF THE CONTROLLING GRAIN        *
C  *          LENGTH IN INCHES                                            *
C  *     DE IS THE DIAMETER OF THE NOZZLE EXIT IN INCHES                  *
C  *     DTI IS THE INITIAL DIAMETER OF THE NOZZLE THROAT IN INCHES       *
C  *     THETA IS THE CANT ANGLE OF THE NOZZLE WITH RESPECT TO THE        *
C  *          MOTOR AXIS IN RADIANS                                       *
C  *     ALFAN IS THE EXIT HALF ANGLE OF THE NOZZLE IN RADIANS            *
C  *     LTAP IS THE LENGTH OF THE GRAIN AT THE NOZZLE END HAVING         *
C  *          ADDITIONAL TAPER NOT REPRESENTED BY ZO IN INCHES            *
C  *     XT IS THE DIFFERENCE IN WEB THICKNESS ASSOCIATED WITH LTAP       *
C  *     ZO IS THE INITIAL DIFFERENCE BETWEEN WEB THICKNESSES AT THE      *
C  *          HEAD AND AFT ENDS OF THE CONTROLLING GRAIN LENGTH           *
C  *********************************************************************
  502 FORMAT( 2X,F5.0,5X,F5.2,4X,F6.2,5X,F6.2,7X,F6.4,7X,F6.4,/,10X,
     1  F6.2,4X,F5.2,4X,F5.2)
      WRITE(6,604) L,TAU,DE,DTI,THETA,ALFAN,LTAP,XT,ZO
  604 FORMAT(//,20X,'BASIC MOTOR DIMENSIONS',/,13X,'L= ',F5.0,/,13X,'TAU
     1= ',F5.2,/,13X,'DE= ',
     21PE11.4,/,13X,'DTI=',1PE11.4,/,13X,'THETA= ',1PE11.4,/,13X,'ALFAN=
     3 ',1PE11.4,/,13X,'LTAP= ',1PE11.4,/,13X,'XT= ',1PE11.4,/,13X,'ZO=
     4',1PE11.4)
      READ(5,503) DELTAY,XOUT,DPOUT,ZETAF,TB,HB,GAM,RADER
C  *********************************************************************
C  *     READ IN BASIC PERFORMANCE CONSTANTS                              *
C  *                                                                      *
C  *     DELTAY IS THE DESIRED BURN INCREMENT DURING TAILOFF IN INCHES   *
C  *     XOUT IS THE DISTANCE BURNED IN INCHES AT WHICH THE PROPELLANT   *
C  *          BREAKS UP                                                   *
C  *     DPOUT IS THE DEPRESSURIZATION RATE IN LB/IN**3 AT WHICH THE     *
C  *          PROPELLANT IS EXTINGUISHED                                  *
C  *     ZETAF IS THE THRUST LOSS COEFFICIENT                             *
C  *     TB IS THE ESTIMATED BURN TIME IN SECONDS                         *
C  *     HB IS THE ESTIMATED BURNOUT ALTITUDE IN FEET                     *
```

TABLE IV-2. (Cont'd)

```
C  *     GAM IS THE RATIO OF SPECIFIC HEATS FOR THE PROPELLANT GASES      *
C  *     RADER IS THE RADIAL EROSION RATE OF THE NOZZLE THROAT IN         *
C  *            INCHES/SEC                                                *
C  ***********************************************************************
  503 FORMAT(7X,F5.3,6X,F7.2,7X,F7.2,7X,F4.3,4X,F5.1,4X,F7.0,5X,F5.3,/,8
     1X,F6.4)
      WRITE(6,606) DELTAY,XOUT,DPOUT,ZETAF,TB,HB,GAM,RADER
  606 FORMAT(//,20X,'BASIC PERFORMANCE CONSTANTS',/,13X,'DELTAY= ',F5.3,
     1/,13X,'XOUT= ',F7.2,/,13X,'DPOUT= ',F7.2,/,13X,'ZETAF= ',F5.3,/,13
     2X,'TB= ',F5.1,/,13X,'HB= ',F7.0,/,13X,'GAM= ',F5.3,/,13X,'RADER= '
     3,F6.4)
▶     NDUM=0
▶     IPT=0
      MN1=.85
      ME1=7.0
      Z=Z0
      S=0.0
      NS=0.0
      KOUNT=0
      ABMAIN=0.0
      ABTO=0.0
      DELY=DELTAY
      TOP=GAM+1.
      BOT=GAM-1.
      ZAP=TOP/(2.*BOT)
      CAPGAM=SQRT(GAM)*(2./TOP)**ZAP
      AE=PI*DE*DE/4.
    1 IF(XT.LE.0.0) TL=0.0
      IF(XT.LE.0.0) GO TO 40
      TL=(Y-TAU+XT+Z/2.)*LTAP/XT
      IF(TL.LE.0.0) TL=0.0
      IF(TL.GE.LTAP) TL=LTAP
   40 DT=DTI+2.*(RADER*T)
      AT=PI*DT*DT/4.
      CALL AREAS
      IF(Y.LE.0.0) VC=VCI
      IF(ABS(ZW).GT.0.0) GO TO 20
      IF(SUMAB.LE.0.0) GO TO 31
      X=(ABPORT+ABSLOT)/SUMAB
   90 MNOZ=AT*X/APNOZ*(2.*(1.+BOT/2.*MN1*MN1)/TOP)**ZAP
      IF(ABS(MNOZ-MN1).LE.0.002) GO TO 2
      MN1=MNOZ
      GO TO 90
    2 VNOZ=GAM*CSTAR*MNOZ*SQRT(((2./TOP)**(TOP/BOT))/(1.+BOT/2.*MNOZ*MNO
     1Z))
      PRAT=(1.+BOT/2.*MNOZ*MNOZ)**(-GAM/BOT)
      JROCK=AT/APNOZ
      IF(IGO.EQ.0.OR.Y.GT.0.0) GO TO 900
```

TABLE IV-2. (Cont'd)

```
      READ(5,97) KA,KB,UFS,CSIG,PMIG,TI1,TI2,RRIG,DELTIG,PBIG
C   *******************************************************************
C   *      READ IN VALUES REQUIRED FOR IGNITION CALCULATIONS           *
C   *       ***NOTE***  NOT REQUIRED IF IGO=0                          *
C   *                                                                  *
C   *      KA AND KB DEFINE THE CHARACTERISTIC VELOCITY IN FT/SEC      *
C   *           CSTR = KA + KB * PRESSURE                              *
C   *      UFS IS THE FLAME-SPREADING SPEED IN IN/SEC                  *
C   *      CSIG IS THE CHARACTERISTIC VELOCITY OF THE IGNITER IN FT/SEC *
C   *      PMIG IS THE MAXIMUM IGNITER PRESSURE IN LBS/IN**2           *
C   *      TI1 IS THE TIME OF MAXIMUM IGNITER PRESSURE IN SECONDS      *
C   *      TI2 IS THE TIME(IN SECONDS) FOR THE IGNITER PRESSURE TO     *
C   *           DROP TO 10 PER CENT OF MAXIMUM VALUE(PMIG)             *
C   *      RRIG IS THE AVERAGE REGRESSION RATE OF THE FIRST HALF OF THE *
C   *           IGNITER PRESSURE TIME TRACE IN LBS/IN**2/SEC           *
C   *      DELTIG IS THE TIME INCREMENT FOR IGNITION TRANSIENT         *
C   *           CALCULATIONS IN SECONDS                                *
C   *      PBIG IS THE BLOWOUT PRESSURE OF THE MAIN MOTOR BLOWOUT PLUG *
C   *           IN LBS/IN**2                                           *
C   *******************************************************************
   97 FORMAT(3X,F7.1,5X,F5.3,6X,F7.1,7X,F7.1,7X,F7.1,6X,F5.3,/,4X,F5.2,
     1  7X,F7.1,9X,F5.3,7X,F7.3)
      WRITE(6,842) KA,KB,UFS,CSIG,PMIG,TI1,TI2,RRIG,DELTIG,PBIG
  842 FORMAT(20X,'IGNITION CONSTANTS',/,13X,'KA= ',F7.1,/,13X,'KB= ',
     1  F5.3,/,13X,'UFS= ',F7.1,/,13X,'CSIG= ',F7.1,/,13X,'PMIG= ',
     1  F7.1,/,13X,'TI1= ',F5.3,/,13X,'TI2= ',F5.2,/,13X,'RRIG= ',
     1  F7.1,/,13X,'DELTIG= ',F5.3,/,13X,'PBIG= ',F7.3,//)
  900 IF(IWO.EQ.0.OR.Y.GT.0.0) GO TO 832
      READ(5,600) PIPK,DTEMP,SIGMAP,SIGMAS,N1,N2,SYCNOM,DCC,PSIC,DELC,LC
     1C,NSEG,HCN,SYNNOM,PSIS,PSIA,K1,K2,PSIINS,DELINS,KEH,KEN,DLINER,TAU
     2L,WA
C   *******************************************************************
C   *     READ IN BASIC PROPERTIES REQUIRED FOR WEIGHT CALCULATIONS    *
C   *       ***NOTE***  NOT REQUIRED IF IWO=0                          *
C   *                                                                  *
C   *      PIPK IS THE TEMPERATURE SENSITIVITY COEFFICIENT OF PRESSURE *
C   *           AT CONSTANT K                                          *
C   *      DTEMP IS THE MAX EXPECTED INCREASE IN TEMPERATURE ABOVE     *
C   *           CONDITIONS UNDER WHICH MAIN TRACE WAS CALCULATED IN    *
C   *           DEGREES FAHRENHEIT                                     *
C   *      SIGMAP IS THE VARIATION IN PHMAX                            *
C   *      SIGMAS IS THE VARIATION IN CASE MATERIAL YIELD STRENGTH     *
C   *      N1 IS THE NUMBER OF STANDARD DEVIATIONS IN PHMAX TO BE USED *
C   *           AS A BASIS FOR DESIGN                                  *
C   *      N2 IS THE NUMBER OF STANDARD DEVIATIONS IN SY TO BE USED AS *
C   *           A BASIS FOR DESIGN                                     *
C   *      SYCNOM IS THE NOMINAL YIELD STRENGTH OF THE CASE MATERIAL   *
C   *           IN LBS/INCH                                            *
```

TABLE IV-2. (Cont'd)

```
C  *     DCC IS THE ESTIMATED MEAN DIAMETER OF THE CASE IN INCHES         *
C  *     PSIC IS THE SAFETY FACTOR ON THE CASE THICKNESS                  *
C  *     DELC IS THE SPECIFIC WEIGHT OF THE CASE MATERIAL IN LBS/IN**3    *
C  *     LCC IS THE LENGTH OF THE CYLINDRICAL PORTION OF THE CASE         *
C  *           INCLUDING FORWARD AND AFT SEGMENTS IN INCHES               *
C  *     NSEG IS THE NUMBER OF CASE SEGMENTS                              *
C  *     HCN IS THE AXIAL LENGTH OF THE NOZZLE CLOSURE IN INCHES          *
C  *     SYNNOM IS THE NOMINAL YIELD STRENGTH OF THE NOZZLE MATERIAL      *
C  *           IN LBS/INCH                                                *
      CONTINUE
C  *     PSIS IS THE SAFETY FACTOR ON THE NOZZLE STRUCTURAL MATERIAL      *
C  *     PSIA IS THE SAFETY FACTOR ON THE NOZZLE ABLATIVE MATERIAL        *
C  *     K1 AND K2 ARE EMPIRICAL CONSTANTS IN THE NOZZLE WT. EQUATION     *
C  *     PSIINS IS THE SAFETY FACTOR ON NOZZLE INSULATION                 *
C  *     DELINS IS THE SPECIFIC WEIGHT OF THE INSULATION IN LBS/IN**3     *
C  *     KEH IS THE EROSION RATE OF INSULATION TAKEN CONSTANT             *
C  *           EVERYWHERE EXCEPT AT THE NOZZLE CLOSURE IN IN/SEC          *
C  *     KEN IS THE EROSION RATE OF INSULATION AT THE NOZZLE CLOSURE      *
C  *           IN IN/SEC                                                  *
C  *     DLINER IS THE SPECIFIC WEIGHT OF THE LINER IN LBS/IN**3          *
C  *     TAUL IS THE THICKNESS OF THE LINER IN INCHES                     *
C  *     WA IS ANY ADDITIONAL WEIGHT NOT CONSIDERED ELSEWHERE IN LBS      *
C  ********************************************************************
  600 FORMAT(7X,F5.4,9X,F6.2,10X,F5.3,10X,F5.3,6X,F5.2,/,5X,F5.2,10X,F10
     1.2,7X,F6.2,8X,F5.2,8X,F5.3,/,6X,F7.2,8X,F3.0,7X,F4.1,10X,F10.2,8X,
     2F5.2,/,7X,F5.2,6X,F6.4,6X,F6.4,10X,F5.2,10X,F6.4,/,6X,F6.4,7X,F6.4
     3,10X,F6.4,8X,F6.4,6X,F7.2)
      WRITE(6,610) PIPK,DTEMP,SIGMAP,SIGMAS,N1,N2,SYCNOM,DCC,PSIC,DELC,L
     1CC,NSEG,HCN,SYNNOM,PSIS,PSIA,K1,K2,PSIINS,DELINS,KEH,KEN,DLINER,TA
     2UL,WA
  610 FORMAT(   20X,'INERT WEIGHT INPUTS',/,13X,'PIPK= ',1PE11.4,/,13X,'
     1DTEMP= ',1PE11.4,/,13X,'SIGMAP= ',1PE11.4,/,13X,'SIGMAS= ',1PE11.4
     2,/,13X,'N1= ',1PE11.4,/,13X,'N2= ',1PE11.4,/,13X,'SYCNOM= ',1PE11.
     34,/,13X,'DCC= ',1PE11.4,/,13X,'PSIC= ',1PE11.4,/,13X,'DELC= ',1PE1
     41.4,/,13X,'LCC= ',1PE11.4,/,13X,'NSEG= ',1PE11.4,/,13X,'HCN= ',1PE
     511.4,/,13X,'SYNNOM= ',1PE11.4,/,13X,'PSIS= ',1PE11.4,/,13X,'PSIA=
     6',1PE11.4,/,13X,'K1= ',1PE11.4,/,13X,'K2= ',1PE11.4,/,13X,'PSIINS=
     7 ',1PE11.4,/,13X,'DELINS= ',1PE11.4,/,13X,'KEH= ',1PE11.4,/,13X,'K
     8EN= ',1PE11.4,/,13X,'DLINER= ',1PE11.4,/,13X,'TAUL= ',1PE11.4,/,13
     9X,'WA= ',1PE11.4)
  832 SUMYA=DELY*(ABP2+ABN2+ABS2)
      IF(Y.EQ.0.0) SUMYA=0.0
      VC=VC+SUMYA
      IF(Y.GT.0.0) GO TO 11
      PONOZ=(A*RHO*CSTAR*SUMAB/AT)**(1./(1.-N))*(1.+(CAPGAM*JROCK)**2/2.
     1)**(N/(1.-N))
      PON=PONOZ
      MDIS=AT*PONOZ/CSTAR
```

TABLE IV-2. (Cont'd)

```
      P2=PONOZ
      PONOZ2=PONOZ
      PNOZ=PRAT*PONOZ
      P4=2.*MDIS*VNOZ/(APHEAD+APNOZ)+PNOZ
      IF(GRAIN.EQ.3) P4=MDIS*VNOZ/APNOZ+PNOZ
    5 PNOZ=PRAT*PONOZ
      PHEAD=2.*MDIS*VNOZ/(APHEAD+APNOZ)+PNOZ
      IF(GRAIN.EQ.3) PHEAD=MDIS*VNOZ/APNOZ+PNOZ
      RHEAD=A*PHEAD**N
      ZIT=MDIS*X/APNOZ
      RN1=RHEAD
      PHEAD2=PHEAD
    3 RNOZ=RN1-((RN1-A*PNOZ**N-ALPHA*ZIT**.8/(L**.2*EXP(BETA*RN1*RHO/ZIT
     1)))/(1.+ALPHA*ZIT**.8*BETA*RHO/ZIT/(L**.2*EXP(BETA*RN1*RHO/ZIT))))
      IF(ABS(RN1-RNOZ).LE.0.002) GO TO 4
      RN1=RNOZ
      GO TO 3
    4 AVE1=(RHEAD+RNOZ)/2.
      IF(Y.GT.0.0) GO TO 7
      RN2=RNOZ
      RH2=RHEAD
      PONJ=PONOZ
      DPCDY=0.0
      AVE2=AVE1
    7 RNAVE=(RNOZ+RN2)/2.
      RHAVE=(RHEAD+RH2)/2.
      MGEN=RHO/2.*((RNOZ+RHEAD)*(ABPORT+ABSLOT)+2.*A*PONOZ**N*ABNOZ)
      DRDY=(AVE1-AVE2)/DELY
      RBAR=(AVE1+AVE2)/2.
      GMAX=1.002*MDIS
      GMIN=0.998*MDIS
      IF(Y.GT.0.0) GO TO 12
      GMAX=1.001*MDIS
      GMIN=0.999*MDIS
      IF(MGEN.GE.GMIN.AND.MGEN.LE.GMAX) GO TO 6
      MDIS=MGEN
      PONOZ=MDIS*CSTAR/AT
      GO TO 5
    6 RE=2.*MDIS*X*L/((APNOZ+APHEAD)*MU)
   17 ME=SQRT(2./BOT*(TOP/2.*(AE*ME1/AT)**(1./ZAP)-1.))
      IF(ABS(ME-ME1).LE.0.002) GO TO 9
      ME1=ME
      GO TO 17
    9 CONTINUE
      IF(IGO.NE.0.AND.Y.LE.0.0) CALL IGNITN
      IF(Y.LE.0.0) WRITE(6,101) RE
  101 FORMAT(///,33X,'******************************',/,33X,'**** EQUILIB
     1RIUM BURNING ****',/,33X,'******************************',//,30X,
```

TABLE IV-2. (Cont'd)

```
    1  'INITIAL REYNOLDS NUMBER= ',1PE11.4)
      PONJ=PONOZ
      CALL OUTPUT
   10 IF(Y.LE..05*TAU) GO TO 16
      SINK1=VC/(CAPGAM*CSTAR)**2*RBAR*DPCDY/12.
      MASS=.01*MDIS
      ANS4=Y+10.0*DELTAY
      IF(KOUNT.GT.0) GO TO 16
      IF(ABS(SINK1).LE.MASS.AND.ANS4.LE.ANS-XT) GO TO 18
      GO TO 16
   18 DELY=10.*DELTAY
      GO TO 55
   16 DELY=DELTAY
   55 DELTAT=2.*DELY/(RHAVE+RNAVE)
      Z=Z+DELTAT*(RNAVE-RHAVE)
      Y=Y+DELY
      T=T+DELTAT
      SUM2=SUMAB
      RN2=RNOZ
      RH2=RHEAD
      AVE2=AVE1
      GO TO 1
   11 MDIS=AT*PONOZ/CSTAR
      GO TO 5
   12 DPCDY=(PHEAD2+PONOZ2)/(RNAVE+RHAVE)*DRDY+(PHEAD2+PONOZ2)/((ABP2+AB
     1N2+ABS2)*2.)*DADY
      IF(ABS(DPCDY).GE.DPOUT.OR.Y.GE.XOUT) GO TO 25
      SINK1=VC/(CAPGAM*CSTAR)**2*RBAR*DPCDY/12.+(PHEAD2+PONOZ2)/2.*(RNAV
     1E+RHAVE)/2.*(ABP2+ABN2+ABS2)/(12.*(CSTAR*CAPGAM)**2)
      STUFF=MGEN-SINK1
      IF(STUFF.GE.GMIN.AND.STUFF.LE.GMAX) GO TO 14
      MDIS=STUFF
      PONOZ=MDIS*CSTAR/AT
      GO TO 5
   14 P1=PONOZ
      PONJ=PONOZ
      PONOZ2=(P1+P2)/2.
      P2=PONOZ
      P3=PHEAD
      PHEAD2=(P3+P4)/2.
      P4=PHEAD
      ANS=TAU-ABS(Z/2.)
      IF(Y.LT.ANS) CALL OUTPUT
      IF(Y.LT.ANS) GO TO 10
   19 ZW=Z
      YW=Y
      SUMBA=SUMAB
      P1=PONOZ
```

TABLE IV-2. (Cont'd)

```
      RH2=RHEAD
      RN2=RNOZ
      RAVE=AVE1
      ABMAIN=SUMAB
      ABTO=0.0
      WRITE(6,51)
   51 FORMAT(//,37X,'**************************',/,37X,'**** TAIL OFF BEG
     1INS ****',/,37X,'**************************',/)
   20 ANS2=TAU+ABS(ZW/2.)
      KOUNT=KOUNT+1
      DELYW=DELTAY
      DY2=DELYW
      IF(ZW) 32,32,33
   32 IF(Y.LT.ANS2.AND.ABS(ZW).GT.DY2) GO TO 211
      SUMAB=ABMAIN
      GO TO 31
  211 SUMDY=SUMDY+DELYW
      SUMAB=(1.+SUMDY/ZW-DELYW/(2.*ZW))*ABTO-(SUMDY/ZW-DELYW/(2.*ZW))*AB
     1MAIN
      GO TO 31
   33 IF(Y.LT.ANS2.AND.ZW.GT.DY2) GO TO 21
      SUMAB=ABTO
      GO TO 31
   21 SUMDY=SUMDY+DELYW
      SUMAB=(1.-SUMDY/ZW+DELYW/(2.*ZW))*ABMAIN+(SUMDY/ZW-DELYW/(2.*ZW))*
     1ABTO
   31 IF(SUMAB.LE.0.0) PONOZ=PONOZ/2.
      IF(SUMAB.LE.0.0) GO TO 25
      PONOZ=(A*RHO*CSTAR*SUMAB/AT)**(1./(1.-N))
      MDIS=AT*PONOZ/CSTAR
      ABAVE=(SUMAB+SUMBA)/2.
      SUMYA=DELY*ABAVE
      VC=VC+SUMYA
      DADY=(SUMAB-SUMBA)/DELY
      PBAR=(P1+PONOZ)/2.
      SUMBA=SUMAB
   22 DPCDY=PBAR/(1.-N)*1./ABAVE*DADY
      IF(PONOZ.LE.30.0) GO TO 25
      RNOZ=A*PONOZ**N
      RHEAD=RNOZ
      RBAR=(RHEAD+RAVE)/2.
      MGEN=RHO*(RNOZ+RHEAD)/2.*SUMAB
      GMAX=1.002*MDIS
      GMIN=0.998*MDIS
      SINK1=VC/(CAPGAM*CSTAR)**2*RBAR*DPCDY/12.
      STUFF=MGEN-SINK1
      IF(STUFF.GE.GMIN.AND.STUFF.LE.GMAX) GO TO 23
      MDIS=STUFF
```

TABLE IV-2. (Cont'd)

```
      PONOZ=PONJ+DPCDY*DELY
      IF(PONOZ.LE.0.0) PONOZ=0.0
      PBAR=(P1+PONOZ)/2.
      GO TO 22
   23 RHAVE=(RH2+RHEAD)/2.
      RNAVE=(RN2+RNOZ)/2.
      RH2=RHEAD
      RN2=RNOZ
      PHEAD=PONOZ
      RAVE=RHEAD
      P1=PONOZ
      PONJ=PONOZ
      IF(ABS(DPCDY).GE.DPOUT) GO TO 25
      IF(Y.GE.XOUT) GO TO 25
      CALL OUTPUT
      GO TO 10
   25 SUMAB=0.0
      RHEAD=0.0
      RNOZ=RHEAD
      PHEAD=PONOZ
      WRITE(6,318)
  318 FORMAT(//,33X,'*********************************',/,33X,'**** BEGI
     1N HALF SECOND TRACE ****',/,33X,'*********************************
     1')
      CALL OUTPUT
      TIME=T
      DELTAT=.5
      TIM=TIME+5.
      PHT=PHEAD
      PONT=PONOZ
      SG=0.0
   29 T=T+DELTAT
      PHEAD=PHT/EXP(CAPGAM**2*AT*CSTAR/VC*(T-TIME)*12.)
      PONOZ=PHEAD
      MDIS=PONOZ*AT/CSTAR
      Y=Y+.5*RHEAD
      CALL OUTPUT
   28 IF(T.LT.TIM.AND.PHEAD.GE.30.0) GO TO 29
  100 WP1=G*SUMMT
      WP2=RHO*(VC-VCI)*G
      WP=(WP1+WP2)/2.
      ISP=ITOT/WP
      ISPVAC=ITVAC/WP
      WRITE(6,102) WP1,WP2,WP,PHMAX,ISP,ISPVAC,ITOT,ITVAC
  102 FORMAT(///,13X,'WP1= ',1PE11.4,/,13X,'WP2= ',1PE11.4,/,13X,'WP= ',
     11PE11.4,/,13X,'PHMAX= ',1PE11.4,/,13X,'ISP= ',1PE11.4,/,13X,'ISPVA
     2C= ',1PE11.4,/,13X,'ITOT= ',1PE11.4,/,13X,'ITVAC= ',1PE11.4)
      LAMBDA=(VC-VCI)/VC
```

TABLE IV-2. (Cont'd)

```
      WRITE(6,103) VCI,VC,LAMBDA
  103 FORMAT(13X,'VCI= ',1PE11.4,/,13X,'VCF= ',1PE11.4,/,13X,'LAMBDA= ',
     1  1PE11.4)
      IF(IWO.EQ.0) GO TO 903
      PMEOP=PHMAX*(1.+N1*SIGMAP)*EXP(PIPK*DTEMP)
      SYC=SYCNOM*(1.-N2*SIGMAS)
      TAUCC=PSIC*PMEOP*DCC/(2.*SYC)
      WCC=PI*TAUCC*DCC*DELC*LCC*(1.+(NSEG-1.)*(40.*TAUCC/LCC))
      TAUCD=TAUCC/2.
      WCH=2.5*PI/2.*DCC*DCC*TAUCD*DELC
      WCN=4.5*PI/2.*DCC*HCN*TAUCD*DELC
      WC=WCC+WCH+WCN
      EPSIL=AE/AT
      DT=2.*SQRT(AT/PI)
      WN=K1*DT*DT/(1.+.5*SIN(ALFAN))*((EPSIL-SQRT(EPSIL))*PMEOP*DT*PSIS/
     1SYNNOM+K2*T*PSIA)
      WINS=T*PSIINS*DELINS*DCC*PI*(KEH*(DCC*.40+(S+NS)*TAU/2.+0.15/
     1PSIINS*(LCC-TAU*(S+NS)))+KEN*.80*HCN)
      WL=TAUL*DLINER*PI*DCC*(DCC/2.+LCC+HCN)
      WM=WC+WN+WINS+WL+WA+WP
      ZETAM=WP/WM
      RATIO=ITOT/WM
      WRITE(6,605)
  605 FORMAT(///,20X,'MOTOR WEIGHT CALCULATIONS')
      WRITE(6,601) PMEOP,TAUCC,WC,WN,WINS,WL,WM,ZETAM,RATIO
  601 FORMAT(13X,'MAX EXPECTED PRESSURE= ',1PE11.4,/,13X,'CYLINDRICAL CA
     1SE THICKNESS= ',1PE11.4,/,13X,'CASE WT= ',1PE11.4,/,13X,'NOZZLE WT
     2= ',1PE11.4,/,13X,'INSULATION WT= ',1PE11.4,/,13X,'LINER WT= ',1PE
     311.4,/,13X,'TOTAL MOTOR WT= ',1PE11.4,/,13X,'ZETAM= ',1PE11.4,/,13
     4X,'RATIO OF ITOT TO WM= ',1PE11.4)
  903 CONTINUE
▶     NDUM=1
▶     IF(IPO.NE.0.AND.IPO.NE.2) CALL OUTPUT
  901 CONTINUE
▶     IF(IOP.NE.0) CALL PLOT(0.0,0.0,999)
      STOP
      END
```

TABLE IV-2. (Cont'd)

```
      SUBROUTINE AREAS
C     ****************************************************************
C     *     SUBROUTINE AREAS CALCULATES BURNING AREAS AND PORT AREAS FOR   *
C     *     CIRCULAR PERFORATED (C.P.) GRAINS AND STAR GRAINS OR FOR A     *
C     *     COMBINATION OF C.P. AND STAR GRAINS                            *
C     ****************************************************************
      INTEGER STAR,GRAIN,ORDER,COP
      REAL MGEN,MDIS,MNOZ,MN1,JROCK,N,L,ME1,ME,ISP,ITOT,MU,MASS,ISPVAC
      REAL LGCI,LGNI,NS,NN,NP,LGSI,NT,LTP,LGC,LS,LF
      REAL M2,MDBAR,ISP2,ITVAC,L1,L2,LFW,LFWSQD
      COMMON/CONST1/ZW,AE,AT,THETA,ALFAN
      COMMON/CONST3/S,NS,GRAIN
      COMMON/VARIA1/Y,T,DELY,DELTAT,PONOZ,PHEAD,RNOZ,RHEAD,SUMAB,PHMAX
      COMMON/VARIA2/ABPORT,ABSLOT,ABNOZ,APHEAD,APNOZ,DADY,ABP2,ABN2,ABS2
      COMMON/VARIA3/ITOT,ITVAC,JROCK,ISP,ISPVAC,MDIS,MNOZ,SG,SUMMT
      COMMON/VARIA4/RNT,RHT,SUM2,R1,R2,R3,RHAVE,RNAVE,RBAR,YB,KOUNT,TL
      COMMON/VARIA5/ABMAIN,ABTO,SUMDY,VCI,VC
      DATA PI/3.14159/
      ABPC=0.0
      ABNC=0.0
      ABSC=0.0
      ABPS=0.0
      ABNS=0.0
      ABSS=0.0
      DABT=0.0
      SG=0.0
      ANUM=PI/4.
      PID2=PI/2.
      RNT=RNT+RNOZ*DELTAT
      RHT=RHT+RHEAD*DELTAT
      IF(Y.LE.0.0) AGS=0.0
    1 K=0
      IF(ABS(ZW).GT.0.0) K=1
      YB=Y
      IF(K.EQ.1) Y=YB-SUMDY/2.
    2 IF(K.EQ.2) Y=YB+ABS(ZW)/2.-SUMDY/2.
      IF(Y.LE.0.0) READ(5,500) INPUT,GRAIN,STAR,NT,ORDER,COP
C     ****************************************************************
C     *     READ THE TYPE OF INPUT FOR THE PROGRAM AND THE BASIC GRAIN     *
C     *          CONFIGURATION AND ARRANGEMENT                             *
C     *     VALUES FOR INPUT ARE                                           *
C     *               1 FOR ONLY TABULAR INPUT                             *
C     *               2 FOR ONLY EQUATION INPUTS (EQUATIONS ARE BUILT      *
C     *                 INTO THE SUBROUTINE)                               *
C     *               3 FOR A COMBINATION OF 1 AND 2                       *
C     *     VALUES FOR GRAIN ARE                                           *
C     *               1 FOR STRAIGHT C.P. GRAIN                            *
C     *               2 FOR STRAIGHT STAR GRAIN                            *
```

TABLE IV-2. (Cont'd)

```
C    *                 3 FOR COMBINATION OF C.P. AND STAR GRAINS           *
C    *      VALUES FOR STAR ARE (WAGON WHEEL IS CONSIDERED A TYPE OF       *
C    *        STAR GRAIN IN THIS PROGRAM)                                   *
C    *                 0 FOR STRAIGHT C.P. GRAIN                            *
C    *                 1 FOR STANDARD STAR                                  *
C    *                 2 FOR TRUNCATED STAR                                 *
C    *                 3 FOR WAGON WHEEL                                    *
C    *      VALUES FOR NT ARE                                               *
C    *                 0 IF THERE ARE NO TERMINATION PORTS                  *
C    *                 X WHERE X IS THE NUMBER OF TERMINATION PORTS         *
C    *      VALUES OF ORDER ESTABLISH HOW A COMBINATION C.P. AND STAR       *
C    *        GRAIN IS ARRANGED                                             *
C    *                 1 IF DESIGN IS STAR AT HEAD END AND C.P. AT NOZZLE   *
C    *                 2 IF DESIGN IS C.P. AT HEAD END AND C.P. AT NOZZLE   *
C    *                 3 IF DESIGN IS C.P. AT HEAD END AND STAR AT NOZZLE   *
C    *                 4 IF DESIGN IS STAR AT HEAD END AND STAR AT NOZZLE   *
C    *              ***NOTE***  IF GRAIN=1, VALUE OF ORDER MUST BE 2        *
C    *              ***NOTE***  IF GRAIN=2, VALUE OF ORDER MUST BE 4        *
      CONTINUE
C    *      VALUES FOR COP ARE (APPLICABLE TO C.P. GRAINS ONLY)             *
C    *                 0 IF BOTH ENDS ARE CONICAL OR FLAT                   *
C    *                 1 IF HEAD END IS CONICAL OR FLAT AND AFT END IS      *
C    *                     HEMISPHERICAL                                    *
C    *                 2 IF BOTH ENDS ARE HEMISPHERICAL                     *
C    *                 3 IF HEAD END IS HEMISPHERICAL AND AFT END IS        *
C    *                     CONICAL OR FLAT                                  *
C    ************************************************************************
  500 FORMAT(9X,I2,9X,I2,8X,I2,6X,F4.0,9X,I2,7X,I2)
      IF(Y.LE.0.0) WRITE(6,607)
  607 FORMAT(//,20X,'GRAIN CONFIGURATION')
      IF(Y.LE.0.0) WRITE(6,600) INPUT,GRAIN,STAR,NT,ORDER,COP
  600 FORMAT(13X,'INPUT= ',I2,/,13X,'GRAIN= ',I2,/,13X,'STAR= ',I2,/,13X
     1,'NT= ',F4.0,/,13X,'ORDER= ',I2,/,13X,'COP= ',I2,//)
      IF(INPUT.EQ.2) GO TO 12
      IF(Y.LE.0.0) GO TO 6
      IF(YT.LE.Y.AND.K.LT.2) GO TO 8
    9 DENOM=YT-YT2
      SLOPE1=(ABPK-ABPK2)/DENOM
      SLOPE2=(ABSK-ABSK2)/DENOM
      SLOPE3=(ABNK-ABNK2)/DENOM
      SLOPE4=(APHK-APHK2)/DENOM
      SLOPE5=(APNK-APNK2)/DENOM
      B1=ABPK-SLOPE1*YT
      B2=ABSK-SLOPE2*YT
      B3=ABNK-SLOPE3*YT
      B4=APHK-SLOPE4*YT
      B5=APNK-SLOPE5*YT
      ABPT=SLOPE1*Y+B1
```

TABLE IV-2. (Cont'd)

```
      ABST=SLOPE2*Y+B2
      ABNT=SLOPE3*Y+B3
      APHT=SLOPE4*Y+B4
      APNT=SLOPE5*Y+B5
      IF(INPUT.EQ.3) GO TO 3
      GO TO 52
    6 READ(5,507) YT,ABPK,ABSK,ABNK,APHK,APNK,VCIT
C   ******************************************************************
C   *     READ IN TABULAR VALUES FOR Y=0.0  (NOT REQUIRED IF INPUT=2)  *
C   *                                                                *
C   *     ABPK IS THE BURNING AREA IN THE PORT IN IN**2              *
C   *     ABSK IS THE BURNING AREA IN THE SLOTS IN IN**2             *
C   *     ABNK IS THE BURNING AREA IN THE NOZZLE END IN IN**2        *
C   *     APHK IS THE PORT AREA AT THE HEAD END IN IN**2             *
C   *     APNK IS THE PORT AREA AT THE NOZZLE END IN IN**2           *
C   *     VCIT IS THE INITIAL VOLUME OF CHAMBER GASES ASSOCIATED WITH *
C   *          TABULAR INPUT IN IN**3                                *
C   ******************************************************************
  507 FORMAT(6X,F6.2,10X,E11.4,10X,E11.4,8X,E11.4,/,22X,E11.4,9X,E11.4,
     1  8X,E11.4)
      WRITE(6,610)
  610 FORMAT(13X,'TABULAR VALUES FOR YT EQUAL ZERO READ IN')
      WRITE(6,583) ABPK,ABSK,ABNK,APHK,APNK
  583 FORMAT(13X,'ABPK=',1PE11.4,5X,'ABSK=',1PE11.4,5X,'ABNK=',1PE11.4,
     1  5X,'APHK=',1PE11.4,5X,'APNK=',1PE11.4)
      WRITE(6,584) VCIT
  584 FORMAT(13X,'VCIT=',1PE11.4,//)
      ABPT=ABPK
      ABST=ABSK
      ABNT=ABNK
      APHT=APHK
      APNT=APNK
      YT2=YT
      IF(INPUT.EQ.3) GO TO 3
      GO TO 52
    8 YT2=YT
      ABPK2=ABPK
      ABNK2=ABNK
      ABSK2=ABSK
      APHK2=APHK
      APNK2=APNK
      READ(5,505) YT,ABPK,ABSK,ABNK,APHK,APNK
C   ******************************************************************
C   *     READ IN TABULAR VALUES FOR Y=Y    (NOT REQUIRED FOR INPUT=2)  *
C   ******************************************************************
  505 FORMAT(6X,F6.2,10X,E11.4,10X,E11.4,8X,E11.4,/,22X,E11.4,9X,E11.4)
      WRITE(6,611) YT
  611 FORMAT(///,13X,'TABULAR VALUES FOR YT= ',F7.3,'  READ IN')
```

TABLE IV-2. (Cont'd)

```
      WRITE(6,583) ABPK,ABSK,ABNK,APHK,APNK
      GO TO 9
   12 ABPT=0.0
      ABNT=0.0
      ABST=0.0
    3 IF(GRAIN.NE.2) GO TO 4
      ABPC=0.0
      ABNC=0.0
      ABSC=0.0
      GO TO 7
    4 IF(Y.LE.0.0) READ(5,501) DO,DI,DELDI,S,THETAG,LGCI,LGNI,THETCN,THE
     1TCH
C     ******************************************************************
C     *    READ IN BASIC GEOMETRY FOR C.P. GRAIN  (NOT REQUIRED FOR     *
C     *         STRAIGHT STAR GRAIN)                                    *
C     *    DO IS THE AVERAGE OUTSIDE INITIAL GRAIN DIAMETER IN INCHES   *
C     *    DI IS THE AVERAGE INITIAL INTERNAL GRAIN DIAMETER IN INCHES  *
C     *    DELDI IS THE DIFFERENCE BETWEEN THE INITIAL INTERNAL GRAIN   *
C     *         DIAMETER AT THE NOZZLE END AND DI IN INCHES             *
C     *    S IS THE NUMBER OF FLAT BURNING SLOT SIDES (NOT INCLUDING    *
C     *         THE NOZZLE END)                                         *
C     *    THETAG IS THE ANGLE THE NOZZLE END OF THE GRAIN MAKES WITH   *
C     *         THE MOTOR AXIS IN RADIANS                               *
C     *    LGCI IS THE INITIAL TOTAL LENGTH OF THE CIRCULAR PERFORATION *
C     *         IN INCHES                                               *
C     *    LGNI IS THE INITIAL SLANT LENGTH OF THE BURNING CONICAL      *
C     *         GRAIN AT THE NOZZLE END IN INCHES                       *
C     *    THETCN IS THE CONTRACTION ANGLE OF THE BONDED GRAIN IN RAD.  *
C     *    THETCH IS THE CONTRACTION ANGLE AT THE HEAD END IN RADIANS   *
C     ******************************************************************
  501 FORMAT(5X,F7.3,6X,F7.3,9X,F7.3,5X,F4.0,9X,F7.5,/,7X,F7.2,7X,F6.2,9
     1X,F7.5,9X,F7.5)
      IF(Y.LE.0.0) WRITE(6,601) DO,DI,DELDI,S,THETAG,LGCI,LGNI,THETCN,TH
     1ETCH
  601 FORMAT(20X,'C.P. GRAIN GEOMETRY',/,13X,'DO= ',F7.3,/,13X,'DI= ',F7
     1.3,/,13X,'DELDI= ',F7.3,/,13X,'S= ',F4.0,/,13X,'THETAG= ',F7.5,/,1
     23X,'LGCI= ',F7.2,/,13X,'LGNI= ',F6.2,/,13X,'THETCN= ',F7.5,/,13X,'
     3THETCH= ',F7.5,//)
      DOSQD=DO*DO
      DISQD=DI*DI
      BNUM=ANUM*DOSQD
      TLL=TL
      IF(ORDER.GE.3) TLL=0.0
      YDI=2.*Y+DI
      YDISQD=YDI*YDI
      ABSC=S*ANUM*(DOSQD-YDISQD)
      IF(ABSC.LE.0.0) ABSC=0.0
      IF(YDI.GT.DO) GO TO 100
```

TABLE IV-2. (Cont'd)

```
      IF(THETAG.GT.0.08727) GO TO 101
      IF(COP.EQ.0) GO TO 700
      IF(COP.EQ.1) GO TO 701
      IF(COP.EQ.2) GO TO 702
      LGC=LGCI-(SQRT(DOSQD-DISQD)-SQRT(DOSQD-YDISQD))/2.-Y*COTAN(THETCN)
      GO TO 710
  702 LGC=LGCI-(SQRT(DOSQD-DISQD)-SQRT(DOSQD-YDISQD))
      GO TO 710
  701 LGC=LGCI-(SQRT(DOSQD-(DI+DELDI)**2)-SQRT(DOSQD-(YDI+DELDI)**2))/
     1  2.-Y*COTAN(THETCH)
      GO TO 710
  700 LGC=LGCI-Y*(COTAN(THETCN)+COTAN(THETCH))
  710 ABPC=PI*YDI*(LGC-TLL-S*Y)
      ABNC=0.0
      GO TO 732
  101 CONTINUE
      IF(COP.EQ.0.OR.COP.EQ.1) GO TO 720
      ABPC=PI*YDI*(LGCI-(SQRT(DOSQD-DISQD)-SQRT(DOSQD-YDISQD))/
     1  2.-TLL-(S+TAN(THETAG/2.))*Y)
      GO TO 730
  720 ABPC=PI*YDI*(LGCI-Y*COTAN(THETCH)-TLL-(S+TAN(THETAG/2.))*Y)
  730 IF(COP.EQ.1.OR.COP.EQ.2) GO TO 731
      ABNC=PI*(LGNI-Y*COTAN(THETAG+THETCN)-Y*TAN(THETAG/2.))*(DI+
     1  DELDI+Y+LGNI*SIN(THETAG)+Y*SIN(THETCN)/SIN(THETAG+THETCN))
      GO TO 732
  731 R3=((DI+DELDI)/2.+LGNI*SIN(THETAG))*COS(THETAG)-SIN(THETAG)*
     1  SQRT((DO/2.)**2-((DI+DELDI)/2.+LGNI*SIN(THETAG))**2)
      ABNC=PI*(LGNI-R3-Y*TAN(THETAG/2.))*((DI+DELDI)/2.+SQRT((DO/
     1  2.)**2-(R3+Y)**2)*SIN(THETAG)+Y+(R3+Y)*COS(THETAG))
  732 IF(ABPC.LE.0.0) ABPC=0.0
      IF(ABNC.LE.0.0) ABNC=0.0
      GO TO 5
  100 ABNC=0.0
      ABPC=0.0
    5 APHT=ANUM*(DI+2.*RHT)**2
      IF(APHT.GE.BNUM) APHT=BNUM
      IF(K.LT.2) APHT1=APHT
      APNT=ANUM*(DI+DELDI+2.*RNT)**2
      IF(APNT.GE.BNUM) APNT=BNUM
      IF(GRAIN.NE.1) GO TO 7
      ABPS=0.0
      ABSS=0.0
      ABNS=0.0
      GO TO 50
    7 IF(Y.LE.0.0) READ(5,502) NS,LGSI,NP,RC,FILL,NN
C     ****************************************************************
C     *     READ IN BASIC GEOMETRY FOR STAR GRAIN  (NOT REQUIRED FOR   *
C     *            STRAIGHT C.P. GRAIN)                                *
```

TABLE IV-2. (Cont'd)

```
C  *     NS IS THE NUMBER OF FLAT BURNING SLOT SIDES (NOT INCLUDING      *
C  *          THE NOZZLE END)                                            *
C  *     LGSI IS THE INITIAL TOTAL LENGTH OF THE STAR SHAPED             *
C  *          PERFORATED GRAIN IN INCHES                                 *
C  *     NP IS THE NUMBER OF STAR POINTS                                 *
C  *     RC IS THE AVERAGE STAR GRAIN OUTSIDE RADIUS IN INCHES           *
C  *     FILL IS THE FILLET RADIUS IN INCHES                             *
C  *     NN IS THE NUMBER OF STAR NOZZLE END BURNING SURFACES            *
C  *********************************************************************
  502 FORMAT(5X,F4.0,7X,F7.2,5X,F4.0,5X,F7.3,9X,F7.3,5X,F4.0)
      IF(Y.LE.0.0) WRITE(6,602) NS,LGSI,NP,RC,FILL,NN
  602 FORMAT(20X,'BASIC STAR GEOMETRY',/,13X,'NS= ',F4.0,/,13X,'LGSI= ',
     1F7.2,/,13X,'NP= ',F4.0,/,13X,'RC= ',F7.3,/,13X,'FILL= ',F7.3,/,13X
     2,'NN= ',F4.0,//)
      PIDNP=PI/NP
      RCSQD=RC*RC
      FY=FILL+Y
      FYSQD=FY*FY
      IF(STAR.EQ.1) GO TO 20
      IF(STAR.EQ.2) GO TO 201
      IF(Y.GT.0.0) GO TO 179
      READ(5,421) TAUWW,L1,L2,ALPHA1,ALPHA2,HW
C  *********************************************************************
C  *     READ IN GEOMETRY FOR WAGON WHEEL (NOT REQUIRED FOR STANDARD     *
C  *          OR TRUNCATED STAR GRAINS)                                  *
C  *     TAUWW IS THE THICKNESS OF THE PROPELLANT WEB IN INCHES          *
C  *     L1 AND L2 ARE THE LENGTHS OF THE TWO PARALLEL SIDES OF THE      *
C  *          TWO SETS OF STAR POINTS IN INCHES                          *
C  *     ALPHA1 AND ALPHA2 ARE THE ANGLES BETWEEN THE SLANT SIDES OF     *
C  *          THE STAR POINTS CORRESPONDING TO L1 AND L2, RESPECTIVELY,*
C  *          AND THE CENTER LINES OF THE POINTS IN RADIANS              *
C  *     HW IS HALF THE WIDTH OF THE STAR POINTS IN INCHES               *
C  *********************************************************************
  421 FORMAT(3(6X,F5.2),2(10X,F7.5),6X,F5.2)
      WRITE(6,422) TAUWW,L1,L2,ALPHA1,ALPHA2,HW
  422 FORMAT(20X,'WAGON WHEEL GEOMETRY',/,13X,'TAUWW= ',F5.2,/,13X,
     1  'L1= ',F5.2,/,13X,'L2= ',F5.2,/,13X,'ALPHA1= ',F7.5,/,13X,
     2  'ALPHA2= ',F7.5,/,13X,'HW= ',F5.2,//)
      ALP2=ALPHA2
      XL2=L2
      LFW=RC-TAUWW-FILL
      LFWSQD=LFW*LFW
      THETFW=ARSIN((HW+FILL)/LFW)
      SLFW=LFW*SIN(THETFW)
  179 KKK=0
      SG=0.0
      ENUM=(RCSQD-LFWSQD-FYSQD)/(2.*LFW*FY)
      ALPHA2=ALP2
```

TABLE IV-2. (Cont'd)

```
      L2=XL2
  190 YTAN=Y*TAN(ALPHA2/2.)
      COSALP=COS(ALPHA2)
      SINALP=SIN(ALPHA2)
      IF(YTAN.GT.L2) GO TO 182
      IF(FY.GT.SLFW) GO TO 181
      SGW=NP*(L2-2.*YTAN+(SLFW-FILL)/SINALP-Y*COTAN(ALPHA2)+FY*
     1  (PID2+THETFW)+(LFW+FY)*(PIDNP-THETFW))
      GO TO 183
  181 IF(Y.GT.TAUWW) GO TO 184
      SGW=NP*(FY*(PIDNP+ARSIN(SLFW/FY))+(PIDNP-THETFW)*LFW)
      GO TO 183
  184 SGW=NP*FY*(THETFW+ARSIN(SLFW/FY)-ARCOS(ENUM))
      GO TO 183
  182 YPO=-SLFW
      IF(ALPHA2.GE.PID2) GO TO 222
      Q=-FILL+L2*TAN(ALPHA2)-Y/COSALP
      XPI=(-Q*TAN(ALPHA2)-SQRT(-Q*Q+FYSQD/COSALP*COSALP))*COSALP*COSALP
      YPI=XPI*TAN(ALPHA2)+Q
      XPO=(YPO-Q)*COTAN(ALPHA2)
      GO TO 223
  222 XPI=Y-L2
      YPI=-SQRT(FYSQD-XPI*XPI)
      XPO=XPI
  223 FYLS=SQRT(SLFW*SLFW+XPI*XPI)
      XPIO2=(XPI-XPO)*(XPI-XPO)
      YPIO2=(YPI-YPO)*(YPI-YPO)
      IF(FY.GT.FYLS) GO TO 186
      IF(Y.GE.TAUWW) GO TO 185
      SGW=NP*(SQRT(XPIO2+YPIO2)+FY*(PID2+THETFW-ARSIN(XPI/FY))+(LFW+FY)*
     1  (PIDNP-THETFW))
      GO TO 183
  185 SGW=NP*(SQRT(XPIO2+YPIO2)+FY*(PID2-ARSIN(XPI/FY)-ARCOS(ENUM)))
      GO TO 183
  186 IF(Y.GT.TAUWW) GO TO 187
      SGW=NP*(FY*(PIDNP+ARSIN(SLFW/FY))+(PIDNP-THETFW)*LFW)
      GO TO 183
  187 SGW=NP*FY*(THETFW+ARSIN(SLFW/FY)-ARCOS(ENUM))
  183 IF(SGW.LE.0.0) SGW=0.0
      IF(Y.GT.0.0) GO TO 188
      AGS2=.5*(PI*RCSQD-NP*LFW*SLFW*(COS(THETFW)-SIN(THETFW)*COTAN(ALPHA
     1 2)-2.*(L2+FILL*TAN(ALPHA2/2.))/LFW)-(PI-THETFW*NP)*LFWSQD-2.*NP*F
     2 ILL*(L2+SLFW/SINALP+LFW*(PIDNP-THETFW)+(PIDNP+PID2-1./SINALP)*
     1  FILL/2.))
      AGS=AGS+AGS2
  188 CONTINUE
      SG=SG+SGW
      IF(KKK.EQ.1) GO TO 24
```

TABLE IV-2. (Cont'd)

```
      L2=L1
      ALPHA2=ALPHA1
      KKK=1
      GO TO 190
  201 IF(Y.LE.0.0) READ(5,503) RP,TAUS
C     ****************************************************************
C     *     READ IN GEOMETRY FOR TRUNCATED STAR  (NOT REQUIRED FOR    *
C     *           STANDARD STAR OR WAGON WHEEL)                       *
C     *     RP IS THE INITIAL RADIUS OF THE TRUNCATION IN INCHES      *
C     *     TAUS IS THE THICKNESS OF THE PROPELLANT WEB AT THE BOTTOM *
C     *           OF THE SLOTS IN INCHES                              *
C     ****************************************************************
  503 FORMAT(5X,F7.3,7X,F7.3)
      IF(Y.LE.0.0) WRITE(6,603) RP,TAUS
  603 FORMAT(20X,'TRUNCATED STAR GEOMETRY',/,13X,'RP= ',F7.3,/,13X,'TAUS
     1= ',F7.3,//)
      THETAS=PIDNP
      RPY=RP+Y
      LS=RC-TAUS-FILL-RP
      RPL=RP+LS
      THETS1=THETAS-ARSIN(FY/RPY)
      IF(THETS1.LE.0.0) GO TO 110
      IF(Y.LE.TAUS) GO TO 103
      THETAC=ARSIN((RCSQD-RPL*RPL-FYSQD)/(2.*FY*RPL))
      IF(THETAC.GE.0.0) GO TO 104
      IF(Y.LT.RC-RP) GO TO 105
      SG=0.0
      GO TO 14
  103 SG=2.*NP*(RPY*THETS1+LS-(RPY*COS(THETAS-THETS1)-RP)+PID2*FY)
      GO TO 14
  104 SG=2.*NP*(RPY*THETS1+LS-(RPY*COS(THETAS-THETS1)-RP)+FY*THETAC)
      GO TO 14
  105 SG=2.*NP*(RPY*THETS1+SQRT(RCSQD-FYSQD)-SQRT(RPY*RPY-FYSQD))
   14 IF(Y.LE.0.0) AGS=PI*(RCSQD-RP*RP)-NP*(PI*FILL*FILL/2.+2.*LS*FILL)
      GO TO 31
  110 THETAF=THETAS
      THETAP=2.*THETAS
      TAUWS=TAUS
      GO TO 111
   20 IF(Y.LE.0.0) READ(5,504) THETAF,THETAP,TAUWS
C     ****************************************************************
C     *     READ IN GEOMETRY FOR STANDARD STAR  (NOT REQUIRED FOR     *
C     *           TRUNCATED STAR OR WAGON WHEEL)                      *
C     *     THETAF IS THE ANGLE LOCATION OF THE FILLET CENTER IN RADIANS *
C     *     THETAP IS THE ANGLE OF THE STAR POINT IN RADIANS          *
C     *     TAUWS IS THE WEB THICKNESS OF THE GRAIN IN INCHES         *
C     ****************************************************************
  504 FORMAT(9X,F7.5,9X,F7.5,8X,F6.3)
```

TABLE IV-2. (Cont'd)

```
      IF(Y.LE.0.0) WRITE(6,604) THETAF,THETAP,TAUWS
  604 FORMAT(20X,'STANDARD STAR GEOMETRY',/,13X,'THETAF= ',F7.5,/,13X,'T
     1HETAP= ',F7.5,/,13X,'TAUWS= ',F6.3,//)
      THETAS=PI/NP
      THETS1=1.00
  111 LF=RC-TAUWS-FILL
      CNUM=(Y+FILL)/LF
      DNUM=SIN(THETAF)/SIN(THETAP/2.)
      ENUM=(RCSQD-LF*LF-FYSQD)/(2.*LF*FY)
      FNUM=SIN(THETAF)/COS(THETAP/2.)
      IF(CNUM.LE.FNUM) GO TO 106
      IF(Y.LE.TAUWS)GO TO 107
      SG=2.*NP*FY*(THETAF+ARSIN(SIN(THETAF)/CNUM)-ARCOS(ENUM))
      GO TO 23
  106 IF(Y.LE.TAUWS) SG=2.*NP*LF*(DNUM+CNUM*(PID2+THETAS-THETAP/2.
     1-COTAN(THETAP/2.))+THETAS-THETAF)
      IF(Y.LE.TAUWS) GO TO 23
      SG=2.*NP*(FY*ARSIN(ENUM-(THETAS-THETAP/2.))+LF*DNUM-FY*COTAN(THETA
     1P/2.))
      GO TO 23
  107 SG=2.*NP*LF*(CNUM*(THETAS+ARSIN(SIN(THETAF)/CNUM))+THETAS-THETAF)
   23 IF(THETS1.LE.0.0) GO TO 14
      IF(Y.LE.0.0) AGS=PI*RC*Q2-NP*LF*LF*(SIN(THETAF)*(COS(THETAF)-
     1SIN(THETAF)*COTAN(THETAP/2.))+THETAS-THETAF+2.*FILL/LF*(SIN(THETAF
     2)/SIN(THETAP/2.)+THETAS-THETAF+FILL/(2.*LF)*(PID2+THETAS-THE
     3TAP/2.-COTAN(THETAP/2.))))
   24 CONTINUE
   31 IF(SG.LE.0.0) SG=0.0
      IF(K.EQ.0.OR.K.EQ.2) SGN=SG
      IF(K.LE.1) SGH=SG
      IF(Y.LE.0.0) SG2=SG
      IF(K.EQ.2) GO TO 37
      RAVEDT=R1+(SG+SG2)/2.*RBAR*DELTAT
      RNDT=R2+(SG+SG2)/2.*RNAVE*DELTAT
      RHDT=R3+(SG+SG2)/2.*RHAVE*DELTAT
      R1=RAVEDT
      R2=RNDT
      R3=RHDT
      SG2=SG
      GO TO 38
   37 IF(KOUNT.NE.1) GO TO 39
      SG3=SG
      R4=R1
      R5=R2
      R6=R3
   39 RAVEDT=R4+(SG+SG3)/2.*RBAR*DELTAT
      RNDT=R5+(SG+SG3)/2.*RNAVE*DELTAT
      RHDT=R6+(SG+SG3)/2.*RHAVE*DELTAT
```

TABLE IV-2. (Cont'd)

```
      RHDT=R6+(SG+SG3)/2.*RHAVE*DELTAT
      R4=RAVEDT
      R5=RNDT
      R6=RHDT
      SG3=SG
   38 ABSS=(AGS-RAVEDT)*NS
      IF(ABSS.LE.0.0.OR.SG.LE.0.0) ABSS=0.0
      ABNS=(AGS-RNDT)*NN
      IF(ABNS.LE.0.0.OR.SG.LE.0.0) ABNS=0.0
      IF(ORDER.LE.2) ABPS=(LGSI-Y*(NS+NN))*SG
      IF(ORDER.LE.2) GO TO 36
      ABPS=(LGSI-TL-Y*(NS+NN))*SG
   36 PIRCRC=PI*RCSQD
      APHS=PIRCRC-AGS+RHDT
      IF(APHS.GE.PIRCRC.OR.SG.LE.0.0) APHS=PIRCRC
      APNS=PIRCRC-AGS+RNDT
      IF(K.LT.2) APHS1=APHS
      IF(APNS.GE.PIRCRC) APNS=PIRCRC
   50 IF(NT.EQ.0.0) GO TO 371
      IF(Y.LE.0.0) READ(5,506) LTP,DTP,THETTP,TAUEFF
C   ****************************************************************
C   *     READ IN GEOMETRY ASSOCIATED WITH TERMINATION PORTS  (NOT     *
C   *          REQUIRED IF NT=0)                                       *
C   *     LTP IS THE INITIAL LENGTH OF THE TERMINATION PASSAGES        *
C   *          IN INCHES                                               *
C   *     DTP IS THE INITIAL DIAMETER OF THE TERMINATION PASSAGE       *
C   *          IN INCHES                                               *
C   *     THETTP IS THE ACUTE ANGLE BETWEEN THE AXIS OF THE PASSAGE    *
C   *          AND THE MOTOR AXIS IN RADIANS                           *
C   *     TAUEFF IS THE ESTIMATED EFFECTIVE WEB THICKNESS AT THE       *
C   *          TERMINATION PORT IN INCHES                              *
C   ****************************************************************
  506 FORMAT(7X,F6.2,7X,F5.2,10X,F7.5,10X,F6.3)
      IF(Y.LE.0.0) WRITE(6,606) LTP,DTP,THETTP,TAUEFF
  606 FORMAT(20X,'TERMINATION PORT GEOMETRY',/,13X,'LTP= ',F6.2,/,13X,'D
     1TP= ',F5.2,/,13X,'THETTP= ',F7.5,/,13X,'TAUEFF= ',F6.3,//)
      DABT=NT*3.14159*((DTP+2.*Y)*(LTP-Y/SIN(THETTP))-(DTP+2.*Y)**2/4.+
     1(Y+DTP/2.)*(DTP/2.)*(1.-1./SIN(THETTP)))
      IF(Y.GE.TAUEFF) DABT=0.0
  371 IF(Y.GT.0.0) GO TO 52
      IF(NT.NE.0.0) GO TO 45
      LTP=0.0
      DTP=0.0
   45 IF(GRAIN.NE.2) GO TO 49
      LGCI=0.0
      LGNI=0.0
   49 IF(GRAIN.EQ.1) LGSI=0.0
      VCI=1.1*(ANUM*DISQD*(LGCI+LGNI)+(ANUM*DOSQD-AGS)*LGSI+NT*LTP*ANUM*
```

TABLE IV-2. (Cont'd)

```
  1  DTP*DTP)+VCIT
52 BBP=0.0
   BBS=0.0
   BBN=0.0
   ABPORT=ABPT+ABPC+ABPS+DABT+BBP
   ABSLOT=ABST+ABSC+ABSS+BBS
   ABNOZ=ABNT+ABNC+ABNS+BBN
   SUMAB=ABPORT+ABSLOT+ABNOZ
   IF(K.EQ.0) GO TO 99
   IF(K.EQ.1) ABMAIN=ABPORT+ABSLOT+ABNOZ
   K=K+1
   IF(K.GT.2) GO TO 69
   GO TO 2
69 ABTO=ABPORT+ABSLOT+ABNOZ
99 CONTINUE
   IF(Y.GT.0.0) GO TO 70
   ABP1=ABPORT
   ABN1=ABNOZ
   ABS1=ABSLOT
70 ABP2=(ABP1+ABPORT)/2.
   ABN2=(ABN1+ABNOZ)/2.
   ABS2=(ABS1+ABSLOT)/2.
   IF(INPUT.EQ.1) GO TO 76
   GO TO (71,72,73,74),ORDER
71 APHEAD=APHS1
   APNOZ=APNT
   SG=SGH
   GO TO 75
72 APHEAD=APHT1
   APNOZ=APNT
   SG=0.0
   IF(GRAIN.EQ.3) SG=(SGH+SGN)/2.
   GO TO 75
73 APHEAD=APHT1
   APNOZ=APNS
   SG=SGN
   GO TO 75
74 APHEAD=APHS1
   APNOZ=APNS
   SG=SGN
   GO TO 75
76 APHEAD=APHT
   APNOZ=APNT
75 Y=YB
   DIFF=SUMAB-SUM2
   DADY=DIFF/DELY
   ABP1=ABPORT
   ABN1=ABNOZ
```

TABLE IV-2. (Cont'd)

```
      ABS1=ABSLOT
      IF(ZW.GE.0.0) GO TO 77
      ABM1=ABMAIN
      ABMAIN=ABTO
      ABTO=ABM1
   77 RETURN
      END
```

TABLE IV-2. (Cont'd)

```
      SUBROUTINE OUTPUT
C     ***********************************************************************
C  *      SUBROUTINE OUTPUT CALCULATES BASIC PERFORMANCE PARAMETERS      *
C  *      AND PRINTS THEM OUT                                              *
C  *      (WEIGHT CALCULATIONS ARE PERFORMED IN THE MAIN PROGRAM)        *
C  *      T IS THE TIME IN SECS                                            *
C  *      Y IS THE DISTANCE BURNED IN INCHES                               *
C  *      RNOZ IS THE NOZZLE END BURNING RATE IN INCHES/SEC               *
C  *      RHEAD IS THE HEAD END BURNING RATE IN INCHES/SEC                *
C  *      PONOZ IS THE STAGNATION PRESSURE AT THE NOZZLE END IN PSIA     *
C  *      PHEAD IS THE PRESSURE AT THE HEAD END OF THE GRAIN IN PSIA     *
C  *      PTAR IS THE PORT TO THROAT AREA RATIO                           *
C  *      MNOZ IS THE MACH NUMBER AT THE NOZZLE END OF THE GRAIN         *
C  *      PATM IS THE ATMOSPHERIC PRESSURE AT ALTITUDE IN PSIA           *
C  *      SUMAB IS THE TOTAL BURNING AREA OF PROPELLANT IN IN**2         *
C  *      SG IS THE BURNING PERIMETER IN INCHES OF THE STAR SEGMENT      *
C  *           (IF ANY)                                                    *
C  *      CFVAC IS THE VACUUM THRUST COEFFICIENT                          *
C  *      FVAC IS THE VACUUM THRUST IN LBS                                *
C  *      F IS THE THRUST IN LBS                                           *
C     ***********************************************************************
      REAL MGEN,MDIS,MNOZ,MN1,JROCK,N,L,ME1,ME,ISP,ITOT,MU,MASS,ISPVAC
      REAL M2,MDBAR,ISP2,ITVAC
      COMMON/CONST1/ZW,AE,AT,THETA,ALFAN
      COMMON/CONST2/CAPGAM,ME,BOT,ZETAF,TB,HB,GAM
      COMMON/VARIA1/Y,T,DELY,DELTAT,PONOZ,PHEAD,RNOZ,RHEAD,SUMAB,PHMAX
      COMMON/VARIA3/ITOT,ITVAC,JROCK,ISP,ISPVAC,MDIS,MNOZ,SG,SUMMT
      COMMON/VARIA5/ABMAIN,ABTO,SUMDY,VCI,VC
▶     COMMON/PLOTT/NUMPLT(16),IPO,NDUM,NP,IOP
▶     DIMENSION TPLOT(200),PNPLOT(200),PHPLOT(200),FPLOT(200),
▶    1  FVPLOT(200),RNPLOT(200),RHPLOT(200),YBPLOT(200),ABPLOT(200),
▶    1  SGPLOT(200),VCPLOT(200)
      DATA G/32.1725/
▶     IF(NDUM.EQ.1) GO TO 2
▶     NP=NP+1
      YB=Y
      IF(Y.LE.0.0) M2=MDIS
      MDBAR=(M2+MDIS)/2.
      SUMMT=SUMMT+MDBAR*DELTAT
      PTAR=1./JROCK
      PRES=(1.+BOT/2.*ME*ME)**(-GAM/BOT)
      ALT=HB*(T/TB)**(7./3.)
      PATM=14.696/EXP(0.43103E-04*ALT)
      IF(MDIS.LE.0.0.OR.PONOZ.LE.0.0) GO TO 45
      CF=CAPGAM*SQRT(2.*GAM/BOT*(1.-PRES**(BOT/GAM)))+AE/AT*(PRES-PATM/P
     1ONOZ)
      CFVAC=CF+AE/AT*PATM/PONOZ
      F=ZETAF*COS(THETA)*PONOZ*AT*((1.+COS(ALFAN))/2.*CF+(1.-COS(ALFAN))
```

TABLE IV-2. (Cont'd)

```
     1/2.*AE/AT*(PRES-PATM/PONOZ))
      IF(F.LE.0.0) F=0.0
      IF(Y.LE.0.0) F2=F
      FBAR=(F+F2)/2.
      FVAC=ZETAF*COS(THETA)*PONOZ*AT*((1.+COS(ALFAN))/2.*CFVAC+(1.-COS(A
     1LFAN))/2.*AE/AT*PRES)
      IF(Y.LE.0.0) FV2=FVAC
      FVBAR=(FV2+FVAC)/2.
      ISP=F/(MDIS*G)
      ISPVAC=FVAC/(MDIS*G)
      ITOT=ITOT+FBAR*DELTAT
      ITVAC=ITVAC+FVBAR*DELTAT
      M2=MDIS
      F2=F
      FV2=FVAC
      IF(PHEAD.GT.PHMAX) PHMAX=PHEAD
      GO TO 47
   45 CFVAC=0.0
      FVAC=0.0
      F=0.0
   47 WRITE(6,1) T,YB,RNOZ,RHEAD,PONOZ,PHEAD,PTAR,MNOZ,SUMAB,SG,PATM,CFV
     1AC,FVAC,F
    1 FORMAT(//,13X,'TIME= ',F7.3,12X,'Y= ',F6.3,/,13X,'RNOZ= ',1PE11.4,
     1'  RHEAD= ',1PE11.4,'  PONOZ= ',1PE11.4,'  PHEAD= ',1PE11.4,/,13X,
     2'PTAR= ',1PE11.4,'   MNOZ= ',1PE11.4,'  SUMAB= ',1PE11.4,'     SG=
     3 ',1PE11.4,/,13X,'PATM= ',1PE11.4,'  CFVAC= ',1PE11.4,'   FVAC= ',
     41PE11.4,'       F= ',1PE11.4)
      IF(IPO.EQ.0) RETURN
      TPLOT(NP)=T
      PNPLOT(NP)=PONOZ
      PHPLOT(NP)=PHEAD
      FPLOT(NP)=F
      FVPLOT(NP)=FVAC
      RNPLOT(NP)=RNOZ
      RHPLOT(NP)=RHEAD
      YBPLOT(NP)=YB
      ABPLOT(NP)=SUMAB
      SGPLOT(NP)=SG
      VCPLOT(NP)=VC
      RETURN
    2 NP=NP+2
      IOP=1
      DO 1004 I=1,16
      IF(NUMPLT(I).EQ.1) GO TO 1003
      GO TO 1004
 1003 GO TO (10,20,30,40,50,55,60,70,75,80,90,95,97,100,110,115),I
   10 CALL PLOTIT(TPLOT,'TIME (SECS)',11,PHPLOT,'PHEAD (PSIA)',12,
     1 PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
```

TABLE IV-2. (Cont'd)

```
▶       GO TO 1004
▶    20 CALL PLOTIT(TPLOT,'TIME (SECS)',11,PNPLOT,'PONOZ (PSIA)',12,PHPLOT
▶      1,'PHEAD (PSIA)',12,NP,1,'DUMMY',5)
▶       GO TO 1004
▶    30 CALL PLOTIT(TPLOT,'TIME (SECS)',11,PHPLOT,'PHEAD',5,PNPLOT
▶      1,'PONOZ',5,NP,3,'PRESSURE (PSIA)',15)
▶       GO TO 1004
▶    40 CALL PLOTIT(TPLOT,'TIME (SECS)',11,RHPLOT,'RHEAD (IN PER SEC)',18,
▶      1PHPLOT,'PHEAD (PSIA)',12,NP,1,'DUMMY',5)
▶       GO TO 1004
▶    50 CALL PLOTIT(TPLOT,'TIME (SECS)',11,RNPLOT,'RNOZ (IN PER SEC)',17,
▶      1PNPLOT,'PONOZ (PSIA)',12,NP,1,'DUMMY',5)
▶       GO TO 1004
▶    55 CALL PLOTIT(TPLOT,'TIME (SECS)',11,RHPLOT,'RHEAD',5,RNPLOT,
▶      1 'RNOZ',4,NP,3,'BURNING RATE (IN PER SEC)',25)
▶       GO TO 1004
▶    60 CALL PLOTIT(TPLOT,'TIME (SECS)',11,ABPLOT,'TOTAL BURNING AREA (SQ
▶      1IN)',26,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶       GO TO 1004
▶    70 CALL PLOTIT(TPLOT,'TIME (SECS)',11,SGPLOT,'STAR PERIMETER (IN)',19
▶      1,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶       GO TO 1004
▶    75 CALL PLOTIT(TPLOT,'TIME (SECS)',11,ABPLOT,'TOTAL BURNING AREA (SQ
▶      1IN)',26,SGPLOT,'STAR PERIMETER (IN)',19,NP,2,'DUMMY',5)
▶       GO TO 1004
▶    80 CALL PLOTIT(TPLOT,'TIME (SECS)',11,FPLOT,'THRUST (LBS)',12,PNPLOT,
▶      1'PONOZ',5,NP,1,'DUMMY',5)
▶       GO TO 1004
▶    90 CALL PLOTIT(TPLOT,'TIME (SECS)',11,FVPLOT,'VACUUM THRUST (LBS)',19
▶      1,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶       GO TO 1004
▶    95 CALL PLOTIT(TPLOT,'TIME (SECS)',11,FPLOT,'THRUST',6,FVPLOT,
▶      1 'VACUUM THRUST',13,NP,3,'THRUST (LBS)',12)
▶       GO TO 1004
▶    97 CALL PLOTIT(TPLOT,'TIME (SECS)',11,VCPLOT,'CHAMBER VOLUME (IN**3)'
▶      1 ,22,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶       GO TO 1004
▶   100 CALL PLOTIT(YBPLOT,'BURNED DISTANCE (IN)',20,ABPLOT,'TOTAL BURNING
▶      1 AREA (SQ IN)',26,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶       GO TO 1004
▶   110 CALL PLOTIT(YBPLOT,'BURNED DISTANCE (IN)',20,SGPLOT,'STAR PERIMETE
▶      1R (IN)',19,PNPLOT,'PONOZ',5,NP,1,'DUMMY',5)
▶       GO TO 1004
▶   115 CALL PLOTIT(YBPLOT,'BURNED DISTANCE (IN)',20,ABPLOT,'TOTAL BURNING
▶      1 AREA (SQ IN)',26,SGPLOT,'STAR PERIMETER (IN)',19,NP,2,'DUMMY',5)
▶ 1004 CONTINUE
        RETURN
        END
```

TABLE IV-2. (Cont'd)

```
      SUBROUTINE IGNITN
C     ******************************************************************
C     *      SUBROUTINE IGNITN CALCULATES THE PRESSURE RISE DURING    *
C     *      THE IGNITION PERIOD                                       *
C     *      ASIG IS THE IGNITER THROAT AREA IN IN**2                  *
C     *      WIGTOT IS THE TOTAL WEIGHT OF THE IGNITER IN LBS          *
C     *      MIGAV IS THE IGNITER AVERAGE MASS FLOW RATE IN SL/SEC     *
C     *      PCIG IS THE IGNITER PRESSURE IN LBS/IN**2                 *
C     ******************************************************************
      COMMON/CONST1/ZW,AE,AT,THETA,ALFAN
      COMMON/CONST2/GAMMA,ME,BOT,ZETAF,TB,HB,GAM
      COMMON/VARIA1/Y,TIG,DELY,DELTAT,PONOZ,PHEAD,RNOZ,RHEAD,SUMAB,PHMAX
      COMMON/VARIA2/ABPORT,ABSLOT,ABNOZ,APHEAD,APNOZ,DADY,ABP2,ABN2,ABS2
      COMMON/VARIA3/ITOT,ITVAC,JROCK,ISP,ISPVAC,MDIS,MNOZ,SG,SUMMT
      COMMON/VARIA5/ABMAIN,ABTO,SUMDY,VCI,VC
      COMMON/IGN1/KA,KB,UFS,RHO,A,XN,L,PMIG,TI1,TI2,CSIG
      COMMON/IGN2/ALPHA,BETA,PBIG,RRIG,DELTIG,X,TOP,ZAP
      COMMON/PLOTT/NUMPLT(16),IPO,NDUM,IPT,IOP
      DIMENSION B(9)
      REAL K(4),L,KA,KB,JROCK,J2,MIG,MIGAV,MSRM,ME,MDIS,MNOZ,MNOZI,MN1
      DATA A1,A2,A3,A4/.17476,-.551481,1.205536,.171185/
      DATA B(1),B(2),B(3),B(4),B(5)/0.,.4,.455737,1.,.296978/
      DATA B(6),B(7),B(8),B(9)/.15876,.2181,-3.050965,3.832864/
C     ******************************************************************
C     *      THE A'S AND B'S ARE CONSTANTS FOR THE RUNGE-KUTTA INTEGRATION *
C     ******************************************************************
      DATA G/32.1725/
      XXX=.05*PONOZ
      IPLUG=0
      PONOZI=PONOZ
      RHEADI=RHEAD
      RNOZI=RNOZ
      PHEADI=PHEAD
      DELTT=DELTAT
      DISM=MDIS
      DELTAT=DELTIG
      SUMABI=SUMAB
      MNOZI=MNOZ
      MNOZ=0.0
      RHEAD=0.0
      RNOZ=0.0
      MDIS=0.0
      ABI=0.0
      TIGI=0.0
      PCI=14.696
      TIG=0.0
      PCNEW=14.696
      SUMAB=0.0
```

TABLE IV-2. (Cont'd)

```
      PCIG=14.696
      PHEAD=14.696
      PONOZ=14.696
      SLOPE=SUMABI/L
      G2=GAMMA*GAMMA
      J2=JROCK*JROCK
      GJ=G2*J2/2.
      MIGAV=.2*AT/G
      ASIG=4.*MIGAV*CSIG/(4.*PMIG-RRIG*(TI2-TI1))
      WIGTOT=G*MIGAV*(5.*(TI2-TI1)/6.)
      WRITE(6,999) ASIG,WIGTOT,MIGAV
  999 FORMAT(///,20X,'IGNITER SIZE CALCULATIONS',/,13X,'ASIG=',F6.2,/,
     1  13X,'WIGTOT=',F7.2,/,13X,'MIGAV=',F8.3,///)
      WRITE(6,10)
   10 FORMAT(33X,'******************************',/,33X,'**** IGNITION TRA
     INSIENT ****',/,33X,'******************************')
   18 NNN=0
      CALL OUTPUT
      WRITE(6,30) PCIG
   30 FORMAT(13X,'PCIG= ',1PE11.4)
    9 CONTINUE
      DO 8 N=1,4
      IF(N.EQ.1) PC=PCI
      IF(N.EQ.2) PC=PCI+B(2)*K(1)
      IF(N.EQ.3) PC=PCI+B(5)*K(1)+B(6)*K(2)
      IF(N.EQ.4) PC=PCI+B(7)*K(1)+B(8)*K(2)+B(9)*K(3)
      TIG=TIGI+B(N)*DELTIG
      SUMAB=ABI+SLOPE*UFS*B(N)*DELTIG
      IF(SUMAB.GT.SUMABI) SUMAB=SUMABI
      PHEAD=PC
      IF(MDIS.NE.0.0) PHEAD=PC*(1.+GJ)
      RHEAD=A*PHEAD**XN
      IF(TIG.LE.TI1) PCIG=PMIG*TIG/TI1
      IF(TIG.GT.TI1.AND.PCIG.GT.PHEAD) PCIG=PMIG-RRIG*(TIG-TI1)
      IF(PCIG.LE.PHEAD) PCIG=PHEAD
      MIG=0.0
      IF(PCIG.GT.PHEAD.AND.TIG.LE.TI2/2.) MIG=PCIG*ASIG/CSIG
      CSTR=KA+KB*PC
      MDIS=PC*AT/CSTR
      IF(PC.LE.PBIG.AND.IPLUG.EQ.0) GO TO 7
      IPLUG=1
      MNOZ=MNOZI
      PNOZ=PC*(1.-GJ)
      ZIT=MDIS*X/APNOZ
      RN1=RHEAD
      AZ=ALPHA*ZIT**.8
      XL=UFS*TIG
      IF(XL.GT.L) XL=L
```

TABLE IV-2. (Cont'd)

```
    4 EX=XL**.2*EXP(BETA*RN1*RHO/ZIT)
      RNOZ=RN1-(RN1-A*PNOZ**XN-AZ/EX)/(1.+AZ*BETA*RHO/(ZIT*EX))
      IF(ABS(RN1-RNOZ).LE.0.002) GO TO 5
      RN1=RNOZ
      GO TO 4
    7 MDIS=0.0
      MNOZ=0.0
      PNOZ=PC
      RNOZ=RHEAD
    5 CONTINUE
      MSRM=RHO*SUMAB*(RNOZ+RHEAD)/2.
      DENOM=(VCI/(12.*CSTR*CSTR*G2))*(1.-(2.*KB*PC)/CSTR)
      DPDT=(MIG+MSRM-MDIS)/DENOM
      IF(DPDT.LT.0.0.AND.PC.LT.20.0) DPDT=0.0
      K(N)=DELTIG*DPDT
    8 CONTINUE
      PCNEW=PCI+A1*K(1)+A2*K(2)+A3*K(3)+A4*K(4)
      PHEAD=PCNEW
      IF(MDIS.GT.0.0) PHEAD=PCNEW*(1.+GJ)
      PONOZ=PCNEW
      XXY=ABS(PONOZ-PONOZI)
      IF(PCNEW.LE.1.001*PCI.AND.SUMAB.EQ.SUMABI.AND.XXY.LE.XXX) GO TO 13
      ABI=SUMAB
      TIGI=TIG
      PCI=PCNEW
      NNN=NNN+1
      IF(NNN.GE.5) GO TO 18
      GO TO 9
   13 CONTINUE
      CALL OUTPUT
      WRITE(6,30) PCIG
      DELTAT=DELTT
      MDIS=DISM
      SUMAB=SUMABI
      PONOZ=PONOZI
      RHEAD=RHEADI
      RNOZ=RNOZI
      PHEAD=PHEADI
      MNOZ=MNOZI
▶     IF(IPO.NE.2.AND.IPO.NE.3) GO TO 53
▶     NDUM=1
▶     CALL OUTPUT
▶     NDUM=0
▶  53 CONTINUE
▶     IPT=0
      RETURN
      END
```

TABLE IV-2. (Cont'd)

```
      SUBROUTINE PLOTIT(X,XHDR,KX,Y,YHDR,NY,T,THDR,NT,NP,NPLOT,DUMMY,ND)
C     *********************************************************************
C     *     SUBROUTINE PLOTIT PLOTS TWO DEPENDENT VARIABLES, Y AND T,      *
C     *          VERSUS AN INDEPENDENT VARIABLE, X                          *
C     *     XHDR, YHDR, AND THDR ARE THE HEADINGS FOR THE X, Y, AND T      *
C     *          AXES, RESPECTIVELY                                         *
C     *     KX, NY, AND NT ARE THE NUMBER OF CHARACTERS IN THE X, Y, AND   *
C     *          T AXES HEADINGS, RESPECTIVELY  (MAX OF 32 IN EACH)         *
C     *     NP IS THE NUMBER OF POINTS TO BE PLOTTED PLUS 2                 *
C     *     VALUES FOR NPLOT ARE                                            *
C     *                     1 FOR Y ONLY PLOTTED VERSUS X                   *
C     *                     2 FOR Y AND T PLOTTED VERSUS X ON SAME AXES     *
C     *                           WITH INDIVIDUAL SCALES                    *
C     *                     3 FOR Y AND T PLOTTED VERSUS X ON SAME AXES     *
C     *                           WITH SAME SCALES                          *
C     *     DUMMY IS THE HEADING FOR THE DOUBLE AXIS (NPLOT=3)              *
C     *     ND IS THE NUMBER OF CHARACTERS IN DUMMY                         *
C     *********************************************************************
      DIMENSION XHDR(8),YHDR(8),THDR(8),DUMMY(8),X(NP),Y(NP),T(NP)
      CALL GSIZE (12.0,11.0,1121)
      NX=-KX
      NM=NP-1
      NN=NP-2
      IF(NPLOT.EQ.1) GO TO 9
      CALL SCALE(T,4.,NM,1)
    9 CALL SCALE(X,8.,NN,1)
      CALL SCALE(Y,4.,NN,1)
      CALL PLOT(6.25,2.,-3)
      IF(NPLOT.NE.3) CALL AXIS(0.,0.,YHDR,NY,4.,180.,Y(NM),Y(NP))
      IF(NPLOT.EQ.3) CALL AXIS(0.,0.,DUMMY,ND,4.,180.,Y(NM),Y(NP))
      CALL AXIS(0.,0.,XHDR,NX,8.,90.,X(NM),X(NP))
      IF(NPLOT.EQ.1) GO TO 12
      DO 11 I=1,NN
   11 T(I)=-T(I)
   12 DO 13 I=1,NN
   13 Y(I)=-Y(I)
      CALL LINE(Y,X,NN,1,1,1)
      CALL PLOT(0.,0.,3)
      IF(NPLOT.EQ.1) GO TO 24
      IF(NPLOT.EQ.2) CALL PLOT(0.,-.5,2)
      IF(NPLOT.EQ.2) CALL AXIS(0.,-.5,THDR,NT,4.,180.,T(NM),T(NP))
      CALL LINE(T,X,NN,1,1,2)
      DO 25 I=1,NN
   25 T(I)=-T(I)
   24 DO 26 I=1,NN
   26 Y(I)=-Y(I)
      IF(NPLOT.EQ.1) GO TO 32
      CALL SYMBOL(-4.35,.52,.1,1,0.,0)
```

TABLE IV-2. (Cont'd)

```
▶       CALL SYMBOL(-4.2,.52,.1,2,0.,0)
▶       CALL SYMBOL(-4.3,.65,.1,YHDR,90.,NY)
▶       CALL SYMBOL(-4.15,.65,.1,THDR,90.,NT)
▶    32 CALL PLOT(8.5,0.,-3)
▶       RETURN
▶       END
```

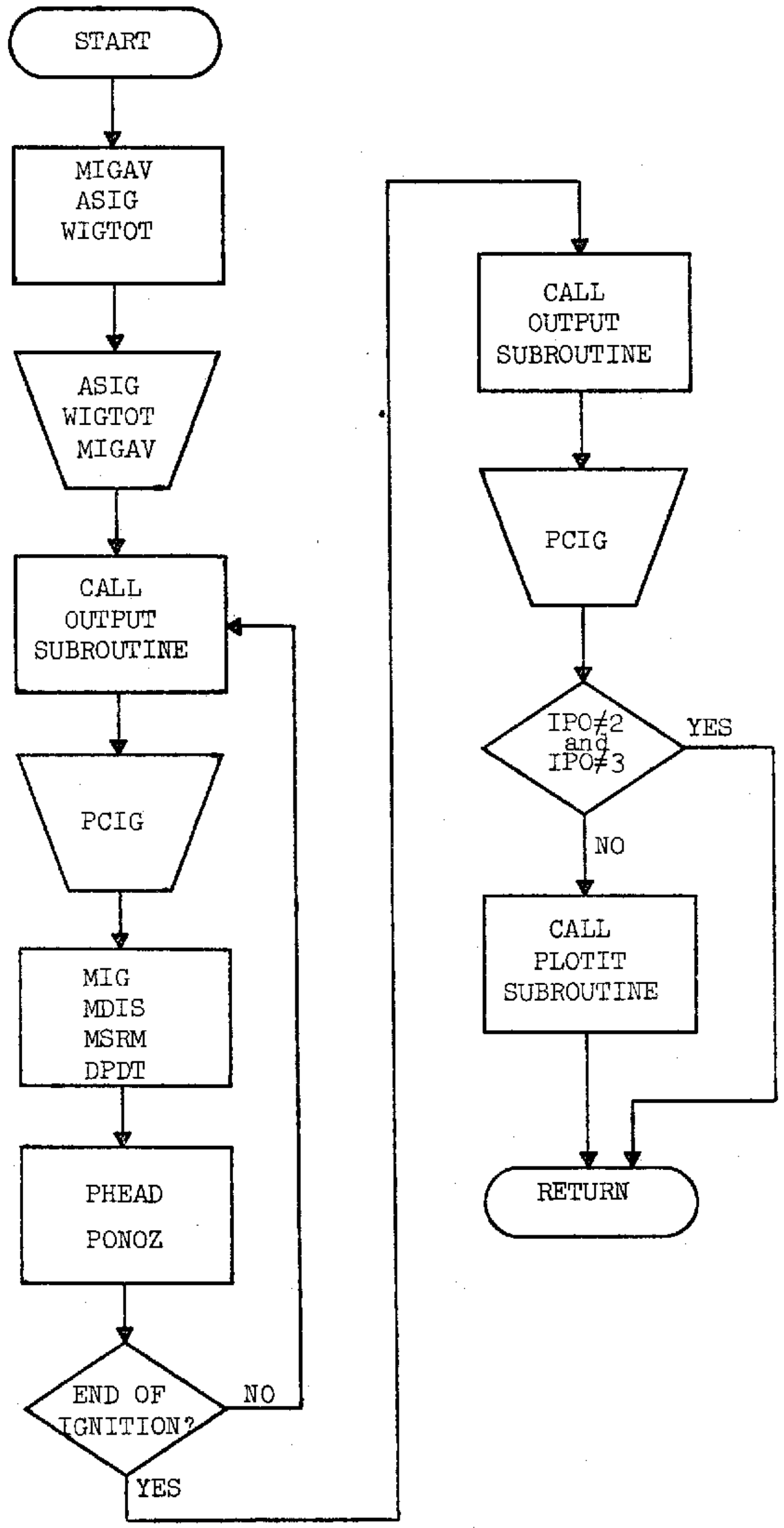

Figure IV-4. Flowchart for ignition subroutine.

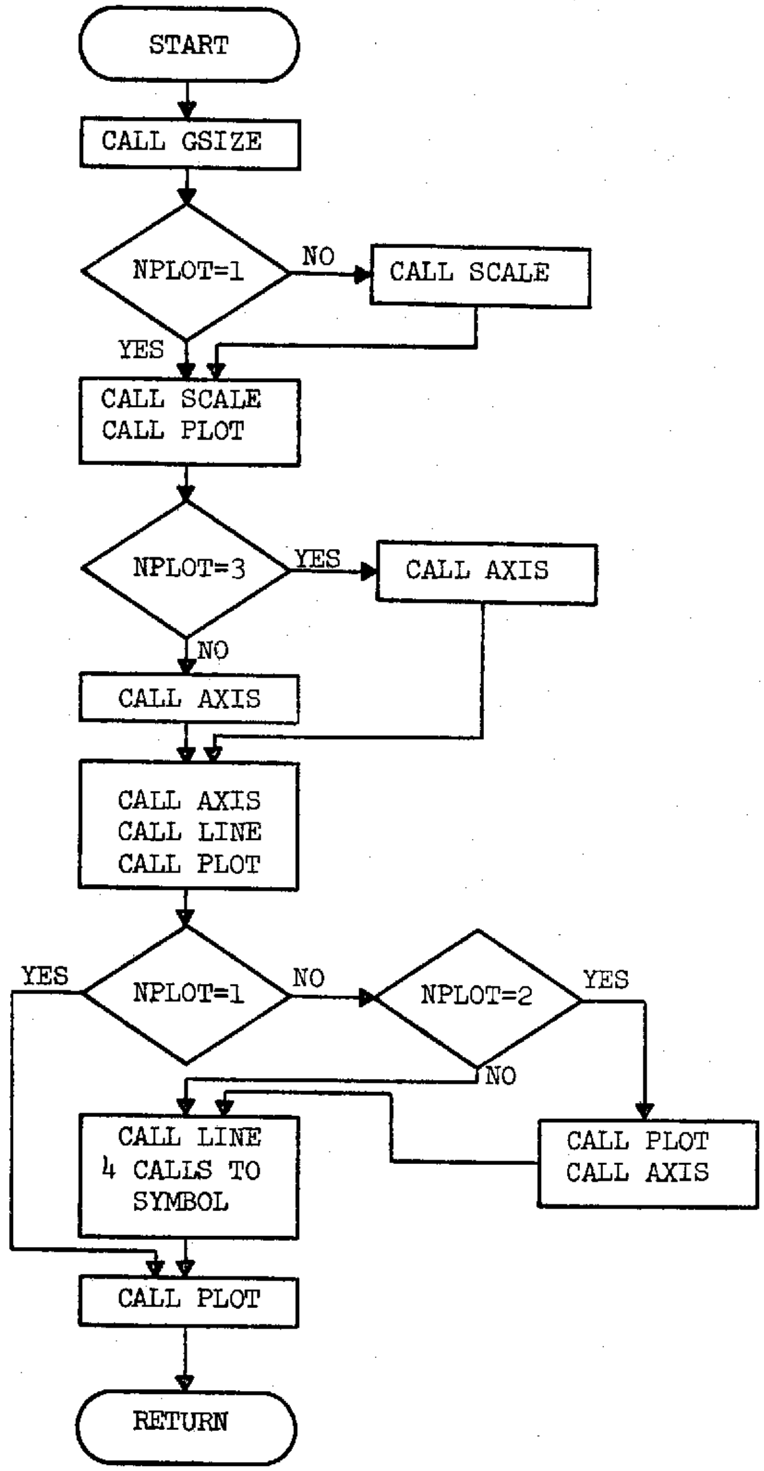

Figure IV-5. Flowchart for plotting subroutine.

V. TEST CASES

In this section two test cases of the extended computer program are presented. Complete input data for one test case and samples of the output data for both cases demonstrating the extended capabilities of the program are presented.

Test Case 1 - Modified SRM 1

The SRM represented in this case is the same as SRM 1 of the original report (Reference 1, Figure V-1) except that the forward segment, a truncated star grain, was replaced by a wagon wheel grain defined in the table of input data (Table V-1, present report). Figure V-1 demonstrates results of the ignition transients calculations for this SRM in the form of the actual plot obtained from the CalComp 663 digital plotter and Table V-2 shows a sample of the associated numerical printout. Plotter output of additional results are given in Figures V-2 and V-3.

Test Case 2 - SRM 2

The SRM represented in this case is identical with SRM 2 of the original report (See Reference 1, Figure V-3 and Table V-4). However, to examine the new program capabilities, the performance of SRM 2 was calculated in two different ways: 1) with the head end of the grain considered conical(COP=0), and 2) with the head end considered hemispherical, the more accurate geometric representation, (COP=3). The aft end in both cases was considered flat because the propellant downstream of the aft slot is not represented by equations but by tabular values. The results for the two cases are shown on Figure V-4 and compared with static test results. It is notable that the two program results are significantly different. The hemispherical end representation gives a somewhat higher pressure level throughout equilibrium burning as would be expected from the nature of the geometric representations. (In retrospect a higher value of THETCH should have been chosen for the conical end approximation)

Although the hemispherical end approximation yields results that are better than the conical end approximation for the first two-thirds of the trace, results for the last third are the opposite. Additional investigation using the computer program indicate that the departures from test results could possibly be the result of a generally high nozzle throat erosion rate (RADER) during the particular test than that used for the program computation.

TABLE V-1. INPUT DATA FOR SRM 1 WITH WAGON-WHEEL IN PLACE OF TRUNCATED STAR GRAIN SEGMENT.

OPTIONS

IGO= 1
IWO= 1
IPO= 1
NUMPLT(JJ)= 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, C, 1, 0, 0, 0

PROPELLANT CHARACTERISTICS

RHO= 0.001990
A= 0.0712
N= 0.250
ALPHA= 0.0
BETA= 0.0
MU= 1.2700E-C7
CSTAR= 5.186CE 03

BASIC MOTOR DIMENSIONS

L= 1243.
TAU= 50.47
DE= 1.4800E 02
DTI= 4.7C00E 01
THETA= 0.0
ALFAN= 3.0340E-01
LTAP= 1.5000E 02
XT= 5.0000E 00
ZO= 0.0

BASIC PERFORMANCE CONSTANTS

DELTAY= 0.250
XOUT= 1CC0.CC
CPCUT= 500.00
ZETAF= C.980
TB= 130.C
HB= 15CC00.
GAM= 1.143
RADER= C.0135

GRAIN CONFIGURATION

INPUT= 3
GRAIN= 3
STAR= 3
NT= C.
ORDER= 1
COP= 0

C.P. GRAIN GEOMETRY

DC= 154.940
DI= 54.000
DELDT= 0.0
S= 7.
THETAG= C.C
LGCI= 1048.50
LGNI= C.C
THETCN= C.75C35
THETCH= 1.57075

BASIC STAR GEOMETRY

NS= 1.
LGSI= 148.00
NP= 10.
RC= 77.470
FILL= 2.500
NN= 0.

WAGON WHEEL GEOMETRY

TAUWW= 13.00
L1= 30.00
L2= 1.00
ALPHA1= 1.57080
ALPHA2= 1.57080
HW= 10.00

IGNITION CONSTANTS

KA= 5145.C
KB= C.01C
UFS= 5CC0.0
CSIG= 490C.C
PMIG= 160C.C
TI1= C.1C0
TI2= 1.50
RRIG= 172C.C
DELTIG= C.CC5
PBIG= 14.696

INERT WEIGHT INPUTS

PIPK= 1.5CC0E-03
DTEMP= 3.CCCCE 01
SIGMAP= 3.0CCCE-C2
SIGMAS= 2.CCCCE-02
N1= 3.CCOCE CC
N2= C.0
SYCNOM= 1.9000E C5
DCC= 1.5550E 02
PSIC= 1.4000E 00
DELC= 2.83CCE-01
LCC= 1.1025E 03
NSEG= 5.COCCE 00
HCN= 6.2CCCE 01
SYNNCM= 1.9C00E C5
PSIS= 1.4CCCE 00
PSIA= 2.0000E 00
K1= 2.C80CE-01
K2= 9.250CE-02
PSIINS= 2.C000E 00
DELINS= 4.6200E-02
KEH= 3.C000E-03
KEN= 1.20CCE-02
DLINER= 3.3000E-02
TAUL= 6.5000E-02
WA= C.0

TABULAR VALUES

VCIT=0

Y	ABPK
0.0	9,000
9.67	9,000
40.0	0
160.0	0

ALL OTHER A's ARE 0.

TABLE V-2. SAMPLE PRINTOUT OF IGNITION COMPUTATIONS FOR MODIFIED SRM 1.

```
      IGNITER SIZE CALCULATIONS
ASIG= 52.95
WIGTOT= 404.82
MIGAV=  10.785


                     ***************************
                     **** IGNITION TRANSIENT ****
                     ***************************


TIME=   0.0              Y=  0.0
RNOZ=  0.0         RHEAD=  0.0          PONOZ=  1.4696E 01  PHEAD=  1.4696E 01
PTAR=  1.3201E 00   MNOZ=  0.0          SUMAB=  0.0            SG=  7.8331E 02
PATM=  1.4696E 01  CFVAC=  0.0           FVAC=  0.0             F=  0.0
PCIG=  1.4696E 01


TIME=   0.025            Y=  0.0
RNOZ=  1.4143E-01  RHEAD=  1.4995E-01   PONOZ=  1.7610E 01  PHEAD=  1.9662E 01
PTAR=  1.3201E 00   MNOZ=  5.2199E-01   SUMAB=  4.3135E 04     SG=  7.8331E 02
PATM=  1.4696E 01  CFVAC=  1.7775E 00    FVAC=  5.2107E 04      F=  0.0
PCIG=  4.0000E 02
```

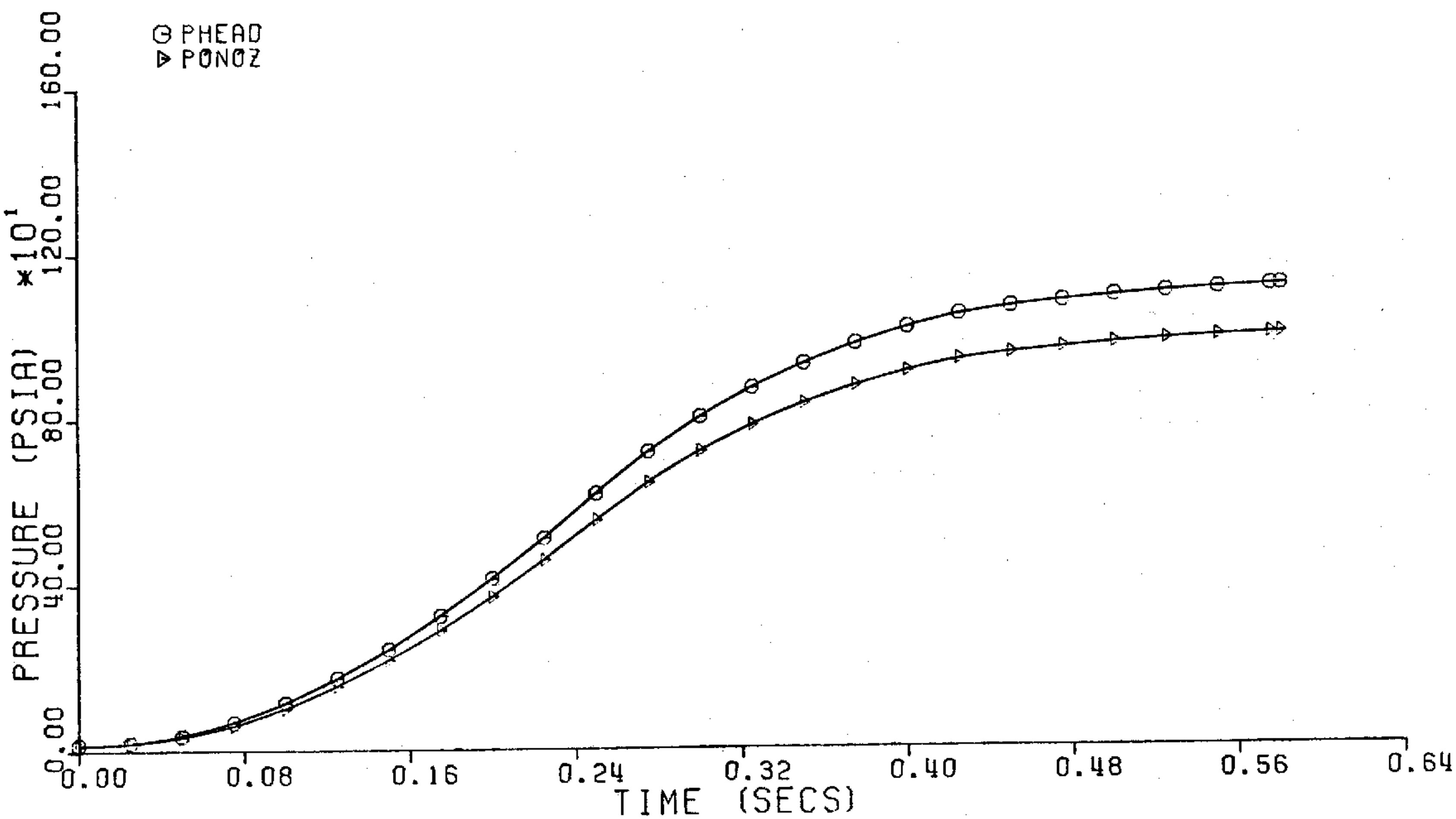

Figure V-1. Ignition transients for SRM 1 with wagon-wheel in place of truncated star grain segment.

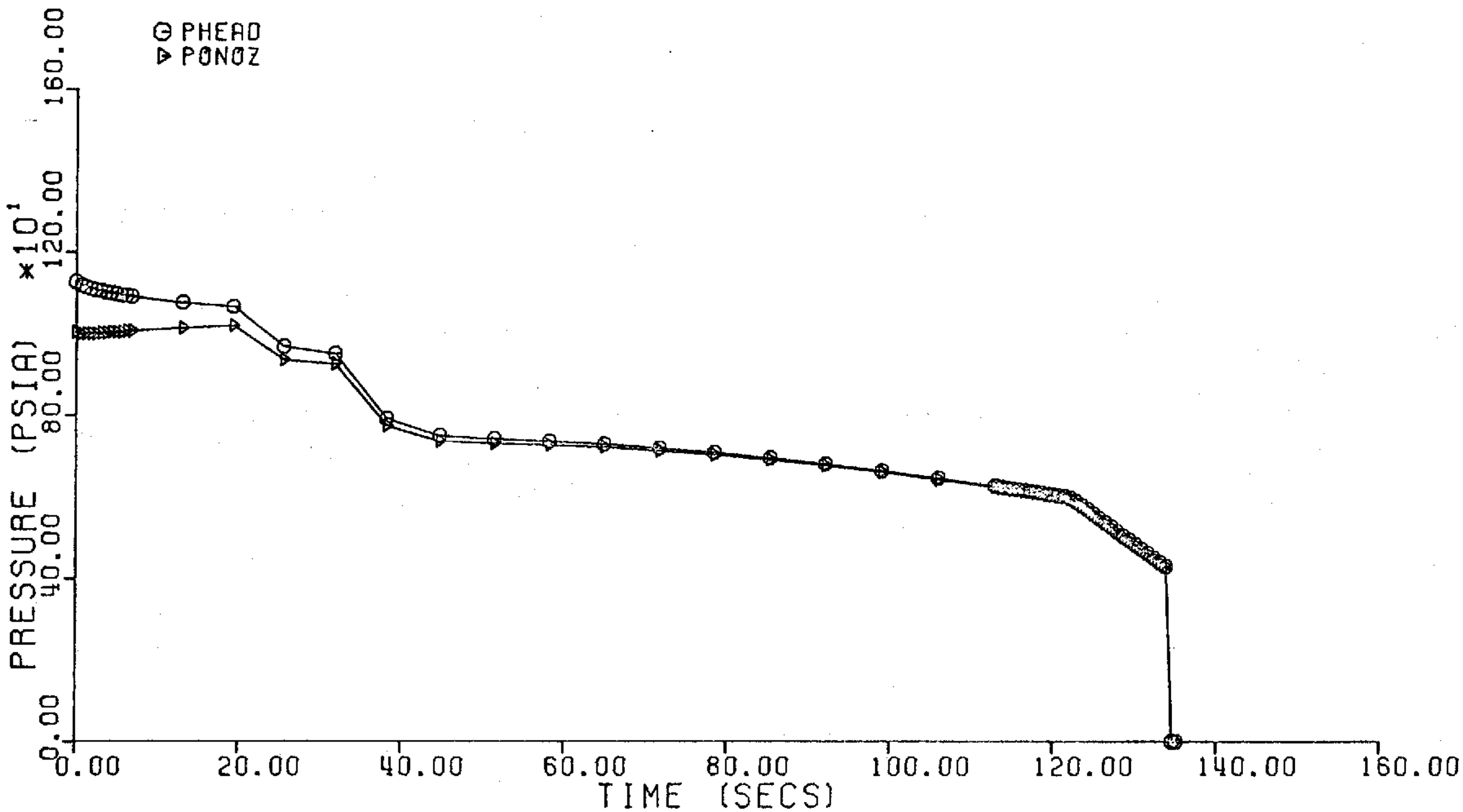

Figure V-2. Equilibrium burning and tail-off for SRM 1 with wagon-wheel in place of truncated star grain segment.

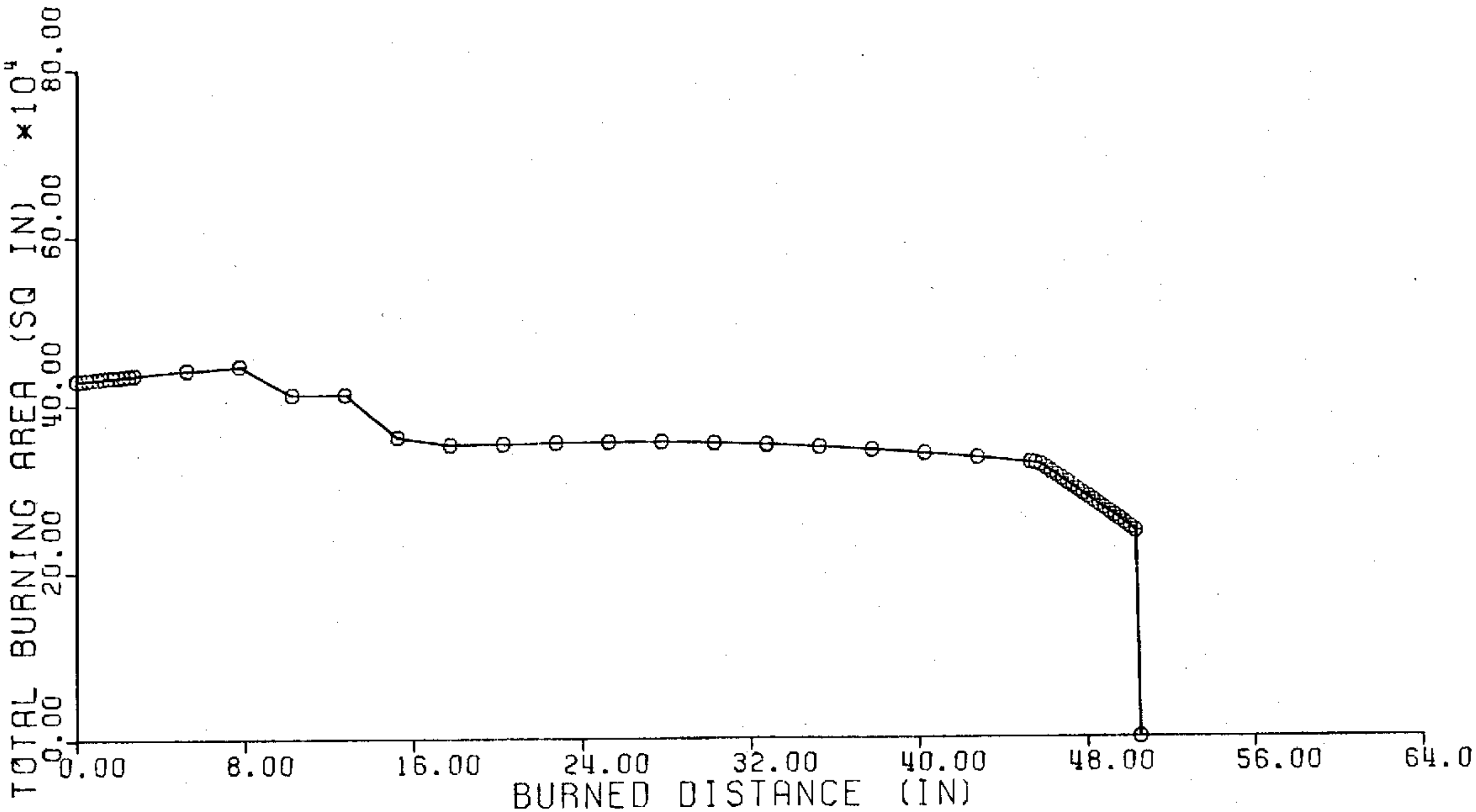

Figure V-3. Burning surface area vs. distance burned for SRM 1 with wagon-wheel in place of truncated star grain segment.

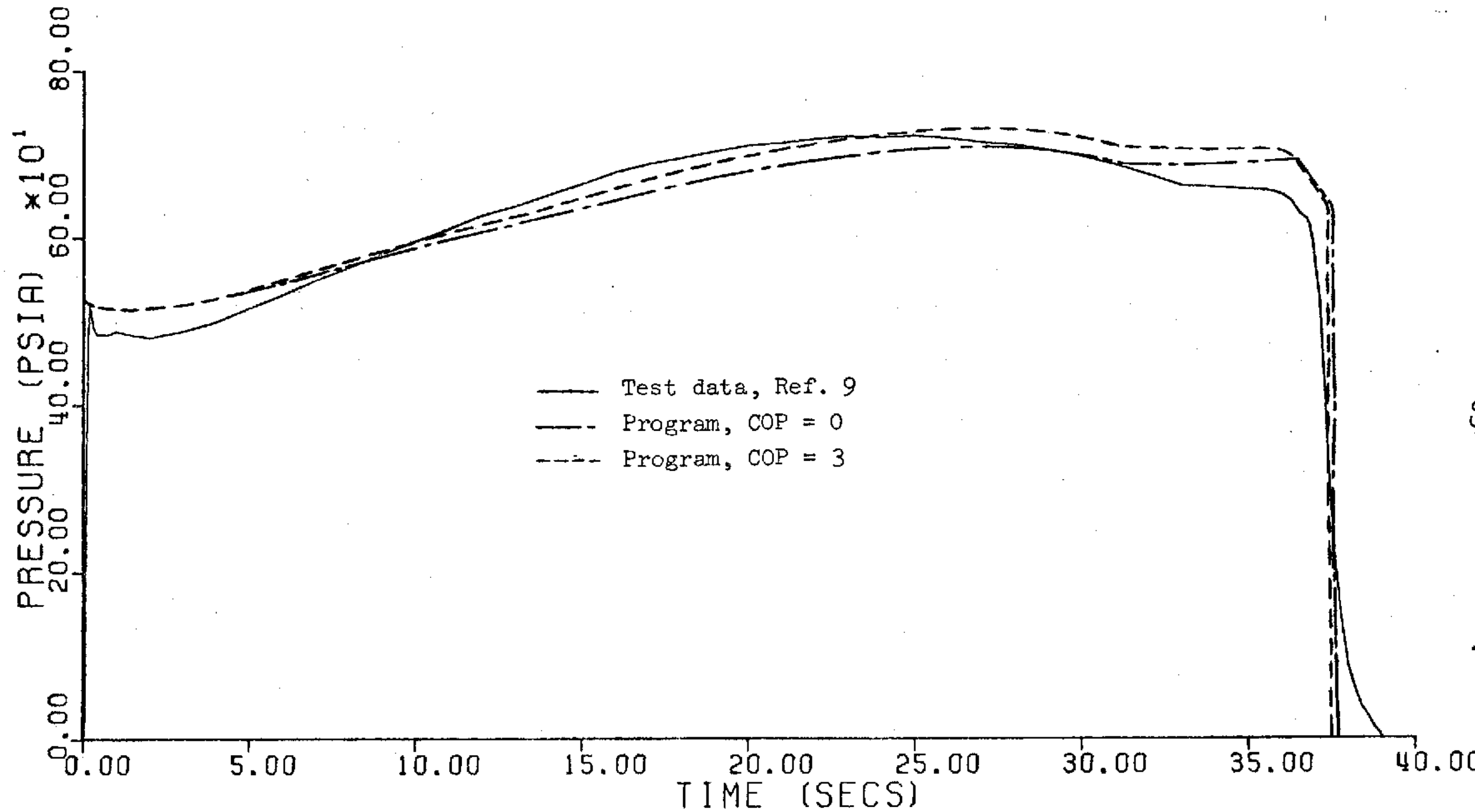

Figure V-4. Comparison of test results for SRM 2 with computer results obtained using various methods of representing head end grain geometry.

VI. CONCLUDING REMARKS

The extended SRM design and analysis program presented in this report considerably improves the capability of the program by permitting calculation of ignition transients and wagon-wheel type grain configurations. The plotting option offers an aid to the designer for rapid interpretation of the results.

A number of changes in the program, notable among which are calculation of initial and final gaseous chamber volume and more accurate geometric representation of the ends of circular-perforated grains should result in somewhat more accurate SRM performance predictions. Additional refinements are of course possible, but, as in the present case, the refinements will add to the complexity of the input preparation and the computer operating time. Before incorporating such changes, the degree of improvement in prediction capability anticipated should be evaluated in light of the basic objective of the present work of providing a simplified program and in light of the approximations inherent in the internal ballistics model used.

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