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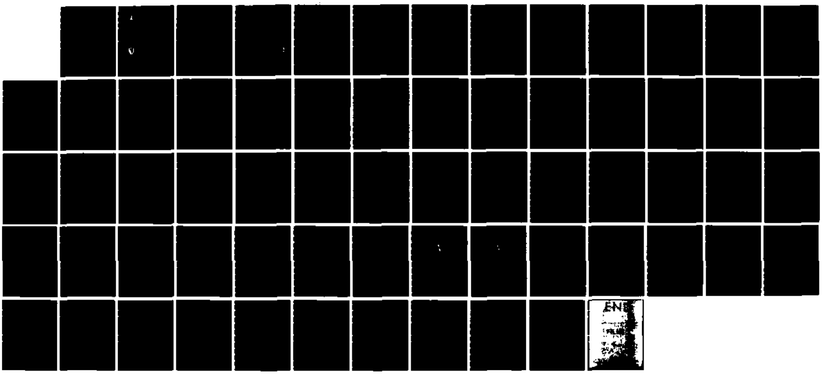

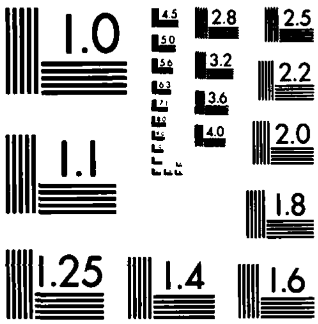

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TECHNICAL REPORT RK-84-4

A MODEL FOR GRAIN MISALIGNMENT IN CYLINDRICAL PORT MOTORS

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APRIL 1984

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35898

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This report presents a mathematical model of the geometry of the propellant grain of a cylindrical port motor cast with a misaligned mandrel. Also presented is an HP-41C calculator program which incorporates this model, and an example demonstrating the application of the misaligned motor geometry.

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CONTENTS

I. INTRODUCTION

The purpose of this report is to present a mathemetical model of the geometry of a cylindrical port motor cast with a misaligned mandrel. This model was developed to determine the burning surface area and free volume of such motors.

This report also includes a detailed description of the geometry model. In formulating this model, two basic types of mandrel misalignment were considered: mandrel displacement and mandrel cocking. In addition to the model description, two appendices are included. Appendix A presents an HP-41C calculator program and Appendix B presents an example of the application of the geometric model.

The details presented in this report are the result of work conducted at the Propulsion Directorate of the US Army Missile Command. The purpose of this work was to obtain a better insight into the geometrical nature of mandrel misalignment.

II. GENERAL

The cylindrical port grain is one of the most versatile and widely used solid rocket motor configurations. This motor geometry is widely employed throughout the industry. One of the more common applications of cylindrical port grains is in subscale ballistic test motors. The characterization of propellant burning rates is one of the primary uses of the subscale test motors. Typically, when a cylindrical port motor is employed in burning rate characterization, the motor is designed with a burning surface area profile that is essentially constant with respect to web distance burned. Thus, when fired, the motor will operate at a relatively constant chamber pressure. The burning rate of the propellant, at the average operating pressure of the motor, is determined by dividing the web thickness of the motor by the burn time. This entire analysis method is based on the assumption that the web thickness of the motor is a known quantity. Therefore, it is essential to this method that the web distance be uniform over the entire length of the grain. As a result of this assumption, a major source of experimental error in the determination of burning rate from ballistic test motor firings is ballistic test motors that do not have a uniform web.

The major cause of variations in the web thickness for cylindrical port motors is mandrel misalignment. Mandrel misalignment essentially means that when the motor was cast the axis of symmetry of the mandrel (and thus of the motor port) did not coincide with the axis of symmetry of the motor case. This condition causes a variation of the web thickness over the length of the grain which means that the burning surface will not contact the motor case wall uniformly. As a result, the burning rate analysis method which is based on the assumption that the entire burning surface contacts the motor case wall at the same instant and is rendered useless.

Since the cylindrical port motor is such a basic propellant development tool, it is essential to obtain a better understanding of the influences of mandrel misalignment on the performance of such motors. The first step in obtaining this understanding is to acquire a knowledge of the geometry of misaligned motors. It should be noted that the effects of mandrel misalignment on the performance of solid rockets were extensively investigated by Maykut [1]. The purpose of these studies was to investigate the effect of various grain asymmetries on the delivered impulse of a rocket motor. In these studies a generalized grain geometry computer code was employed. One feature of this code was the ability to solve for the surface histories of various asymmetric propellant grains [2]. While this code was capable of analyzing the geometry of a misaligned cylindrical port motor, the general nature of the code made it somewhat cumbersome to use. As a result, it was considered advantageous to independently develop a geometry model for the specific class of motors considered in this study.

III. MANDREL MISALIGNMENT

The first step in considering mandrel misalignment in a cylindrical port rocket motor is to consider the general geometry of the motor. In a perfectly aligned motor, the port of the grain and the motor case will have the same axis of symmetry. Figure 1 shows the geometry of such a motor. The problem created by mandrel misalignment is that the motor port and motor case do not have a common axis of symmetry. In order to begin evaluation of the nature of mandrel misalignment, first consider the case where the port and case axes are parallel but do not coincide. A cross-section of the motor taken through a plane perpendicular to the axes of symmetry will reveal circular port and motor case cross-sections. These circles are not, however, concentric. As the propellant port burns out radially the radius of the port will increase. Eventially one point on the port cross-section will contact the case wall. This point defines the region where the misaligned motor differs from the perfectly aligned motor. Until the point of contact the aligned and misaligned motors will exhibit the same burning surface area history.

For the aligned motor, wall contact occurs along the entire periphery and thus indicates the time of motor burnout, while for the misaligned motor, wall contact creates a sliver zone. This sliver zone is the cross-sectional area of propellant remaining at the point of first wall contact. The misaligned motor will continue to operate as the sliver zone burns out. This sliver zone has a surface area that decreases as web distance burned increases. The sliver will result in an extended motor tail-off on the pressure-time trace for the misaligned motor. Figure 2 presents the burning profile for a misaligned cross-section.

The next step is to develop a mathematical model of the misaligned cross-section. Consider the misaligned port for the propellant grain at a given cross-section:

The radius of the propellant grain is given by:

$$R(\tau) = R(0) + \tau \tag{1}$$

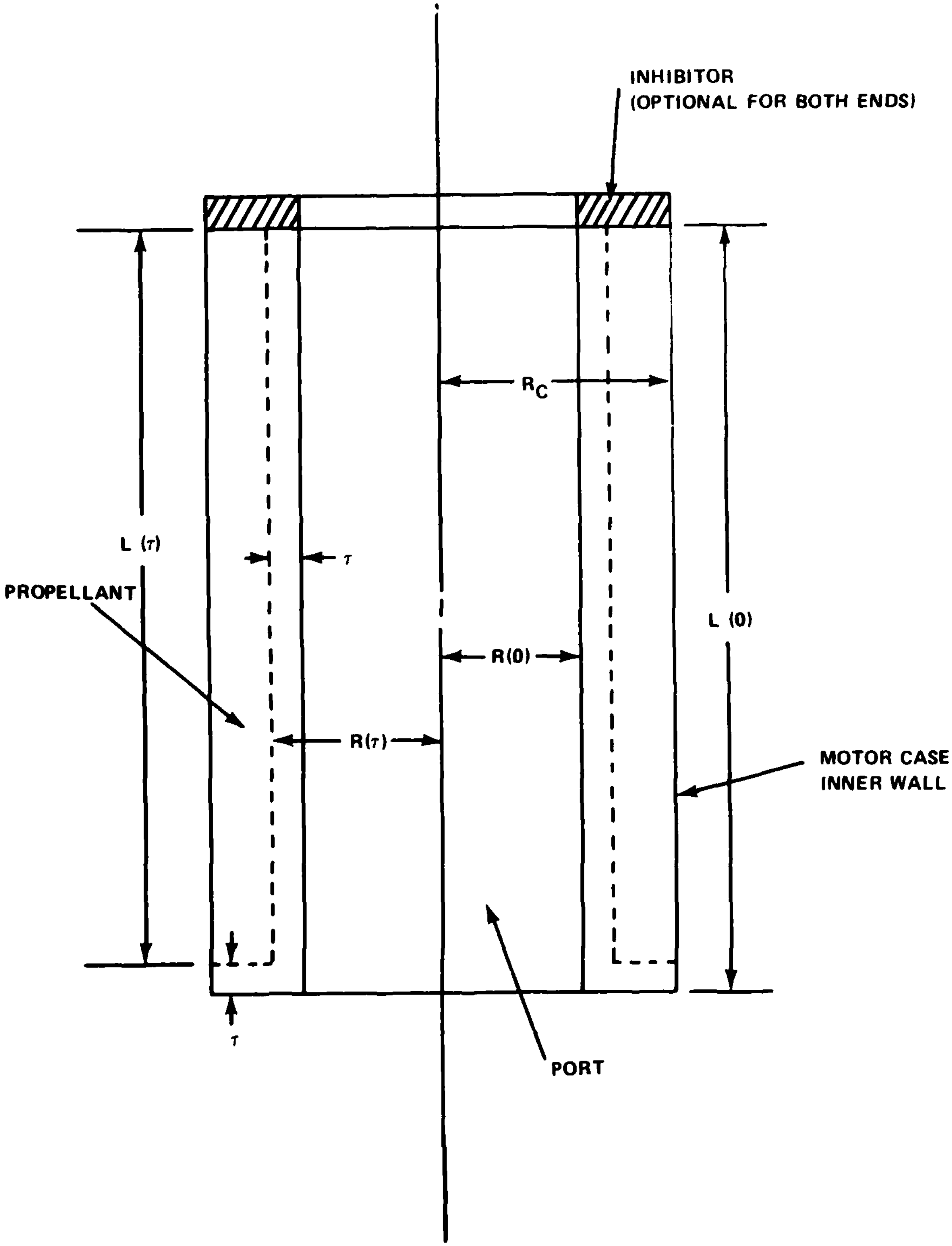

Figure 1. Cross-section of cylindrical port motor (perfectly alined).

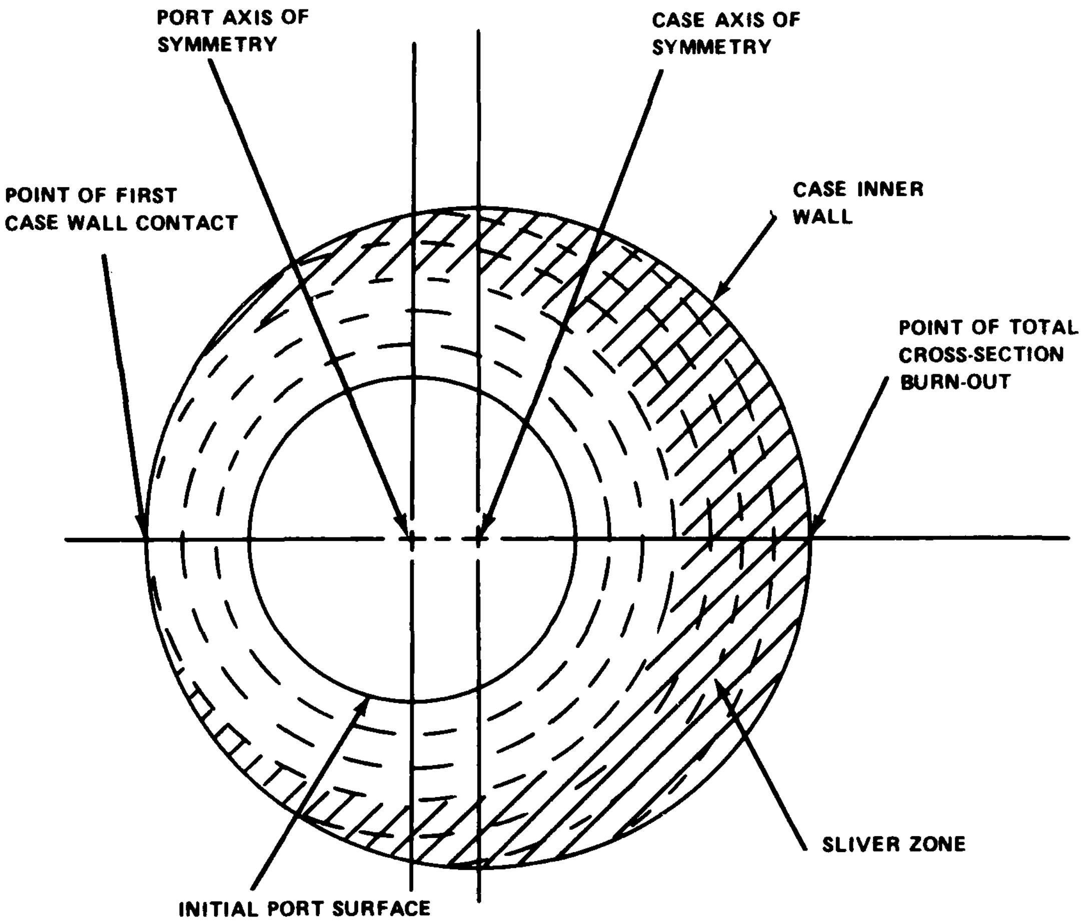

Figure 2. Cross-section burn profile for C-P grain cast with misaligned mandrel.

Where:

$R(\tau)$ is the radius of the grain

$R(0)$ is the initial grain radius

and τ is the web distance burned.

The intersection of the propellant port and the motor case is given by the coordinates:

$$(X_I, \pm Y_I)$$

If

$$R(\tau) < R_C - \Delta X$$

There is no intersection

If

$$R(\tau) \geq R_C - \Delta X$$

$$X_I = \frac{R^2(\tau) - R_C^2 - \Delta X^2}{2\Delta X} \tag{2}$$

$$Y_I = \sqrt{R_C^2 - X_I^2} \tag{3}$$

Where

R_C is the inside radius of the motor case

ΔX is the magnitude of the mandrel offset

X_I is the X-coordinate of the intersection and

Y_I is the Y-coordinate of the intersection.

The perimeter of the burning surface of propellant at a given cross-sectional plane is given by:

$$P(\tau) = \frac{\pi}{180} \theta R(\tau) \tag{4}$$

Where:

If

$$R(\tau) \leq R_C - \Delta X$$

$$\theta_1 = 360° \tag{5}$$

If

$$X_I < -\Delta X$$

$$\theta_1 = 360° - 2 \operatorname{Tan}^{-1} \frac{Y_I}{-\Delta X - X_I} \tag{6}$$

If

$$X_I = -\Delta X$$

$$\theta_1 = 180° \tag{7}$$

If

$X_I > -\Delta X$

$$\theta_1 = 2\ \mathrm{TAN}^{-1}\ \frac{Y_I}{X_I + \Delta X} \tag{8}$$

Where:

$P(\tau)$ is the perimeter of the propellant.

The cross-sectional area of propellant at a given cross-sectional plane is given by:

$$A_{cr}(\tau) = \frac{\pi}{360}\left(R_c^2\ \theta_2 - R^2(\tau)\ \theta_1\right) + 2\ A_1 \tag{9}$$

Where

If

$R(\tau) \leq R_c - \Delta X$

$$\theta_2 = 360° \tag{10}$$

$$A_1 = 0 \tag{11}$$

If

$X_I < 0$

$$\theta_2 = 360° - 2\ \mathrm{TAN}^{-1}\ \frac{Y_I}{-X_I} \tag{12}$$

If

$X_I = 0$

$$\theta_2 = 180° \tag{13}$$

If

$X_I > 0$

$$\theta_2 = 2\ \mathrm{TAN}^{-1}\ \frac{Y_I}{X_I} \tag{14}$$

And

$$A_1 = [S\ (S-\Delta X)\ (S-R(\tau))\ (S-R_c)]^{1/2} \tag{15}$$

Where:

$$S = 1/2\ (\Delta X + R\ (\tau) + R_c) \tag{16}$$

Where:

A_{cr} (τ) is the propellant cross-sectional area

At a cross-sectional plane, the distance for the shortest propellant web is given by:

$$\tau_{sw} = R_c - R(0) - \Delta X \tag{17}$$

The web distance for total propellant burnout at a cross-section is given by:

$$\tau_{pbo} = R_c - R(0) + \Delta X \tag{18}$$

A complete cross-sectional view of the propellant grain is shown in Figure 3.

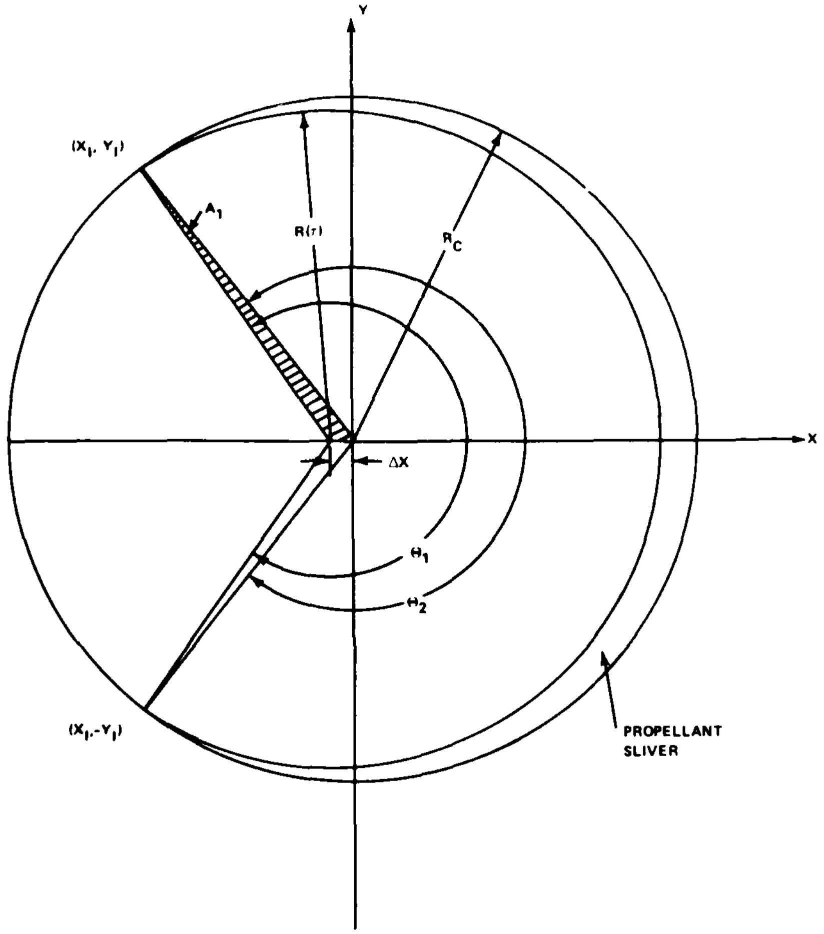

Figure 3. Cross-sectional view of C-P grain cast with an offset mandrel.

IV. MOTOR GEOMETRY

With the cross-sectional geometry of the propellant grain completely detailed, the next step is to consider the geometry of the entire motor. In order to consider the motor geometry a set of coordinate systems must be established. Two coordinate systems will be considered, one for the motor case and one for the mandrel. Descriptions of the coordinate systems are as follows:

For the motor case -

- X - An axis in a plane perpendicular to the axis of symmetry of the motor case
- Y - An axis in the same plan as the X-axis and perpendicular to the X-axis and the axis of symmetry of the motor case
- Z - The axis of symmetry of the motor case.

For the mandrel -

- $\overline{X}$ - An axis in a plane perpendicular to the axis of symmetry of the mandrel
- $\overline{Y}$ - An axis in the same plane as the $\overline{X}$-axis and perpendicular to the $\overline{X}$-axis and the axis of symmetry of the mandrel
- $\overline{Z}$ - The axis of symmetry of the mandrel.

Two possible cases of mandrel misalignment will be considered. The first case is a displaced mandrel and the second is a cocked mandrel. The following are descriptions of the two resulting motor geometries.

A. Displaced Mandrel

In the case of the displaced mandrel, the assumption is made that the sides of the mandrel are parallel to walls of the motor case but the axis of symmetry of the mandrel ($\overline{Z}$-axis) is displaced a distance ΔX from the axis of symmetry of the motor case (Z-axis). Thus, the X and $\overline{X}$ axes are colinear, the Y and $\overline{Y}$, and the Z and $\overline{Z}$ axes, respectively, are parallel. The geometry is presented in Figure 4.

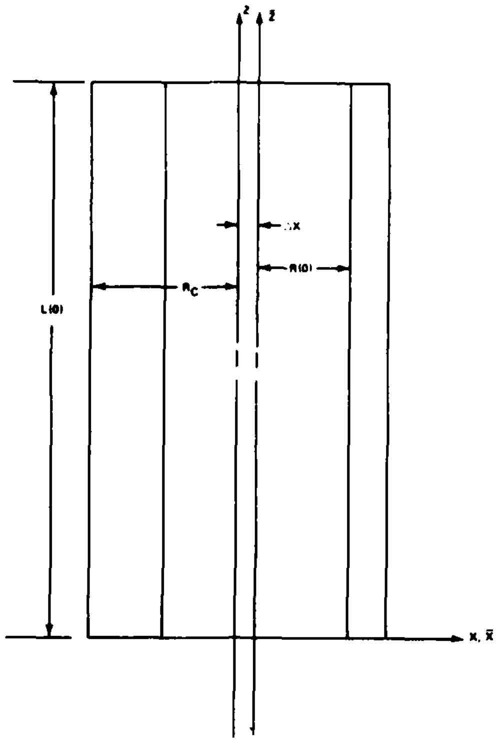

Figure 4. Displaced mandrel configuration.

For the displaced mandrel the propellant cross-section at each Z-coordinate is the same. Therefore, for a given web distance burned the propellant perimeter and cross-sectional area are constant with respect to Z. Thus, the propellant burning surface area is given by:

$$A_b(\tau) = L(\tau)\, P(\tau) + A_{cr}(\tau)\, N_{eb} \tag{19}$$

Where

$R(\tau)$ is given by Equation (1)

and $$L(\tau) = L(0) - 2\tau N_{eb} \tag{20}$$

Where

$A_b(\tau)$ is the burning surface area of the motor

$L(\tau)$ is the length of the grain

$L(0)$ is the initial length of the grain and

N_{eb} is the number of ends that are burning.

The free volume of the motor is given by:

$$V(\tau) = \pi R_c^2 L(0) - L(\tau)\, A_{cr}(\tau) \tag{21}$$

Where

$V(\tau)$ is the free volume of the motor.

B. Cocked Mandrel

In the case of the cocked mandrel two general geometries will be considered. These are a mandrel that is cocked at the top of the motor case and a mandrel that is cocked at both the top and the bottom of the motor case. The following presents the details of the two geometries.

1. Mandrel Cocked With Respect to the Motor Case Top

In the case of the cocked mandrel the assumption is made that the axis of symmetry of the mandrel ($\bar{Z}$-axis) is cocked with respect to the axis of symmetry of the motor case (Z-axis). In the case where the mandrel is cocked with the respect to the top of the motor case, the assumption is made that the coordinate systems of the motor case and the mandrel have the same origin. However, the $\bar{X}$-$\bar{Y}$-$\bar{Z}$ coordinate system is created by rotating the X-Y-Z system about the Y-axis. Therefore, the X-, Z-, $\bar{X}$-, and $\bar{Z}$-axes are coplanar and the Y- and $\bar{Y}$ -axes are identical. The geometry is presented in Figure 5.

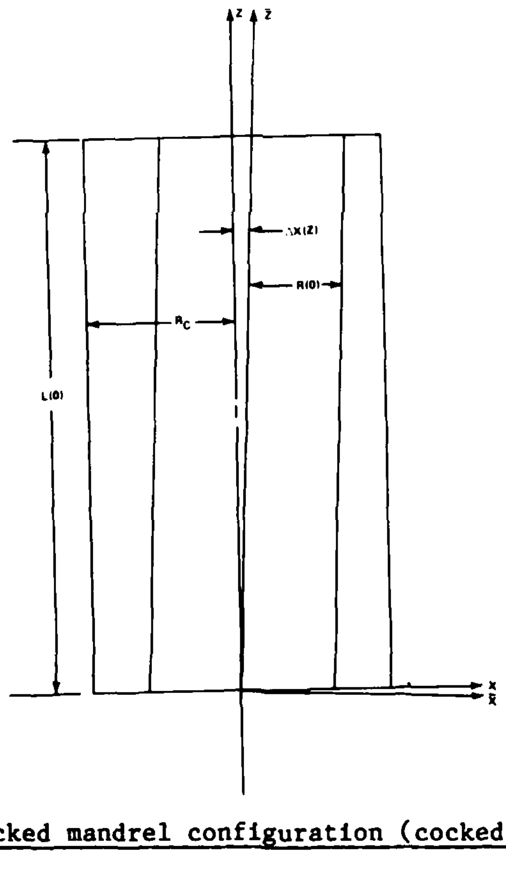

Figure 5. Cocked mandrel configuration (cocked at top).

In order to determine the geometry of a grain created with a cocked mandrel three simplifying assumptions are implied. These are:

a. Axial distances along the propellant grain will be determined along the Z-axis instead of the $\overline{Z}$-axis.

b. The propellant cross-section of the unburned portion in the X-Y plane is circular instead of elliptical.

c. The propellant burns radially, in the X-Y plane instead of the $\overline{X}$-Y plane.

These assumptions are justified by the fact that the angle between the Z and $\overline{Z}$ axes (which is the same angle between the X and $\overline{X}$ axes) will be very small and thus the cosine of the included angle will be very close to unity. In order for distances along the $\overline{Z}$-axis to exceed distances along the Z-axis by more than .1% the included angle must exceed 2.5°. This angle should be well within the region of mandrel misalignment that is normally encountered. Thus, because of the very small included angle the unburned propellant port should be essentially circular in the X-Y plane. Also, this small included angle means that web distances burned along the X-axes are essentially unchanged when projected on the X-axis. And finally, the effects of assumptions a. and c. above tend to cancel each other and thus increase the accuracy.

The geometry of a propellant grain cast with a cocked mandrel can be considered to experience four distinct phases as the motor progresses from the initial state to motor burnout. These four phases are:

PHASE 1. The port of the propellant is totally circular. The short propellant web had not burned out at any axial cross-section.

PHASE 2. The short propellant web has burned out for cross-sections in upper portion of the grain. The remainder of the grain has a circular port.

PHASE 3. The short propellant web had burned out for the entire length of the grain. There are no cross-sections for which total propellant burn out has occurred.

PHASE 4. The cross-section at the bottom of the motor has experienced total propellant burn out.

The next step is to consider the geometry of the motor during each of the following four phases:

PHASE 1

$$0 \leq \tau \leq \tau_1$$

Where

$$\tau_1 = \frac{R_c - R(0) - \Delta X_T}{\left(1 - \dfrac{\Delta X_T\ N_{top}}{L(0)}\right)} \tag{22}$$

$$\Delta X_T = \Delta X\ (Z = L(0)) \tag{23}$$

Where

τ_1 is the web distance burned for short web burn out at the top of the grain.

N_{top} = 0 If the top end is inhibited

= 1 If the top end is uninhibited

and ΔX_T is the initial off-set of the mandrel axis at the top of the grain.

The burning area of the motor is:

$$A_b(\tau) = P(\tau)\ L(\tau) + (N_{bot} + N_{top})\ A_{cr}(\tau) \tag{24}$$

Where

$$L\ (\tau) = L\ (0) - \tau\ (N_{bot} + N_{top}) \tag{25}$$

N_{bot} = 0 If the bottom is inhibited (26)

= 1 If the bottom is uninhibited (27)

and for all phases

$R(\tau)$ is determined from Equation (1)

The free volume of the motor is given by Equation (21).

PHASE 2

$$\tau_1 \leq \tau < \tau_2$$

Where

$$\tau_2 = \frac{R_c - R(0)}{\left(1 + \dfrac{N_{bot}\ \Delta X_T}{L(0)}\right)} \tag{28}$$

Where

τ_2 is the web distance burned for short web burn out at the bottom of the grain

The burning surface area of the motor is given by:

$$A_b(\tau) = P(\tau, Z_{bot})(Z_{ub} - Z_{bot}) + \int_{Z_{ub}}^{Z_{top}} P(\tau, z)dz \qquad (29)$$

$$+ N_{bot} A_{cr}(\tau, Z_{bot}) + N_{top} A_{cr}(\tau, Z_{top})$$

Where

Z_{bot} - is the Z-coordinate of the bottom of the grain

Z_{ub} - is the Z-coordinate at which the cross-section is at the exact point of short web burn out and

Z_{top} - is the Z-coordinate of the top of the grain.

Where

$$Z_{bot}(\tau) = \tau N_{bot} \qquad (30)$$

$$Z_{ub}(\tau) = \frac{L(0)(R_c - R(0) - \tau)}{\Delta X_T} \qquad (31)$$

$$Z_{top}(\tau) = L(0) - \tau N_{top} \qquad (32)$$

and note that for all phases:

$$\Delta X(Z) = \Delta X_T \frac{Z}{L(0)} \qquad (33)$$

The integral term can be approximated by applying the trapezoidal rule over 11 points:

$$\int_{Z_{ub}}^{Z_{top}} P(\tau, z)\, dz = \frac{\Delta Z}{2} \sum_{i=1}^{10} (P(\tau, Z_i) + P(\tau, Z_i - \Delta Z)) \qquad (34)$$

Where:

$$\Delta Z = \frac{Z_{top}(\tau) - Z_{ub}(\tau)}{10} \tag{35}$$

$$Z_i = Z_{ub} + i\,(\Delta Z) \qquad i = 1, 2, \ldots, 10 \tag{36}$$

Thus, the burning surface area is given by:

$$A_b(\tau) = P(\tau, Z_{bot})\,(Z_{ub} - Z_{bot}) + \frac{\Delta Z}{2} \sum_{i=1}^{10} \left(P(\tau, Z_i) + P(\tau, Z_i - \Delta Z)\right)$$

$$+ N_{bot}\,A_{cr}\,(\tau, Z_{bot}) + N_{top}\,A_{cr}\,(\tau, Z_{top}) \tag{37}$$

The free volume of the motor is given by:

$$V(\tau) = \pi R_c^2\,L(0) - A_{cr}\,(\tau, Z_{bot})\,(Z_{ub} - Z_{bot}) - \int_{Z_{ub}}^{Z_{top}} A_{cr}\,(\tau, Z)\,dz \tag{38}$$

This can be approximated by:

$$V(\tau) = \pi R_c^2\,L(0) - A_{cr}\,(\tau, Z_{bot})\,(Z_{ub} - Z_{bot})$$

$$- \frac{\Delta Z}{2} \sum_{i=1}^{10} A_{cr}\,(\tau, Z_i) + A_{cr}\,(\tau, Z_i - \Delta Z)) \tag{39}$$

The grain length is given in Equation (25).

PHASE 3

$$\tau_2 \leq \tau < \tau_3$$

Where

$$\tau_3 = \frac{R_c - R(0)}{\left(1 - \dfrac{\Delta X_T\,N_{top}}{L(0)}\right)} \tag{40}$$

Where

τ_3 is the web distance burned for total propellant burn out at the bottom cross-section.

The burning surface area of the motor is given by:

$$A_b(\tau) = \int_{Z_{bot}}^{Z_{top}} P(\tau,Z)\, dz + N_{bot}\, A_{cr}\left(\tau, Z_{bot}\right) + N_{top}\, A_{cr}\left(\tau, Z_{top}\right) \tag{41}$$

This can be approximated by:

$$A_b(\tau) = \frac{\Delta Z}{2} \sum_{i=1}^{10} \left(P\left(\tau, Z_i\right) + P\left(\tau, Z_i - \Delta Z\right)\right) \tag{42}$$

$$+ N_{bot}\, A_{cr}\left(\tau, Z_{bot}\right) + N_{top}\, A_{cr}\left(\tau, Z_{top}\right)$$

Where

$Z_{bot}(\tau)$ is determined from Equation (30) and

$Z_{top}(\tau)$ is determined from Equation (32)

$$\Delta Z = \frac{Z_{top}(\tau) - Z_{bot}(\tau)}{10} \tag{43}$$

and $Z_i = Z_{bot} + i\,(\Delta Z) \qquad i = 1, 2, \ldots, 10$ (44)

The free volume of the motor is given by:

$$V(\tau) = \pi R_c^2 L(0) - \int_{Z_{bot}}^{Z_{top}} A_{cr}(\tau, Z)\, dz \tag{45}$$

This can be approximated by:

$$V(\tau) = \pi R_c^2\, L(0) - \frac{\Delta Z}{2} \sum_{i=1}^{10} \left(A_{cr}\left(\tau, Z_i\right) + A_{cr}\left(\tau, Z_i - \Delta Z\right)\right) \tag{46}$$

The grain length is given in Equation (25).

PHASE 4

$$\tau_3 \leq \tau < \tau_{mbo}$$

where

$$\tau_{mbo} = \frac{R_c - R(0) + \Delta X_T}{\left(1 + \frac{\Delta X_T \ N_{top}}{L\ (0)}\right)} \quad (47)$$

Where

τ_{mbo} is the web distance burned for total motor propellant burn out.

The relationships for burning surface area and motor free volume are the same as those presented for Phase 3 with the exception that:

$$Z_{bot}\ (\tau) = (\tau - R_c - R(0))\ \frac{L(0)}{\Delta X_T} \quad (48)$$

The length of the propellant grain is given by:

$$L(\tau) = Z_{top}\ (\tau) - Z_{bot}\ (\tau) \quad (49)$$

2. Mandrel cocked with respect to both the motor case bottom and top

A variation of the cocked mandrel geometry can be achieved by considering the case where the mandrel is cocked at both the top and bottom of the motor case. In this case the $\overline{Z}$-axis is created by rotating the Z-axis about an axis which is parallel to the Y-axis and that passes through the centroid of the unburned propellant grain. This geometry is shown in Figure 6.

The geometry of propellant grain can be determined by applying the relationships derived from the situation where mandrel is cocked about the bottom of the motor case.

The burning surface area of the propellant grain is given by:

$$A_b\ (\tau) = 2\ A_b\ (\tau,\ L(0),\ N_{bot}) \quad (50)$$

Where:

$A_b\ (\tau,\ L(0),\ N_{bot})$

is the surface area determined for a propellant grain created by a mandrel cocked at the top only.

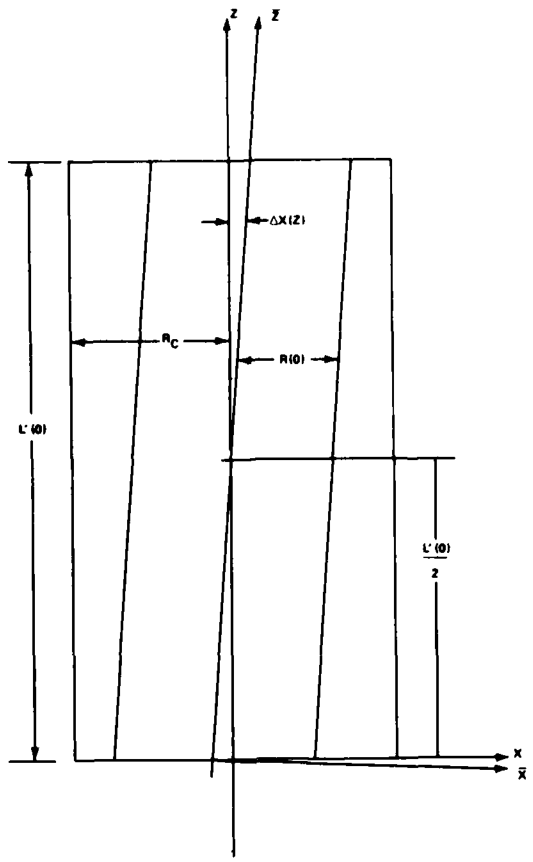

Figure 6. Cocked mandrel configuration (cocked at bottom and top).

The inputs to the burning surface area relationships are:

$$L(0) = \frac{L'(0)}{2} \tag{51}$$

and

$$N_{bot} = 0 \tag{52}$$

Where

L'(0) is the initial length of the propellant grain created by a mandrel cocked at both the bottom and top.

Likewise the free volume of motor is given by:

$$V(\tau) = 2V\ (\tau,\ L(0),\ N_{bot}) \tag{53}$$

Note that these relationships apply only for the cases where either the top and bottom of the grain are both inhibited or both uninhibited.

Thus,

if $N_{top} = 0$ both ends are inhibited (54)

if $N_{top} = 1$ both ends are uninhibited (55)

Also, note that the geometry for grains which were generated by cocking the mandrel about horizontal axes located on various points on the Z-axis can also be determined from the previous relationships. These results can be obtained by adding the results for two appropriate motor geometries which were cocked at the top of the motor case.

V. CONCLUSIONS

The mathematical model presented in this report provides a means to determine the geometrical profile of cylindrical port motors cast with misaligned mandrels. This model should serve as a valuable tool in determining the effect of mandrel misalignment on the pressure-time traces of ballistic test motors. In this application the model could be used to make some determination on the accuracy of burning rate data obtained from motors with various degrees of misalignments. Thus, this model could be used to establish a set of criteria for the accuracy of burning rate data obtained from cylindrical port ballistic test motors.

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APPENDIX A

HP-41C PROGRAM

The mathematical model presented in this report has been incorporated into a program for an HP-41C calculator. This appendix is intended to provide all the information required to install and operate this program. This program, when installed on an HP-41 calculator system, will prove to be a useful analysis tool. The program as presented will provide the user with a convenient and accurate method for evaluating the geometry of misaligned cylindrical port motors. The following provides complete operating instructions, a set of sample problems, and a listing of the program. Also provided is all the required storage register and calculator status information needed to implement the program.

A. Operating Instruction

In order to implement the program presented in this report the following equipment is required:

1 - HP-41CV calculator
or
1 - HP-41C calculator with 1 HP 82170A quad memory module

1 HP 83143A thermal printed/plotter
or
1 - HP 83162A thermal printer/plotter with HP 82160A HP-IL module

To operate the program the printer should be mated with the calculator in the appropriate manner. The calculator should then be configured to size 43 and placed in the user mode. Table A-1 provides a step by step key sequence required to operate this program.

TABLE A-1. Program Instructions

STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1.	Load Program.			
2.	Clear all resisters.		XEQ[CLRG]	
3.	Initialize program.		Σ+	THIS PROGRAM DETERMINES THE GEOMETRY OF CP GRAIN WITH AN OFF CENTER OR COCKED MANDREL
4.	Key in case radius.	R_c	R/S	COCKED? Y=1, N=0
5.	Indicate if the mandrel is cocked.	1 or 0	R/S	
5.a	If mandrel is cocked.	1	R/S	COCKED AT TOP ONLY Y=1, N=0
5.b	If mandrel is not cocked go to Step 6.	0	R/S	LGRAIN = ?
5.b.1	If mandrel is cocked indicate if it is cocked at the top only.	1 or 0	R/S	
5.b.1.a	If mandrel is cocked at top only.	1	R/S	BOTTOM BURNING Y=1, N=0
5.b.1.b	If mandrel is not cocked at the top only, go to Step 5.b.2.	0	R/S	TOP BURNING Y=1, N=0
5.b.2	If mandrel is cocked at top only indicate if the bottom is burning.	N_{bot}	R/S	TOP BURNING Y=1, N=0
5.b.2.a	If mandrel is cocked indicate if the top is burning.	N_{top}	R/S	LGRAIN = ?

Table A-1. Program Instructions - Continued

STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
6.	Key in grain length.	L(0)	R/S	RGRAIN = ?
7.	Key in grain radius.	R(0)	R/S	
7.a	If grain is cocked go to Step 8.			OFF SET = ?
7.b	If grain is not cocked.			NO. END BURN = ?
7.b.1	If grain is not cocked enter number of ends burning.	N_{eb}	R/S	OFF SET = ?
8.	Key in mandrel off set.	ΔX or ΔX_T	R/S	TAU START = ?
9.	Key in starting web distance burned.	τ_{start}	R/S	TAU STOP = ?
10.	Key in stopping web distance burned.	τ_{stop}	R/S	
10.a	If start and stop are equal go to step 11.			
10.b	If start and stop are not equal.			DELTA TAU % = ?
10.b.1	If start and stop are not equal enter the web distance increment then go to step 11.	$\Delta\tau$	R/S	
11.	Write program run information.			
11.a	If mandrel is not cocked.			GEOMETRY FOR CP GRAIN WITH AN OFFSET OF X.XXXXX IN AND X ENDS BURNING SHORT WEB = X.XXXXXX MAX WEB = X.XXXXXX

Table A-1. Program Instructions - Continued

STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
11.b	If mandrel is cocked at the top and bottom.			GEOMETRY FOR COCKED CP GRAIN WITH AN OFF SET OF X.XXXXX IN AND X ENDS BURNING SHORT WEB = X.XXXXXX MAX WEB = X.XXXXXX
11.c	If mandrel is cocked at the top only.			GEOMETRY FOR COCKED AT TOP ONLY CP GRAIN WITH AN OFFSET OF X.XXXXXX IN AND X ENDS BURNING SHORT WEB = X.XXXXXX MAX WEB = X.XXXXXX
12.	Display motor geometries for web distance burned values from τ_{start} to τ_{stop} in increments of $\Delta\tau$. Also display the geometry for the point of short web burn out. In addition program will stop at τ_{mbo} if τ_{stop} exceeds τ_{mbo}.			TAU = X.XXXXXX IN % Web = XX.XXXX% Ab = XXX.XXXX SQ In VOL = XXX.XXXX CU IN TAU = X.XXXXXX IN % Web = XX.XXXX% Ab = XXX.XXXX SQ IN VOL = XXX.XXXX CU IN SHORT WEB BURN OUT
13.	(Optional) Evaluate a single motor geometry.		1/X	TAU = ?
14.	(Optional) Key in web distance burned to be evaluated.		R/S	TAU = X.XXXXXX IN % WEB = XX.XXXX% Ab = XXX.XXXX SQ IN VOL = XXX.XXXX CU IN
15.	(Optional) Evaluate the same motor geometry with a new offset value, Return to step 8.		$\sqrt{X}$	OFF SET = ?
16.	To evaluate a new problem go to step 3.			

When operating the program, note that as long as the program registers are not cleared all input values are maintained until they are specifically replaced. If any portion of the input sequence is initiated, the previous value for any input variable will be retained if R/S is entered after the respective prompt. Thus, for an input value to be changed at a prompt, a numeric entry must be made.

Another item that should be noted when operating the program is the value of $\Delta\tau$. If the mandrel is not cocked the value of $\Delta\tau$ is the input as a percentage of τ_{pbo}. If the mandrel is cocked, $\Delta\tau$ is input as a percentage of τ_{mbo}. In addition, if the mandrel is not cocked, the short web value that is output is τ_{sw} and the maximum web value is τ_{pbo}. If the mandrel is cocked the short web value is τ_1 and the maximum web value is τ_{mbo}.

B. Sample Problems

With the operation of the program completely detailed, the next step is to demonstrate the use of the program on some sample problems. For a sample motor geometry the 2 X 4 ballistic test motor was chosen. The basic dimensions of this motor are as follows:

$$R_c = 1.00 \text{ in.}$$

$$L(0) = 3.75 \text{ in.}$$

$$R(0) = .75 \text{ in.}$$

In the first sample problem, the program exercised was for a grain configuration which was cast with a mandrel cocked at the top only. For this same geometry the "ONE" and "START" options were also demonstrated. The "START" program option allows the user to evaluate the same basic configuration with a different degree of mandrel misalignment. The "ONE" option allows the user to evaluate the present configuration at a single web distance burned. The program was also exercised for two other grain configurations, a grain cast with a mandrel cocked at both the top and bottom and a grain cast with a displaced mandrel. The complete details of these sample problems are as follows:

Mandrel Cocked at Top Only

```
XEQ "OFCNTR"

THIS PROGRAM
DETERMINES THE
GEOMETRY OF
CP GRAIN WITH
AN OFF CENTER
OR COCKED
MANDREL

RCASE=?
      1.000000000    RUN
COCKED?
Y=1, N=0
      1.000000000    RUN
COCKED AT TOP ONLY
Y=1, N=0
      1.000000000    RUN
BOTTOM BURNING?
Y=1, N=0
      1.000000000    RUN
TOP BURNING?
Y=1, N=0
      1.000000000    RUN
LGRAIN=?
      3.750000000    RUN
RGRAIN=?
       .750000000    RUN
OFF SET=?
       .040000000    RUN
TAU START=?
       .200000000    RUN
TAU STOP=?
       .220000000    RUN
DELTA TAU %=?
      2.000000000    RUN

GEOMETRY FOR
COCKED
AT TOP ONLY
CP GRAIN WITH
AN OFFSET OF 0.04000 IN
AND 2. ENDS BURNING
SHORT WEB=0.212264 IN
MAX WEB=0.286939 IN


TAU=0.200000 IN
% WEB=69.7011 %
Ab=20.6088 SQ IN
VOL=10.7548 CU IN

TAU=0.205739 IN
% WEB=71.7011 %
Ab=20.5920 SQ IN
VOL=10.8731 CU IN

TAU=0.211478 IN
% WEB=73.7011 %
Ab=20.5739 SQ IN
VOL=10.9912 CU IN

TAU=0.212264 IN
% WEB=73.9753 %
Ab=20.5713 SQ IN
VOL=11.0074 CU IN

SHORT WEB
BURN OUT


TAU=0.217216 IN
% WEB=75.7011 %
Ab=20.2429 SQ IN
VOL=11.1086 CU IN

TAU=0.220000 IN
% WEB=76.6713 %
Ab=19.9221 SQ IN
VOL=11.1645 CU IN
```

"START" for Mandrel Cocked at Top Only

```
XEQ "START"
OFF SET=?
       .035000000    RUN
TAU START=?
       .230000000    RUN
TAU STOP=?
       .240000000    RUN
DELTA TAU %=?
      5.000000000    RUN

GEOMETRY FOR
COCKED
AT TOP ONLY
CP GRAIN WITH
AN OFFSET OF 0.03500 IN
AND 2. ENDS BURNING
SHORT WEB=0.217026 IN
MAX WEB=0.282365 IN
```

```
TAU=0.230000 IN
% WEB=81.4550 %
Ab=18.7354 SQ IN
VOL=11.3627 CU IN

TAU=0.240000 IN
% WEB=84.9965 %
Ab=15.6999 SQ IN
VOL=11.5358 CU IN
```

"ONE" for Mandrel Cocked at Top Only

```
                XEQ "ONE"
TAU=?
        .260000000    RUN

TAU=0.260000 IN
% WEB=92.0795 %
Ab=4.7974 SQ IN
VOL=11.7406 CU IN
```

Mandrel Cocked at Top and Bottom

```
                XEQ "OFCNTR"

THIS PROGRAM
DETERMINES THE
GEOMETRY OF
CP GRAIN WITH
AN OFF CENTER
OR COCKED
MANDREL

RCASE=?
       1.000000000    RUN
COCKED?
Y=1, N=0
       1.000000000    RUN
COCKED AT TOP ONLY
Y=1, N=0
       0.000000000    RUN
TOP BURNING?
Y=1, N=0
       1.000000000    RUN
LGRAIN=?
       3.750000000    RUN
RGRAIN=?
        .750000000    RUN
OFF SET=?
        .040000000    RUN
TAU START=?
        .200000000    RUN
TAU STOP=?
        .220000000    RUN
DELTA TAU %=?
       2.000000000    RUN

GEOMETRY FOR
COCKED
CP GRAIN WITH
AN OFFSET OF 0.04000 IN
AND 2. ENDS BURNING
SHORT WEB=0.214578 IN
MAX WEB=0.283943 IN

TAU=0.200000 IN
% WEB=70.4368 %
Ab=20.6088 SQ IN
VOL=10.7548 CU IN

TAU=0.205679 IN
% WEB=72.4368 %
Ab=20.5922 SQ IN
VOL=10.8718 CU IN

TAU=0.211358 IN
% WEB=74.4368 %
Ab=20.5743 SQ IN
VOL=10.9887 CU IN

TAU=0.214578 IN
% WEB=75.5708 %
Ab=20.5636 SQ IN
VOL=11.0550 CU IN

SHORT WEB
BURN OUT

TAU=0.217037 IN
% WEB=76.4368 %
Ab=20.4475 SQ IN
VOL=11.1054 CU IN

TAU=0.220000 IN
% WEB=77.4805 %
Ab=20.1830 SQ IN
VOL=11.1656 CU IN
```

Displaced Mandrel

```
THIS PROGRAM
DETERMINES THE
GEOMETRY OF
CP GRAIN WITH
AN OFF CENTER
OR COCKED
MANDREL

RCASE=?
      1.000000000    RUN
COCKED?
Y=1, N=0
      0.000000000    RUN
LGRAIN=?
      3.750000000    RUN
RGRAIN=?
       .750000000    RUN
NO. END BURN=?
      2.000000000    RUN
OFF SET=?
       .040000000    RUN
TAU START=?
       .200000000    RUN
TAU STOP=?
       .220000000    RUN
DELTA TAU %=?
      2.000000000    RUN

GEOMETRY FOR
CP GRAIN WITH
AN OFFSET OF 0.04000 IN
AND 2. ENDS BURNING
SHORT WEB=0.210000 IN
MAX WEB=0.290000 IN


TAU=0.200000 IN
% WEB=68.9655 %
Ab=20.6088 SQ IN
VOL=10.7548 CU IN

TAU=0.205800 IN
% WEB=70.9655 %
Ab=20.5918 SQ IN
VOL=10.8743 CU IN

TAU=0.210000 IN
% WEB=72.4138 %
Ab=20.5787 SQ IN
VOL=10.9608 CU IN

SHORT WEB
BURN OUT


TAU=0.211600 IN
% WEB=72.9655 %
Ab=18.7221 SQ IN
VOL=10.9917 CU IN

TAU=0.217400 IN
% WEB=74.9655 %
Ab=16.5252 SQ IN
VOL=11.0932 CU IN

TAU=0.220000 IN
% WEB=75.8621 %
Ab=15.8357 SQ IN
VOL=11.1353 CU IN
```

C. Installation Information

With the operational aspects of the program presented, the next step is to provide the information required to install the program on an HP-41C calculator system. Presented below is a complete listing of the program. From this listing the program can be directly keyed into the calculator. To facilitate an understanding of the program listing, the storage resister assignments are presented in Table A-2, and to aid in the installation and operation of the program information about the required calculator status is presented in Table A-3.

```
 01◆LBL "OFC
NTR"
 02 FIX 9
 03 CF 22
 04 CF 01
 05 CF 02
 06 CF 03
 07 ADV
 08 "THIS PR
OGRAM"
 09 AVIEW
 10 "DETERMI
NES THE"
 11 AVIEW
 12 "GEOMETR
Y OF"
 13 AVIEW
 14 "CP GRAI
N WITH"
 15 AVIEW
 16 "AN OFF
CENTER"
 17 AVIEW
 18 "OR COCK
ED"
 19 AVIEW
 20 "MANDREL      Input
"
 21 AVIEW
 22 ADV
 23 "RCASE=?
"
 24 PROMPT
 25 FS? 22
 26 STO 09
 27 CF 22
 28 "COCKED?
"
 29 AVIEW
 30 "Y=1, N=
0"
 31 PROMPT
 32 FS? 22
 33 STO 40
 34 CF 22
 35 1
 36 RCL 40
 37 -
 38 X<=0?
 39 SF 02
 40 FC? 02
 41 GTO 76
 42 "COCKED
AT TOP O"
 43 "⊢NLY"
 44 AVIEW
 45 "Y=1, N=
0"
 46 PROMPT
 47 FS? 22
 48 STO 42
 49 CF 22
 50 1
 51 RCL 42
 52 -
 53 X<=0?
 54 SF 03
 55 0
 56 FC? 03
 57 STO 37
 58 FC? 03
 59 GTO 65
 60 "BOTTOM
BURNING?"
 61 AVIEW
 62 "Y=1, N=
0"
 63 PROMPT
 64 FS? 22
```

```
 65 STO 37
 66 CF 22
 67♦LBL 65
 68 "TOP BUR
NING?"
 69 AVIEW
 70 "Y=1, N=
0"                      Input
 71 PROMPT
 72 FS? 22
 73 STO 36
 74 CF 22
 75♦LBL 76
 76 "LGRAIN=
?"
 77 PROMPT
 78 FS? 22
 79 STO 02
 80 FC? 22
 81 GTO 43
 82 FC? 02
 83 GTO 43
 84 2
 85 FC? 03
 86 ST/ 02
 87♦LBL 43
 88 CF 22
 89 "RGRAIN=
?"
 90 PROMPT
 91 FS? 22
 92 STO 01
 93 CF 22
 94 FS? 02
 95 GTO 11
 96 "NO. END
BURN=?"
 97 PROMPT
 98 FS? 22
 99 STO 17
100 CF 22
101 RCL 17
102 INT
103 STO 17
104 2
105 RCL 17
106 -
107 CHS
108 X<=0?
109 GTO 10
110 2
111 STO 17
112♦LBL 10
113 RCL 17
114 CHS
115 X<=0?
116 GTO 11
117 0
118 STO 17              Evaluate the
119♦LBL 11              same motor
120♦LBL "STA            configuration
RT"                     with a new
121 CF 01               mandrel offset
122 "OFF SET
=?"
123 PROMPT
124 FS? 22
125 STO 38
126 CF 22
127 RCL 38
128 STO 08
129 "TAU STA
RT=?"
130 PROMPT
131 FS? 22
132 STO 21
133 CF 22
134 "TAU STO
P=?"                    Input
135 PROMPT
136 FS? 22
137 STO 22
138 CF 22
139 0
140 STO 00
141 XEQ "GEO
"
142 FS? 02
143 XEQ "GEO
2"
144 RCL 22
145 RCL 21
146 -
147 X<=0?
148 GTO 20
149 "DELTA T
AU %=?"
150 PROMPT
151 FS? 22
152 STO 20
153 FC? 22
154 GTO 20
155 RCL 20
156 100
157 /
158 RCL 16
159 *
160 FC? 02              Input
161 GTO 89
162 RCL 16
```

```
163 /
164 RCL 27
165 *
166◆LBL 89
167 STO 20
168◆LBL 20
169 CF 22
170 ADV
171 "GEOMETR
Y FOR"
172 AVIEW
173 FC? 02
174 GTO 79
175 "COCKED"
176 AVIEW
177 FC? 03
178 GTO 79
179 "AT TOP
ONLY"
180 AVIEW
181◆LBL 79
182 "CP GRAI
N WITH"
183 AVIEW
184 FIX 5
185 RCL 08
186 FS? 02
187 RCL 38
188 "AN OFFS
ET OF "
189 ARCL X
190 "⊢ IN"
191 AVIEW
192 FIX 0
193 RCL 17
194 FC? 02
195 GTO 80
196 2
197 RCL 36
198 RCL 37
199 +
200 FC? 03
201 *
202◆LBL 80
203 "AND "
204 ARCL X
205 "⊢ ENDS
BURNING"
206 AVIEW
207 FIX 6
208 RCL 10
209 FS? 02
210 RCL 24
211 "SHORT W
```

Output information on the case being evaluated

```
EB="
212 ARCL X
213 "⊢ IN"
214 AVIEW
215 RCL 16
216 FS? 02
217 RCL 27
218 "MAX WEB
="
219 ARCL X
220 "⊢ IN"
221 AVIEW
222◆LBL 95
223 FIX 9
224 ADV
225 RCL 21
226 STO 00
227 FC? 02
228 RCL 10
229 FS? 02
230 RCL 24
231 -
232 CHS
233 X<=0?
234 SF 01
235◆LBL 30
236 FS? 02
237 XEQ "GEO
2"
238 FS? 02
239 GTO 81
240 XEQ "GEO
"
241◆LBL 81
242 XEQ "OUT
PUT"
243 RCL 22
244 RCL 21
245 -
246 X<=0?
247 STOP
248 RCL 20
249 ST+ 00
250 RCL 22
251 RCL 00
252 -
253 X<=0?
254 GTO 35
255 RCL 16
256 FS? 02
257 RCL 27
258 RCL 00
259 -
260 X<=0?
```

```
261 GTO 31
262 FS? 01
263 GTO 30
264 RCL 10
265 FS? 02
266 RCL 24
267 RCL 00
268 -
269 X<=0?
270 GTO 32
271 GTO 30
272◆LBL 31
273 RCL 16
274 FS? 02
275 RCL 27
276 STO 00
277 FS? 02
278 XEQ "GEO
2"
279 FS? 02
280 GTO 82
281 XEQ "GEO
"
282◆LBL 82
283 XEQ "OUT
PUT"
284 GTO 75
285◆LBL 32
286 RCL 00
287 STO 23
288 SF 01
289 RCL 10
290 FS? 02
291 RCL 24
292 RCL 00
293 -
294 X=0?
295 GTO 47
296 RCL 10
297 FS? 02
298 RCL 24
299 STO 00
300 FS? 02
301 XEQ "GEO
2"
302 FS? 02
303 GTO 83
304 XEQ "GEO
"
305◆LBL 83
306 XEQ "OUT
PUT"
307◆LBL 47
308 RCL 23
309 STO 00
310 ADV
311 "SHORT W
EB"
312 AVIEW
313 "BURN OU
T"
314 AVIEW
315 ADV
316 GTO 30
317◆LBL 35
318 RCL 22
319 STO 00
320 FS? 02
321 XEQ "GEO
2"
322 FS? 02
323 GTO 84
324 XEQ "GEO
"
325◆LBL 84
326 XEQ "OUT
PUT"
327 STOP
328◆LBL "OUT
PUT"
329 1
330 FC? 03
331 2
332 FC? 02
333 1
334 ST* 13
335 ST* 14
336 ADV
337 FIX 6
338 RCL 00
339 "TAU="
340 ARCL X
341 "⊢ IN"
342 AVIEW
343 RCL 00
344 FC? 02
345 RCL 16
346 FS? 02
347 RCL 27
348 /
349 100
350 *
351 FIX 4
352 "% WEB="
353 ARCL X
354 "⊢ %"
355 AVIEW
356 RCL 13
357 "Ab="
358 ARCL X
359 "⊢ SQ IN
```

Output the motor geometry for the given web distance burned

```
"
360 AVIEW
361 RCL 14
362 "VOL="
363 ARCL X
364 "⊢ CU IN
"
365 AVIEW
366 FIX 9
367 RTN
368◆LBL "GEO
"
369 RCL 01
370 RCL 00
371 +
372 STO 03
373 RCL 02
374 RCL 00
375 RCL 17
376 *
377 -
378 FC? 02
379 STO 04
380 RCL 09
381 RCL 08
382 +
383 RCL 01
384 -
385 STO 16
386 RCL 16
387 FS? 02
388 RCL 27
389 RCL 00
390 -
391 CHS
392 X<=0?
393 GTO 01
394◆LBL 75
395 ADV
396 "MOTOR B
URNED"
397 AVIEW
398 "OUT"
399 AVIEW
400 ADV
401 STOP
402◆LBL 01
403 RCL 09
404 RCL 01
405 -
406 RCL 08
407 -
408 STO 10
409 RCL 00
410 -
```

Calculate the geometry for a motor cast with an offset mandrel

```
411 X<0?
412 GTO 00
413 RCL 09
414 X↑2
415 RCL 03
416 X↑2
417 -
418 PI
419 *
420 RCL 17
421 *
422 RCL 03
423 2
424 *
425 PI
426 *
427 RCL 04
428 *
429 +
430 STO 13
431 RCL 09
432 X↑2
433 PI
434 *
435 RCL 02
436 *
437 RCL 09
438 X↑2
439 RCL 03
440 X↑2
441 -
442 PI
443 *
444 RCL 04
445 *
446 -
447 STO 14
448 360
449 STO 06
450 STO 07
451 RCL 03
452 2
453 *
454 PI
455 *
456 STO 05
457 RCL 09
458 X↑2
459 RCL 03
460 X↑2
461 -
462 PI
463 *
464 STO 19
465 RTN
```

```
466◆LBL 00
467 RCL 03
468 X↑2
469 RCL 09
470 X↑2
471 -
472 RCL 08
473 X↑2
474 -
475 2
476 /
477 RCL 08
478 /
479 STO 15
480 X↑2
481 CHS
482 RCL 09
483 X↑2
484 +
485 ABS
486 SQRT
487 STO 18
488 RCL 08
489 RCL 03
490 +
491 RCL 09
492 +
493 2
494 /
495 STO 11
496 RCL 03
497 -
498 RCL 11
499 RCL 08
500 -
501 *
502 RCL 11
503 RCL 09
504 -
505 *
506 RCL 11
507 *
508 SQRT
509 STO 12
510 RCL 15
511 X≠0?
512 GTO 02
513 180
514 STO 07
515 GTO 04
516◆LBL 02
517 X<0?
518 GTO 03
519 RCL 18
520 RCL 15
521 /
522 ATAN
523 2
524 *
525 STO 07
526 GTO 04
527◆LBL 03
528 RCL 18
529 RCL 15
530 /
531 CHS
532 ATAN
533 2
534 *
535 CHS
536 360
537 +
538 STO 07
539◆LBL 04
540 RCL 15
541 RCL 08
542 +
543 X≠0?
544 GTO 05
545 180
546 STO 06
547 GTO 07
548◆LBL 05
549 RCL 15
550 RCL 08
551 +
552 X<0?
553 GTO 06
554 RCL 08
555 RCL 15
556 +
557 1/X
558 RCL 18
559 *
560 ATAN
561 2
562 *
563 STO 06
564 GTO 07
565◆LBL 06
566 RCL 08
567 RCL 15
568 +
569 CHS
570 1/X
571 RCL 18
572 *
573 ATAN
574 2
575 *
```

```
576 CHS
577 360
578 +
579 STO 06
580♦LBL 07
581 PI
582 180
583 /
584 RCL 06
585 *
586 RCL 03
587 *
588 STO 05
589 RCL 09
590 X↑2
591 RCL 07
592 *
593 RCL 03
594 X↑2
595 RCL 06
596 *
597 -
598 PI
599 *
600 360
601 /
602 RCL 12
603 2
604 *
605 +
606 RCL 17
607 *
608 RCL 04
609 RCL 05
610 *
611 +
612 STO 13
613 RCL 09
614 X↑2
615 RCL 07
616 *
617 RCL 03
618 X↑2
619 RCL 06
620 *
621 -
622 PI
623 *
624 360
625 /
626 RCL 12
627 2
628 *
629 +
630 RCL 04
631 *
632 CHS
633 PI
634 RCL 09
635 X↑2
636 *
637 RCL 02
638 *
639 +
640 STO 14
641 RCL 09
642 X↑2
643 RCL 07
644 *
645 RCL 03
646 X↑2
647 RCL 06
648 *
649 -
650 PI
651 *
652 360
653 /
654 RCL 12
655 2
656 *
657 +
658 STO 19
659 RTN
660♦LBL "ONE"
661 CF 01
662 "TAU=?"
663 PROMPT
664 FS? 22
665 STO 21
666 CF 22
667 RCL 21
668 STO 22
669 100
670 STO 20
671 GTO 95
672♦LBL "GEO2"
673 RCL 09
674 RCL 01
675 -
676 RCL 38
677 -
678 1
679 RCL 38
680 RCL 36
681 *
682 RCL 02
683
```

Calculate the motor geometry for a single web distance burned

```
684 -
685 /
686 STO 24
687 RCL 37
688 RCL 38
689 *
690 RCL 02
691 /
692 1
693 +
694 1/X
695 RCL 09
696 RCL 01
697 -
698 *
699 STO 25
700 RCL 37
701 RCL 38
702 *
703 RCL 02
704 /
705 CHS
706 1
707 +
708 1/X
709 RCL 09
710 RCL 01
711 -
712 *
713 STO 26
714 RCL 09
715 RCL 01
716 -
717 RCL 38
718 +
719 RCL 38
720 RCL 36
721 *
722 RCL 02
723 /
724 1
725 +
726 /
727 STO 27
728 RCL 00
729 RCL 24
730 -
731 X>0?
732 GTO 71
733 RCL 01
734 RCL 00
735 +
736 STO 03
737 RCL 02
738 RCL 36
```

Calculate the geometry for a motor cast with a cocked mandrel.

```
739 RCL 37
740 +
741 RCL 00
742 *
743 -
744 STO 04
745 RCL 36
746 RCL 37
747 +
748 PI
749 *
750 RCL 09
751 X↑2
752 RCL 03
753 X↑2
754 -
755 *
756 2
757 PI
758 *
759 RCL 03
760 *
761 RCL 04
762 *
763 +
764 STO 13
765 RCL 09
766 X↑2
767 RCL 03
768 X↑2
769 -
770 PI
771 *
772 RCL 04
773 *
774 CHS
775 RCL 09
776 X↑2
777 PI
778 *
779 RCL 02
780 *
781 +
782 STO 14
783 RTN
784♦LBL 71
785 RCL 00
786 RCL 25
787 -
788 X>0?
789 GTO 72
790 RCL 00
791 RCL 37
792 *
793 STO 28
```

```
794 RCL 09
795 RCL 01
796 -
797 RCL 00
798 -
799 RCL 38
800 /
801 RCL 02
802 *
803 STO 29
804 STO 41
805 RCL 02
806 RCL 00
807 RCL 36
808 *
809 -
810 STO 30
811 RCL 28
812 -
813 STO 04
814 XEQ "ARE
A"
815 RCL 29
816 RCL 28
817 -
818 STO 23
819 RCL 31
820 *
821 ST+ 13
822 RCL 23
823 RCL 34
824 *
825 ST- 14
826 RTN
827♦LBL 72
828 RCL 00
829 RCL 26
830 -
831 X>0?
832 GTO 73
833 RCL 37
834 RCL 00
835 *
836 STO 28
837 STO 41
838 RCL 02
839 RCL 00
840 RCL 36
841 *
842 -
843 STO 30
844 RCL 28
845 -
846 STO 04
847 XEQ "ARE
A"
848 RTN
849♦LBL 73
850 RCL 00
851 RCL 27
852 -
853 X>0?
854 GTO 75
855 RCL 00
856 RCL 09
857 -
858 RCL 01
859 +
860 RCL 02
861 *
862 RCL 38
863 /
864 STO 28
865 STO 41
866 RCL 02
867 RCL 00
868 RCL 36
869 *
870 -
871 STO 30
872 RCL 28
873 -
874 STO 04
875 XEQ "ARE
A"
876 RTN
877♦LBL "ARE
A"
878 RCL 28
879 RCL 02
880 /
881 RCL 38
882 *
883 STO 08
884 XEQ "GEO
"
885 RCL 05
886 STO 31
887 RCL 19
888 STO 34
889 RCL 30
890 RCL 02
891 /
892 RCL 38
893 *
894 STO 08
895 XEQ "GEO
"
896 RCL 05
897 STO 33
```

Integrate to obtain surface area and volume using a trapezoidal rule. Approximation

```
898 RCL 19
899 STO 35
900 RCL 31
901 RCL 33
902 +
903 2
904 /
905 STO 32
906 RCL 34
907 RCL 35
908 +
909 2
910 /
911 STO 39
912 CF 21
913 VIEW 41
914 SF 21
915 RCL 30
916 RCL 41
917 -
918 10
919 /
920 STO 17
921 ST+ 41
922 CF 21
923 VIEW 41
924 SF 21
925♦LBL 99
926 RCL 41
927 RCL 02
928 /
929 RCL 38
930 *
931 STO 08
932 XEQ "GEO
"
933 RCL 05
934 ST+ 32
935 RCL 19
936 ST+ 39
937 RCL 17
938 ST+ 41
939 CF 21
940 VIEW 41
941 SF 21
942 RCL 41
943 1.00001
944 *
945 RCL 30
946 -
947 X<0?
948 GTO 99
949 RCL 17
950 ST* 32
951 ST* 39
952 RCL 34
953 RCL 37
954 *
955 ST+ 32
956 RCL 35
957 RCL 36
958 *
959 ST+ 32
960 RCL 32
961 STO 13
962 RCL 09
963 X↑2
964 PI
965 *
966 RCL 02
967 *
968 RCL 39
969 -
970 STO 14
971 RTN
972 END
```

TABLE A-2. Register Assignments

RESISTER	VARIABLE	UNITS
00	τ	in
01	R(0)	in
02	L(0)	in
03	R	in
04	L	in
05	P	in
06	θ_1	deg
07	θ_2	deg
08	ΔX	in
09	R_c	in
10	τ_{sw}	in
11	S	in
12	A_1	in^2
13	A_b	in^2
14	V	in^3
15	X_I	in
16	τ_{pbo}	in
17	N_{eb}, ΔZ	NA, in
18	Y_I	in
19	A_{cr}	in^2
20	$\Delta\tau$	in
21	τ_{start}	in
22	τ_{stop}	in
23	used	NA
24	τ_1	in
25	τ_2	in
26	τ_3	in
27	τ_{mbo}	in
28	Z_{bot}	in
29	Z_{ub}	in
30	Z_{top}	in
31	$P(Z_{bot})$	in
32	$P(Z_{ub})$, P	in, in
33	$P(Z_{top})$	in
34	A_{cr} (Z_{bot})	in^2
35	A_{cr} (Z_{top})	in
36	N_{top}	NA
37	N_{bot}	NA
38	ΔX_T	In
39	Σ A_{cr}	in^2
40	used	NA
41	Z	in^2
42	used	NA

TABLE A-3. Calculator Status

Calculator mode		USER	
Size		43	
Program registers		276	
Total registers		319	
Key Assignments	Σ+	OFCNTR	
	1/X	ONE	
	X	START	
Flag Status	Flag No.	Set Flag Indicates	Cleared Flag Indicates
	01	Web distance burned has exceeded the short web	Web distance burned has not exceeded the short web
	02	Mandrel is Cocked	Mandrel is not cocked
	03	Mandrel is cocked at top only	Mandrel is cocked top and bottom

APPENDIX B

MISALIGNED 2 X 4 MOTOR

The 2 X 4 ballistic test motor is the basic burning rate characterization motor employed by the Propulsion Directorate. This motor has a cylindrical port and in normal applications has both end surfaces uninhibited.

Initial port radius:
$R(0) = .75$ in

Initial grain length:
$L(0) = 3.75$ in

Case Radius:
$R_C = 1.00$ in

This motor was used as an example to demonstrate the application of the misaligned motor geometry model. For this motor the burning surface area histories were generated for geometries reflecting a perfectly aligned mandrel, a displaced mandrel, a mandrel cocked at the top, and a mandrel cocked at both the top and bottom. For the three modes of mandrel misalignment, surface area histories were generated for ΔX_T values of 0.00 in., 0.01 in., 0.02 in., 0.03 in., 0.04 in., 0.05 in., 0.06 in., 0.07 in., 0.08 in., 0.09 in., and 0.10 in. All these surface area histories were generated using the HP-41C calculator and the previously detailed program. The burning surface area history for an aligned 2 X 4 motor grain is presented in Figure B-1. The burning surface area histories for a 2 X 4 motor cast with a displaced mandrel is presented in Figure B-2. The burning surface area histories for a 2 X 4 motor cast with a mandrel cocked at the top is presented in Figure B-3. The burning surface area histories for a 2 X 4 motor cast with a mandrel cocked at both the top and bottom is presented in Figure B-4.

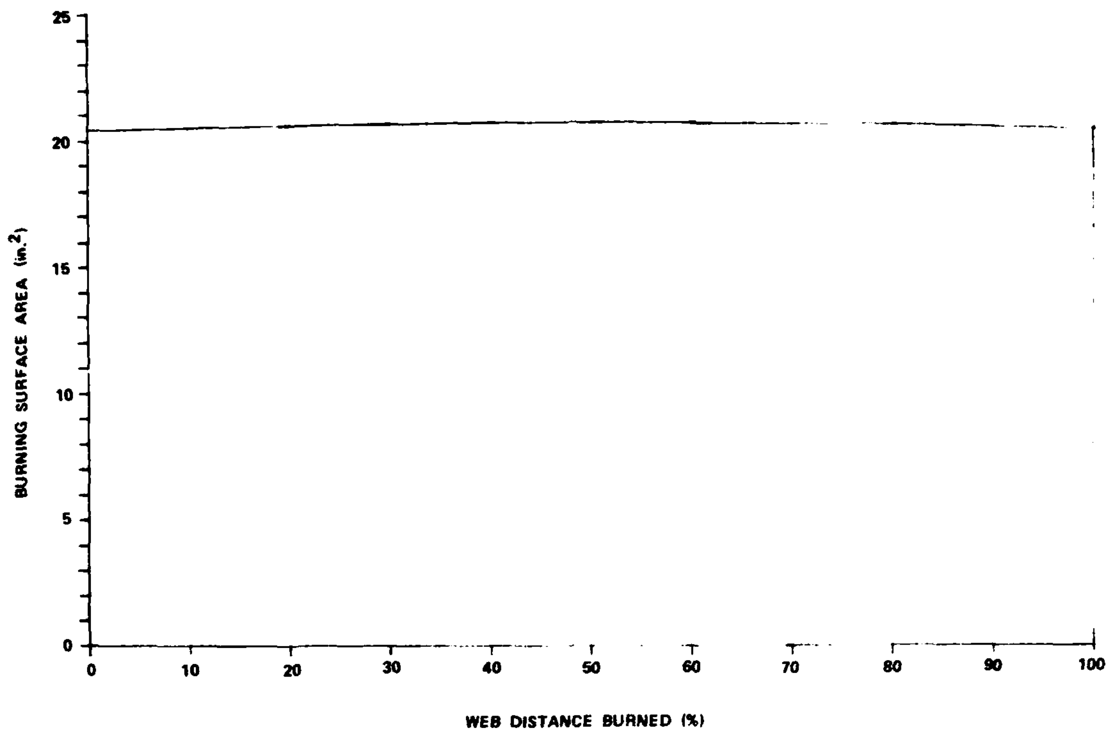

Figure B-1. Burning surface area history of 2 X 4 motor cast with no mandrel misalignment.

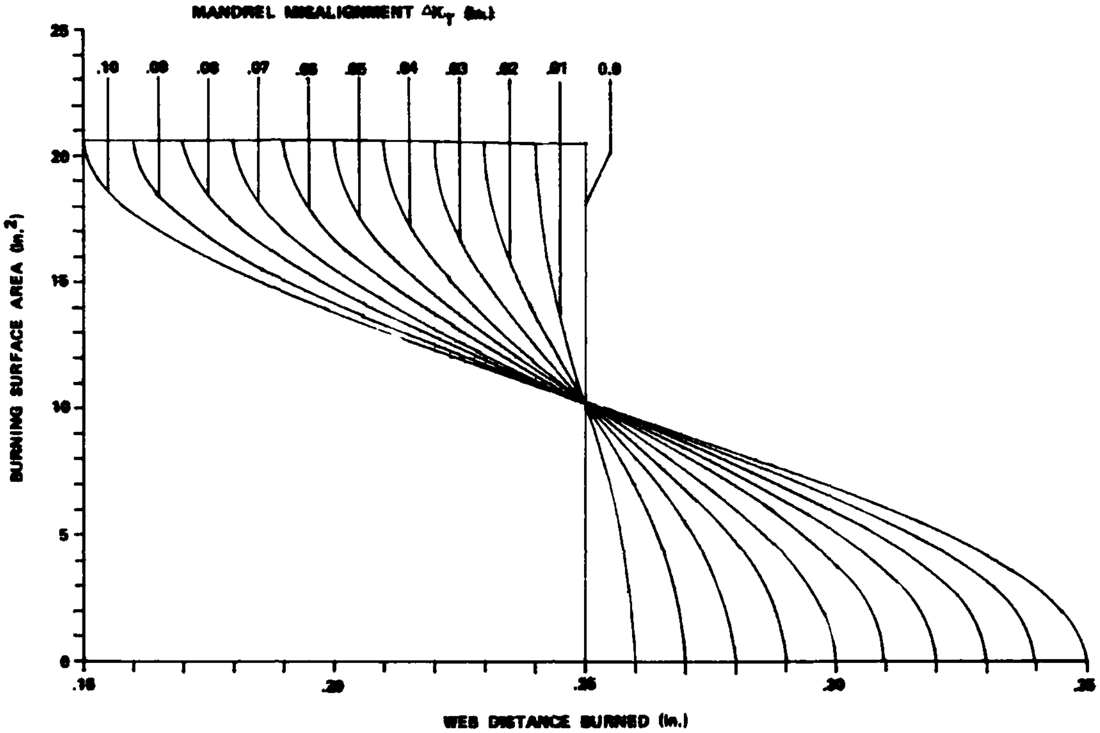

Figure B-2. Burning surface area history of 2 X 4 motor cast with a displaced mandrel.

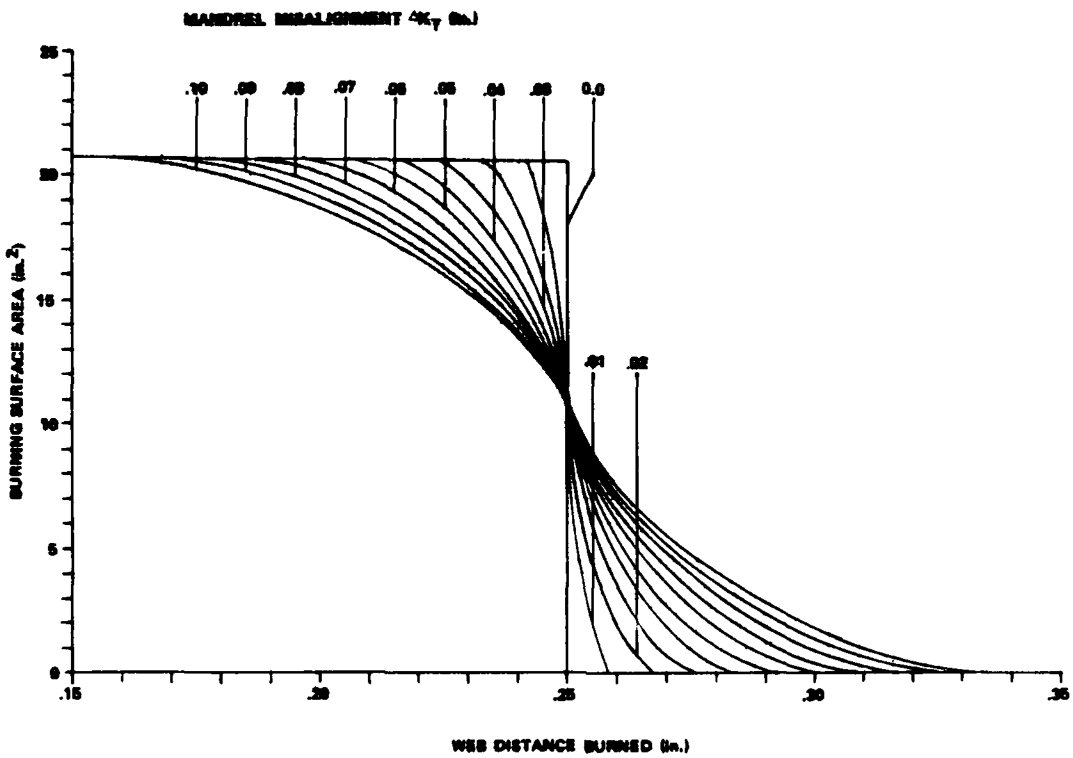

Figure B-3. Burning surface area history of 2 X 4 motor cast with a mandrel cocked at the top.

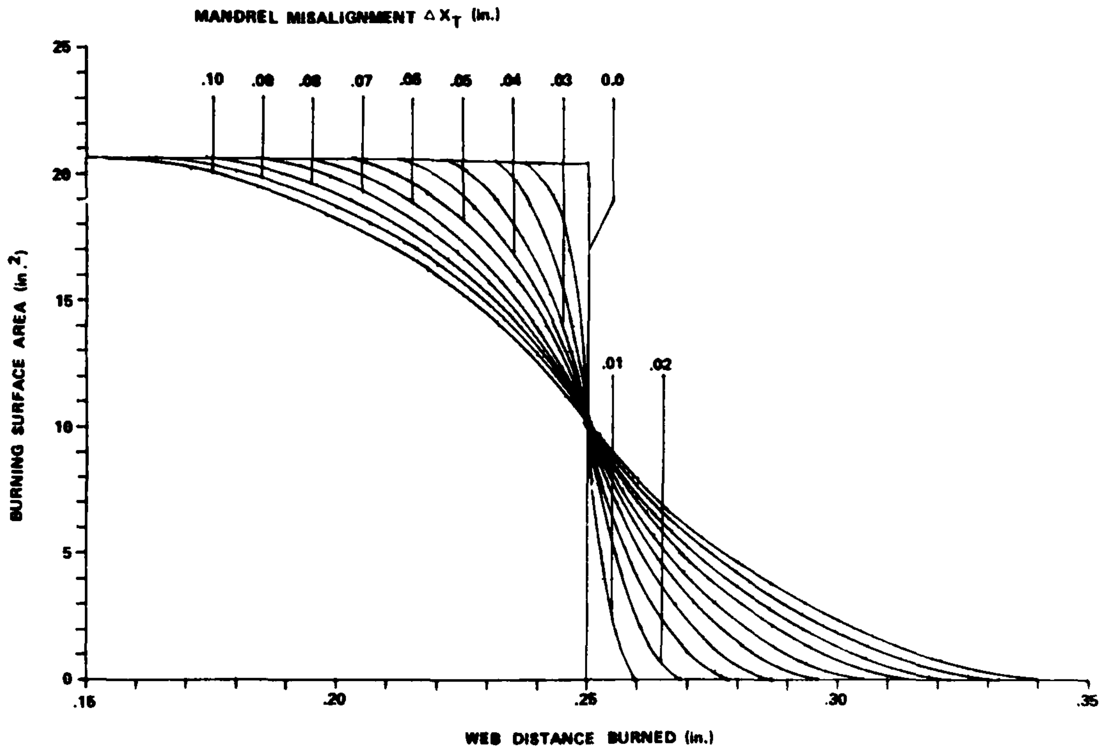

Figure B-4. Burning surface area history of 2 X 4 motor cast with a mandrel cocked at the top and bottom.

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