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MEMORANDUM REPORT ARBRL-MR-03014

DEVELOPMENT OF GENERAL FORM-FUNCTIONS
FOR MULTIPERFORATED CYLINDRICAL
PROPELLANT GRAINS

Fraz R. Lynn

April 1980

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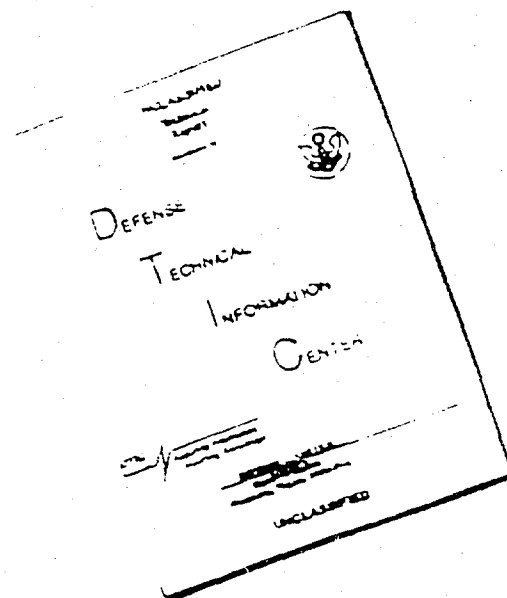


US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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LIST OF SYMBOLS

D	Initial grain diameter
E	End-area of grain sliver
GL	Initial grain length
GRL	Instantaneous grain length
PD	Initial perforation diameter
PRFD	Instantaneous perforation diameter
RAD	Instantaneous grain radius
SURF	Total surface area of grain sliver
VOL	Volume of grain sliver
WI	Inner web of 19-perforated grain
WM	Middle web of 19-perforated grain
WO	Outer web of 19-perforated grain

I. INTRODUCTION

Interior ballistic calculations usually require a knowledge of the geometry of propellant grains at each phase of burning from ignition to burnout. Any calculational scheme for providing the surface area or volume of a grain at any instant is often referred to as a "form-function". Investigators have determined form functions for a wide variety of grain shapes^{1,2}. This report concerns itself with providing a general method of constructing form-functions for one of the most popular classes of grains, namely, the multiperforated cylinder. The shape is that of a right circular cylinder pierced its entire length by some number of uniform cylindrical perforations.

Many approaches to analyzing particular members of this class, for example, the seven- or nineteen-perforated grains, have been taken in the past. Instead of examining many such special cases here, a general method is presented that leads to the construction of form-functions which can determine surface area and volume for virtually any cylindrical grain with any number ($n > 2$) of arbitrarily placed perforations; the special excluded cases are discussed as well. The method neither employs approximations in calculation nor does it assume equal rates of regression for the inner and outer grain surfaces. Thus this approach supercedes several previous efforts and, moreover, provides the opportunity to analyze many novel cylindrical grain designs in a straightforward manner. Non-cylindrical grains as, for instance, hexagonal-surfaced ones, are barred, although similar methods could clearly be employed.

Finally, two FORTRAN subroutines which perform the required computations are provided and are used in connection with a sample exercise wherein a form-function for a nineteen-perforated grain with three independent webs is developed.

In what follows, all angle measurements are in radians.

II. OUTLINE OF THE METHOD

A. SUBDIVISION OF THE GRAIN END AREA

The circular cross-section of the grain in question is first geometrically decomposed by straight lines into classes of mutually congruent "slivers", defined below. At any point in burning, the

1. Corner, J., *"Theory of the Interior Ballistics of Guns"*, John Wiley & Sons, New York, 1950, pp. 30-35.
2. Stals, J., *"Form-Functions for Multicomponent Propellant Charges Including Inhibited Grains and Sliver Burn"*, MRL Technical Note 371, Materials Research Laboratories, Maribyrnong, Victoria, Australia, September 1975.

individual contribution of each class to the remaining surface and volume is noted, the totals simply being the sums, over all classes, of the number of members in each class multiplied by that class's contributions.

There are two types of "slivers", hereafter referred to without quotes: inner and outer. An inner sliver is any region of cross-section bounded by a triangle with the center of a perforation at each vertex, but with no portion of any other perforation contained within the boundaries. An outer sliver is any region of cross-section bounded by an arc of the grain's outer surface, two radii enclosing an angle less than π , and a chord segment joining the centers of two perforations. No portion of

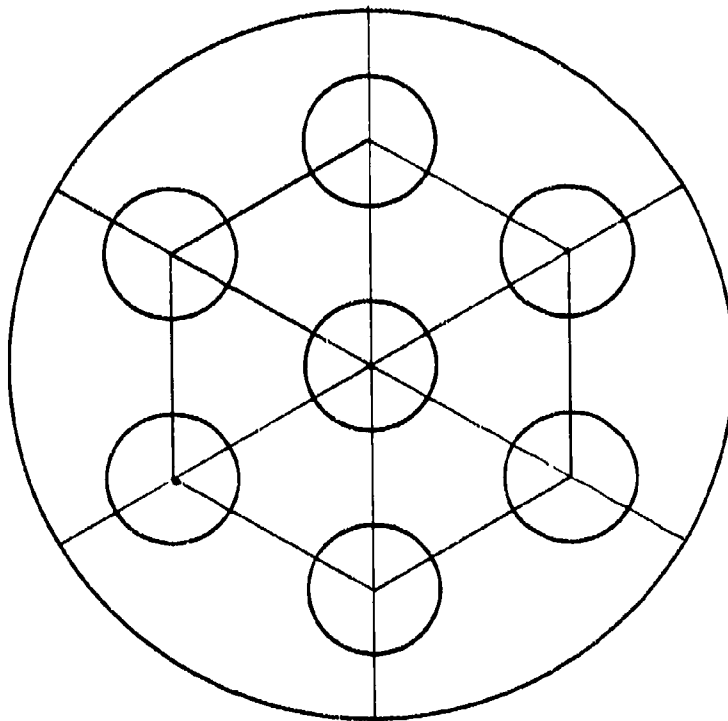


Figure 1. A Sample Grain Partitioned

any other perforation may be contained within its boundaries.

For example, the grain in Figure 1 has been divided into two classes of slivers, one class of six inner slivers and one class of six outer slivers.

A complete analysis of the general outer sliver and the general inner sliver follows.

B. OUTER SLIVERS

In addition to the above-mentioned assumptions about the grain and its dissection into slivers, we require that, throughout burning, the outer slivers remain within their original boundaries until extinction. Initially, an outer sliver appears as PQA_2A_3 in Figure 2 with A_1 the center of the grain and A_2 and A_3 the centers of the sliver's perforations. In what follows, we adhere to the convention that side S_1 of triangle $A_1A_2A_3$ is the segment connecting the centers of the sliver's perforations. Further, the restriction that angle $PA_1Q < \pi$ forces the grain to have at least three perforations with not altogether arbitrary placement. We assume lengths S_1, S_2 , and S_3 to be known.

From the law of cosines we have the following angles

$$A_3A_1A_2 = \arccos \left(\frac{S_2^2 + S_3^2 - S_1^2}{2 \cdot S_2 \cdot S_3} \right)$$

$$A_3A_2A_1 = \arccos \left(\frac{S_1^2 + S_3^2 - S_2^2}{2 \cdot S_1 \cdot S_3} \right)$$

$$A_2A_3A_1 = \arccos \left(\frac{S_1^2 + S_2^2 - S_3^2}{2 \cdot S_1 \cdot S_2} \right)$$

Then, the area of triangle $A_1A_2A_3$ is

$$1/2 S_1 \cdot S_3 \cdot \sin(A_3A_2A_1)$$

As burning progresses, the sliver erodes as shown in Figure 3 with, possibly, some degenerate angles. We require knowledge of the grain's instantaneous radius, RAD, grain length, GRL, and perforation diameter, PRFD. The surfaces of all perforations are assumed to erode at the same rate, but this need not be the same rate of regression as that of at the outer surface. Clearly, burnout of the sliver occurs when either

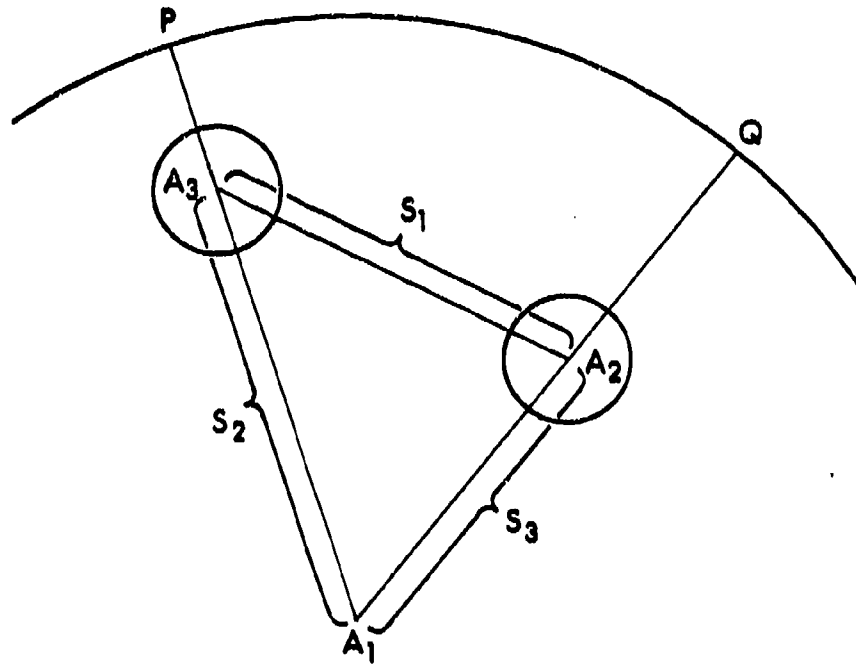


Figure 2. General Outer Sliver Before Burning

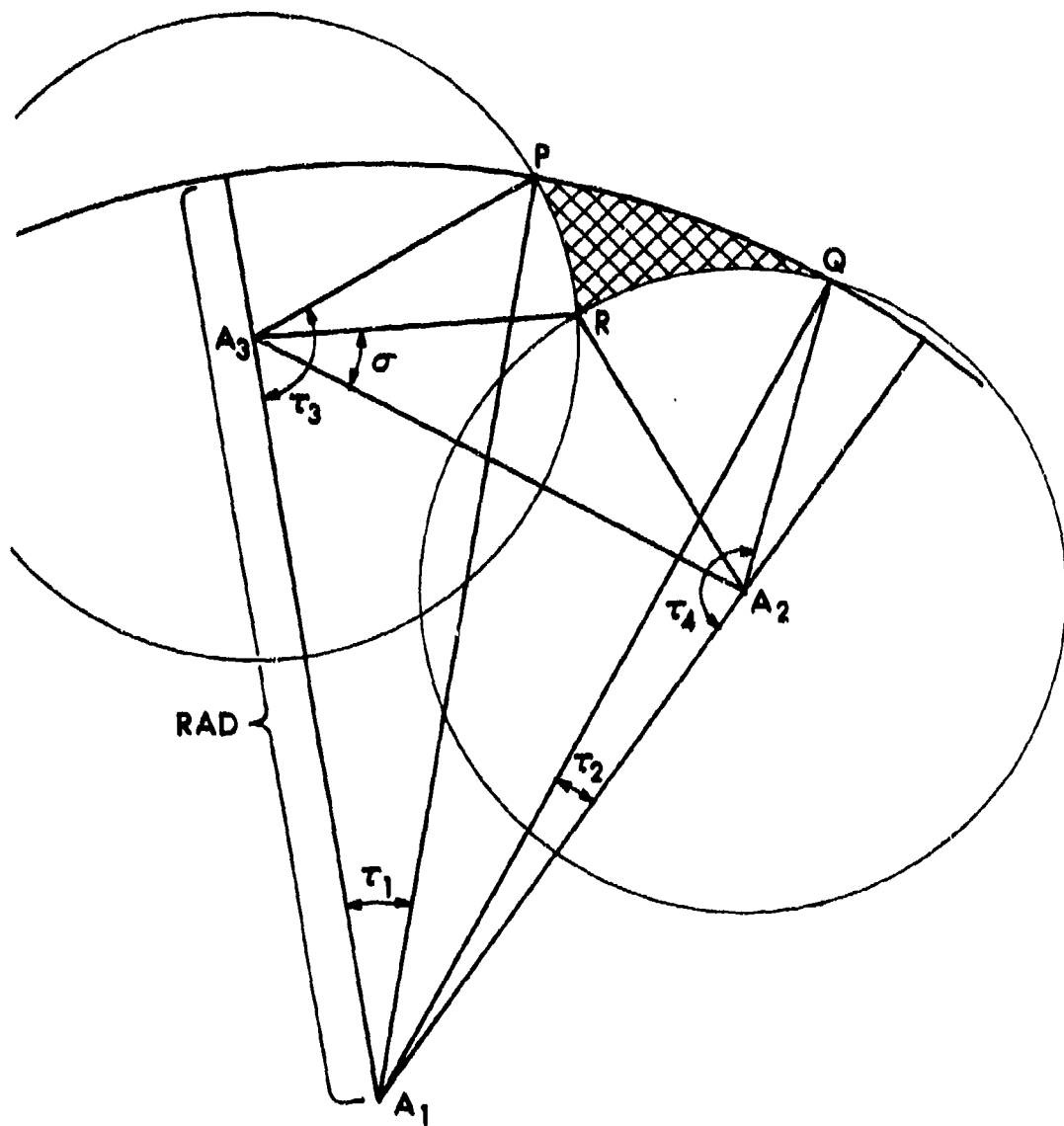


Figure 3. General Outer Sliver During Burning

$$\tau_1 + \tau_2 \geq A_3 A_1 A_2$$

or

$$GRL \leq 0$$

An error condition occurs whenever either

$$\tau_3 < A_2 A_3 A_1$$

or

$$\tau_4 < A_3 A_2 A_1$$

at some step during burning and signals violation of our requirement that the sliver stay within its original boundaries. A grain exhibiting this error in one of its outer slivers cannot be analyzed beyond that point by the present method. Very thin outer slivers are likely to give rise to this error.

Using the familiar minimum and maximum functions we derive by law of cosines

$$\tau_1 = \arccos \left[\min \left(1, \frac{S_2^2 + RAD^2 - 1/4 \cdot PRFD^2}{2 \cdot S_2 \cdot RAD} \right) \right]$$

$$\tau_2 = \arccos \left[\min \left(1, \frac{S_3^2 + RAD^2 - 1/4 \cdot PRFD^2}{2 \cdot S_3 \cdot RAD} \right) \right]$$

$$\tau_3 = \arccos \left[\max \left(-1, \frac{S_2^2 - RAD^2 + 1/4 \cdot PRFD^2}{S_2 \cdot PRFD} \right) \right]$$

$$\tau_4 = \arccos \left[\max \left(-1, \frac{S_3^2 - \text{RAD}^2 + 1/4 \cdot \text{PRFD}^2}{S_3 \cdot \text{PRFD}} \right) \right]$$

where the maxima and minima are taken to ensure values of π and 0, respectively, for τ_1 in degenerate triangles.

By definition of cosine we have

$$\sigma = \arccos \left[\min \left(1, \frac{S_1}{\text{PRFD}} \right) \right]$$

with the minimum taken to guarantee a value of zero should triangle RA_2A_3 be degenerate.

Should the burnout criteria fail, the sliver is not yet extinguished. Then we calculate

$$\text{area triangle } A_1A_3P = 1/2 \cdot \text{RAD} \cdot S_2 \cdot \sin(\tau_1)$$

$$\text{area triangle } A_1A_2Q = 1/2 \cdot \text{RAD} \cdot S_3 \cdot \sin(\tau_2)$$

$$\text{area triangle } A_2A_3R = 1/4 \cdot \text{PRFD} \cdot S_1 \cdot \sin(\sigma)$$

$$\text{area sector } A_1PQ = 1/2 \cdot (A_3A_1A_2 - \tau_1 - \tau_2) \cdot \text{RAD}^2$$

$$\text{area sector } A_3PR = 1/8 \cdot (\tau_3 - \sigma - A_2A_3A_1) \cdot \text{PRFD}^2$$

$$\text{area sector } A_2QR = 1/8 \cdot (\tau_4 - \sigma - A_3A_2A_1) \cdot \text{PRFD}^2$$

Then the sliver's end area, PQR, is given by

$$E = \text{area } A_1A_3P + \text{area } A_1PQ + \text{area } A_1A_2Q$$

$$- \text{area } A_1A_2A_3 - \text{area } A_2A_3R - \text{area } A_3PR - \text{area } A_2QR$$

or, more simply,

$$E = 1/2 \text{ RAD} \cdot \left\{ S_2 \cdot \sin(\tau_1) + \text{RAD} \cdot (A_3A_1A_2 - \tau_1 - \tau_2) + S_3 \cdot \sin(\tau_2) \right\}$$

$$- \text{area } A_1A_2A_3$$

$$- 1/4 \cdot \text{PRFD} \cdot \left\{ S_1 \cdot \sin(\sigma) + 1/2 \cdot \text{PRFD} \cdot (\tau_3 + \tau_4 - 2\sigma - A_1A_2A_3 - A_1A_3A_2) \right\}$$

and its contribution, VOL, to grain volume is

$$\text{VOL} = E \cdot \text{GRL}$$

Next, note that

$$\text{length arc PQ} = \text{RAD} \cdot (A_2A_1A_3 - \tau_1 - \tau_2)$$

$$\text{length arc PR} = 1/2 \cdot \text{PRFD} \cdot (\tau_3 - \sigma - A_1A_3A_2)$$

$$\text{length arc QP} = 1/2 \cdot \text{PRFD} \cdot (\tau_4 - \sigma - A_1A_2A_3)$$

Then the sliver's contribution, SURF, to grain surface area is twice its end area, E, plus its lateral surface area, or

$$\text{SURF} = 2 \cdot E +$$

$$\text{GRL} \cdot \left\{ \text{RAD} \cdot (A_2A_1A_3 - \tau_1 - \tau_2) + 1/2 \text{ PRFD} \cdot (\tau_3 + \tau_4 - 2\sigma - A_1A_2A_3 - A_1A_3A_2) \right\}$$

When extinction occurs, however, we have

$$\text{VOL} = \text{SURF} = 0$$

C. INNER SLIVERS

As in the case of outer slivers, we require that every inner sliver remain within its original boundaries throughout burning until extinction. Initially, an inner sliver appears as $A_1A_2A_3$ in Figure 4 with A_1 , A_2 , and A_3 the centers of the sliver's three perforations.

We assume lengths S_1 , S_2 , and S_3 to be known and calculate angles A_1 , A_2 , A_3 and the area of triangle $A_1A_2A_3$ in the same way as in the case of the outer sliver.

As burning progresses, the sliver erodes as shown in Figure 5 with, possibly, some degenerate angles. We require knowledge of the grain's instantaneous length, GRL, and perforation diameter, PRFD. As before, the surfaces of all perforations are assumed to erode at the same rate. Burnout of the sliver occurs when either

$$\tau_{12} + \tau_{13} + \tau_{23} \geq \pi/2$$

or

$$\text{GRL} \leq 0$$

An error condition occurs when an expanding perforation crosses any portion of the line-of-centers of the two opposite perforations before either of them engulfs that point, signaling violation of our requirement that the sliver remain within its original boundaries.

The critical points are clearly the feet of altitudes which cut opposite sides internally, as in Figure 6. The error condition arises whenever

$$d_1 < \min(d_2, d_3)$$

This is equivalent to having the altitude be less than the smaller of the two segments into which its foot divides the opposite side. In Figure 7, suppose

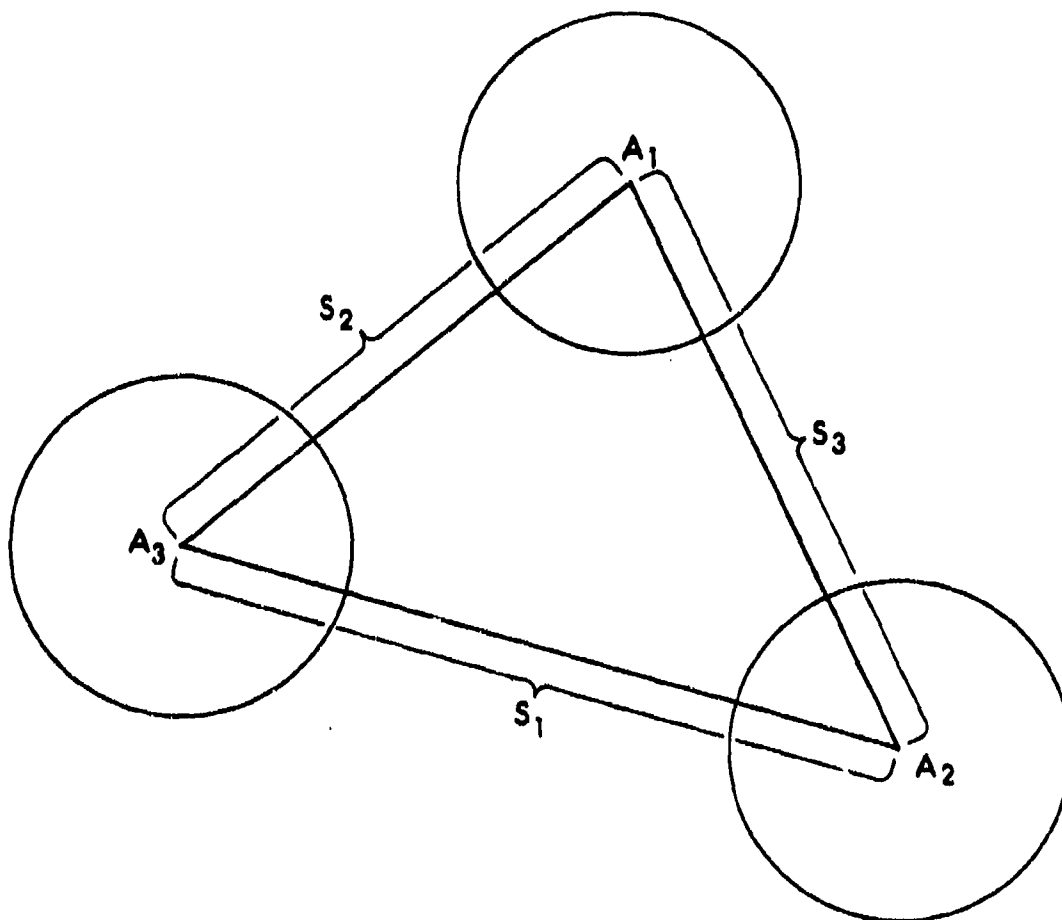


Figure 4. General Inner Sliver Before Burning

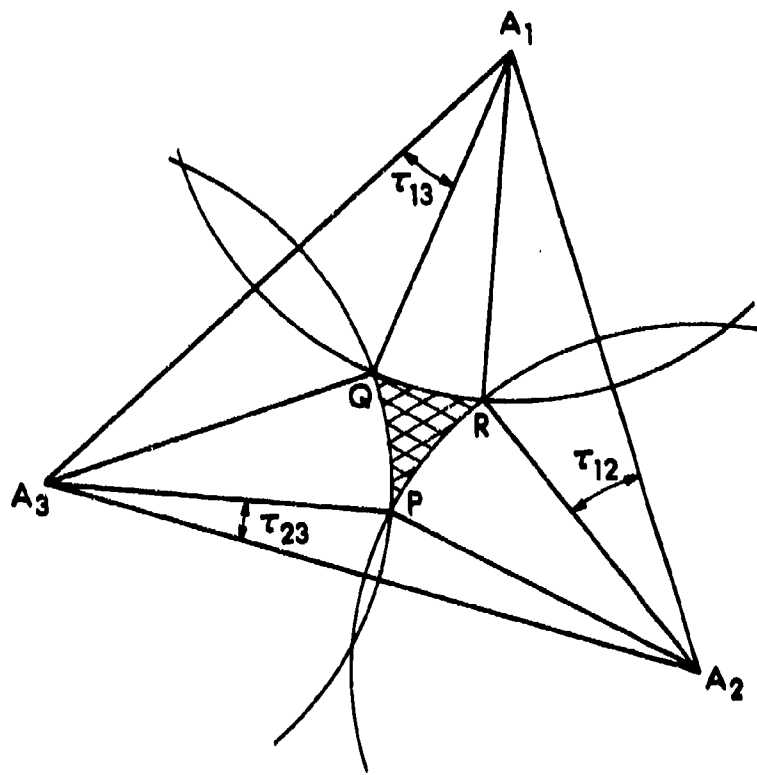


Figure 5. General Inner Sliver During Burning

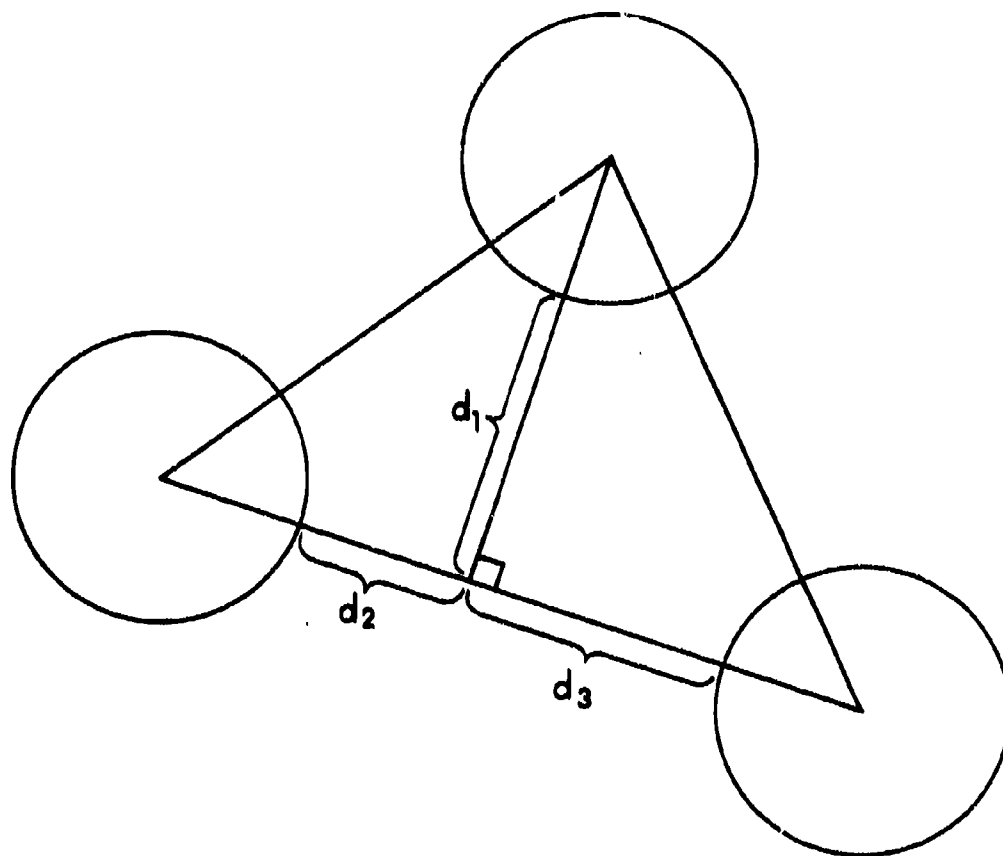


Figure 6. Critical Distances for the Inner Sliver

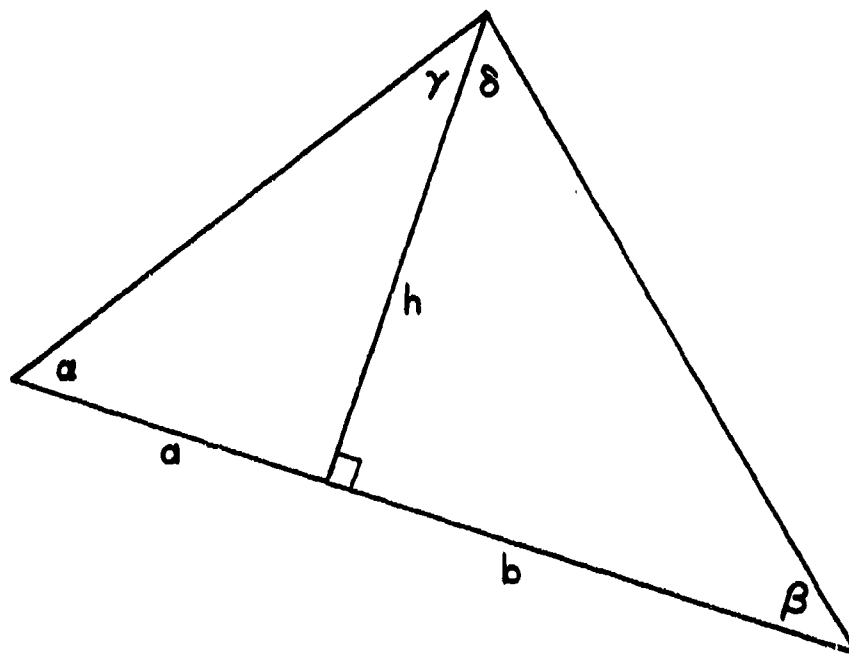


Figure 7. Geometric Dissection of Critical Triangle

$$h < \min (a,b)$$

$$\longrightarrow h < a, h < b$$

$$\longrightarrow \alpha < \gamma, \beta < \delta$$

$$\longrightarrow \alpha < \pi/4, \beta < \pi/4$$

and conversely. Thus, the error arises only in obtuse triangles where both acute angles are smaller than $\pi/4$. We note that the inner sliver error condition need only be checked once, based as it is on original grain dimensions alone.

Should the error arise due to a problem with an inner sliver, the grain may be repartitioned to attempt to cure the fault. A good policy is to try to avoid grossly obtuse slivers.

Referring once more to Figure 5, we have by definition of cosine

$$\tau_{12} = \arccos \left[\min \left(1, \frac{S_3}{PRFD} \right) \right]$$

$$\tau_{13} = \arccos \left[\min \left(1, \frac{S_2}{PRFD} \right) \right]$$

$$\tau_{23} = \arccos \left[\min \left(1, \frac{S_1}{PRFD} \right) \right]$$

where the minima are taken to ensure a value of zero for τ_{ij} in degenerate triangles.

Should the burnout criteria fail, the sliver is not yet extinguished. Then we calculate

$$\text{area triangle } A_1A_2R = 1/4 \cdot PRFD \cdot S_3 \cdot \sin (\tau_{12})$$

$$\text{area triangle } A_1A_3Q = 1/4 \cdot \text{PRFD} \cdot S_2 \cdot \sin(\tau_{13})$$

$$\text{area triangle } A_2A_3P = 1/4 \cdot \text{PRFD} \cdot S_1 \cdot \sin(\tau_{23})$$

$$\text{area sector } A_1QR = 1/8 \cdot \text{PRFD}^2 \cdot (A_2A_1A_3 - \tau_{13} - \tau_{12})$$

$$\text{area sector } A_2PR = 1/8 \cdot \text{PRFD}^2 \cdot (A_1A_2A_3 - \tau_{12} - \tau_{23})$$

$$\text{area sector } A_3PQ = 1/8 \cdot \text{PRFD}^2 \cdot (A_1A_3A_2 - \tau_{13} - \tau_{23})$$

Then the sliver's end area, PQR, is given by

$$E = \text{area } A_1A_2A_3 - \text{area } A_1A_2R - \text{area } A_1A_3Q$$

$$- \text{area } A_2A_3P - \text{area } A_1QR - \text{area } A_2PR - \text{area } A_3PQ$$

or, more simply,

$$E = \text{area } A_1A_2A_3$$

$$- 1/4 \cdot \text{PRFD} \cdot \left\{ S_3 \cdot \sin(\tau_{12}) + S_2 \cdot \sin(\tau_{13}) + S_1 \cdot \sin(\tau_{23}) \right. \\ \left. + \text{PRFD} \cdot (\pi/2 - \tau_{12} - \tau_{13} - \tau_{23}) \right\}$$

and its contribution, VOL, to grain volume is

$$\text{VOL} = E \cdot \text{GRL}$$

Next, note that

$$\text{length arc PQ} = 1/2 \cdot \text{PRFD} \cdot (A_1 A_3 A_2 - \tau_{13} - \tau_{23})$$

$$\text{length arc QR} = 1/2 \cdot \text{PRFD} \cdot (A_2 A_1 A_3 - \tau_{12} - \tau_{13})$$

$$\text{length arc PR} = 1/2 \cdot \text{PRFD} \cdot (A_1 A_2 A_3 - \tau_{12} - \tau_{23})$$

Then the sliver's contribution, SURF, to grain surface area is twice its end area, E, plus its lateral surface area, or

$$\text{SURF} = 2 \cdot E + \text{GRL} \cdot \text{PRFD} \cdot (\pi/2 - \tau_{12} - \tau_{13} - \tau_{23})$$

When extinction occurs, however, we have

$$\text{VOL} = \text{SURF} = 0$$

III. SUBROUTINES "GENIS" AND "GENOS"

Subroutines GENIS (GENERAL INNER SLIVER) and GENOS (GENERAL OUTER SLIVER) employing the above calculational methods have been written in FORTRAN and are listed in the Appendix.

For each class of slivers, two arrays are necessary, S(3) and A(4). In array S, the calling routine must store the three sides of triangle $A_1 A_2 A_3$ (Figures 2 and 4) taking care, in the case of the outer sliver, that S(1) contains the chord segment joining the centers of the two perforations bounding that sliver. Array A is a work array which will be used to store the angles of $A_1 A_2 A_3$ and its area for later use.

PRFD is the grain's instantaneous perforation diameter, GRL its instantaneous length and, for outer slivers, RAD, the grain's radius. Units of measurement should, of course, be uniform.

The routine will return SURF, the sliver's contribution to grain surface area, and VOL, its volume contribution.

Branching within each routine is controlled by argument IFLAG which the calling routine should initialize to a negative number and not touch thereafter. Extinction of the sliver will be signaled by a value

of IFLAG = 1. Thus complete extinction of the grain occurs when the branch flag for each class of slivers is 1.

IV. A SAMPLE CASE

Suppose that a nineteen-perforated grain, one-sixth of which is shown in Figure 8, is characterized by three independent webs WI, WM, WO and some perforation diameter, PD, and length GL.

There are four classes of slivers:

- (i) 6 inner slivers congruent to FED
- (ii) 6 inner slivers congruent to BED
- (iii) 12 inner slivers congruent to BEC
- (iv) 12 outer slivers congruent to CIHB.

We note that grain diameter, D, is given by

$$D = 5 \cdot PD + 2 \cdot (WI + WM + WO)$$

and we have segments

$$\overline{FE} = WI + PD$$

$$\overline{EC} = WM + PD$$

$$\overline{FC} = \overline{FE} + \overline{EC} = WI + WM + 2 \cdot PD$$

$$\overline{AB} = 1/2 \cdot \overline{FC} = 1/2 \cdot (WI + WM) + PD$$

$$\overline{FB} = \overline{AB} \cdot \sqrt{3} = \{ 1/2 \cdot (WI+WM) + PD \} \cdot \sqrt{3}$$

$$\overline{EB} = \sqrt{\overline{BJ}^2 + \overline{EJ}^2} = \sqrt{(\overline{FB} - \overline{FJ})^2 + (1/2 \cdot \overline{FE})^2}$$

$$= 1/2 \cdot \sqrt{3 \cdot (WM+PD)^2 + (WI+PD)^2}.$$

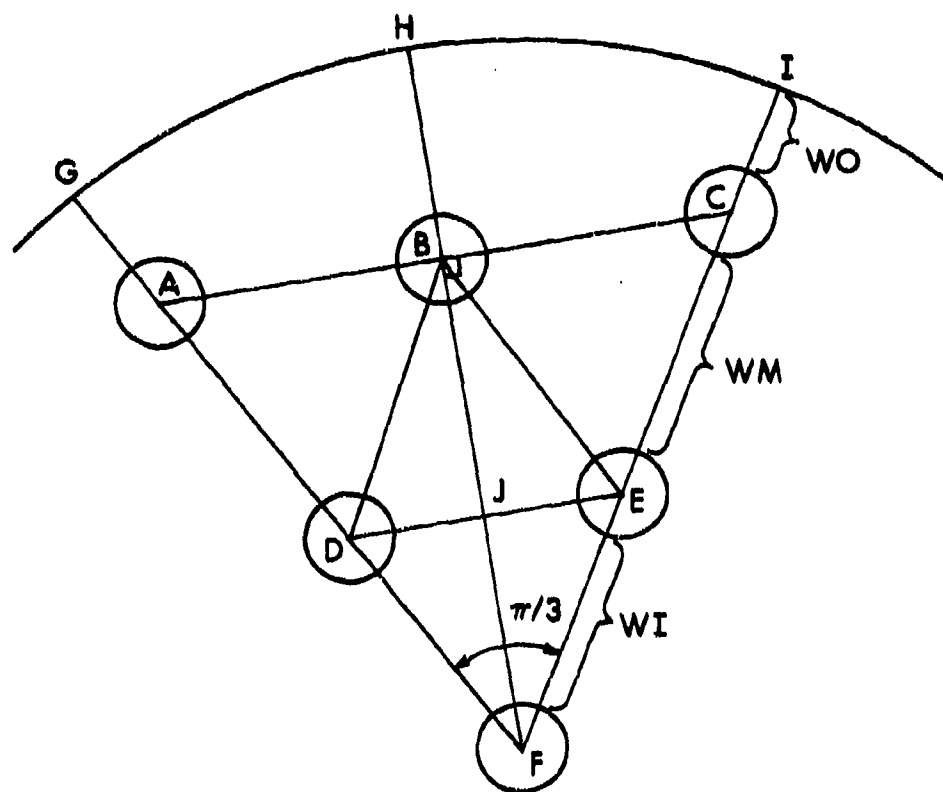


Figure 8. One-Sixth of Sample Nineteen-Perforated Grain

Let arrays SIDE (3,4) and ANGL (4,4) be used for our side and work arrays, respectively. Then, considering each sliver class in turn, set:

$$(i) \text{ SIDE } (1,1) = \text{SIDE } (2,1) = \text{SIDE } (3,1) = \overline{FE} = WI + PD$$

$$(ii) \text{ SIDE } (1,2) = \text{SIDE } (2,2) = \overline{EB} = 1/2 \cdot \sqrt{3(WM+PD)^2 + (WI+PD)^2}$$

$$\text{SIDE } (3,2) = \overline{ED} = WI + PD$$

$$(iii) \text{ SIDE } (1,3) = \overline{BC} = 1/2 \cdot (WI+WM) \cdot PD$$

$$\text{SIDE } (2,3) = \overline{EB} = 1/2 \cdot \sqrt{3(WM+PD)^2 + (WI+PD)^2}$$

$$\text{SIDE } (3,3) = \overline{EC} = WM + PD$$

$$(iv) \text{ SIDE } (1,4) = \overline{BC} = 1/2 \cdot (WI + WM) + PD$$

$$\text{SIDE } (2,4) = \overline{FC} = WI + WM + 2 \cdot PD$$

$$\text{SIDE } (3,4) = \overline{FB} = \{1/2 \cdot (WI+WM) + PD\} \cdot \sqrt{3}$$

where, as noted, SIDE (1,4) must be the indicated segment, $\overline{BC}$, for the outer slivers.

Let array NCHECK (4) be set aside for the branch flags.

Now, while the subroutines can be called throughout the burning of the grain, it is efficient to employ the more obvious method of subtracting the nineteen cylindrical perforations from the grain to deduce surface area and volume until at least one set of perforations touch. That is, until twice the depth burned is WEB, where

$$WEB = \min \{WO, WM, WI, \overline{BC} - PD, \overline{BE} - PD, GL\}$$

$$= \min \{WO, WM, WI, 1/2 \cdot (WI+WM),$$

$$1/2 \cdot \sqrt{3 \cdot (WM+PD)^2 + (WI+PD)^2} - PD, GL\}$$

Afterward, we employ GENIS and GENOS, remembering to sum the individual sliver contributions to produce SSUM and VSUM, the grain's surface area and volume, respectively, at any instant.

A rendering of a program which determines grain surface area and volume for our burning grain with a fixed depth-burned increment, DELTA, is in the Appendix. It solicits grain dimensions from the user and simply prints a table of the surface and volume for the grain at increasing depths burned through extinction. The ACOS function is included because the FORTRAN library of the minicomputer's operating system doesn't contain it. The outer grain surface is assumed to erode at the same rate as the perforation surfaces although this need not have been forced.

Further development is possible. By adding a third subscript to our SIDE and ANGL arrays, the program could be extended to handle several such grains. If the intermediate results were saved, it would be possible to present them in plotted form. This last has been done in Figures 9 and 10 which display the ratio of surface area to initial surface area plotted against fraction of grain burned for two hypothetical grains. The first has all three webs equal, while the second, Figure 10, has three unequal webs.

V. ACKNOWLEDGEMENT

Special acknowledgement is due Dr. Joseph J. Rocchio for his many helpful suggestions in the writing of this report.

SAMPLE 19-PF PROPELLANT WITH EQUAL WEBS

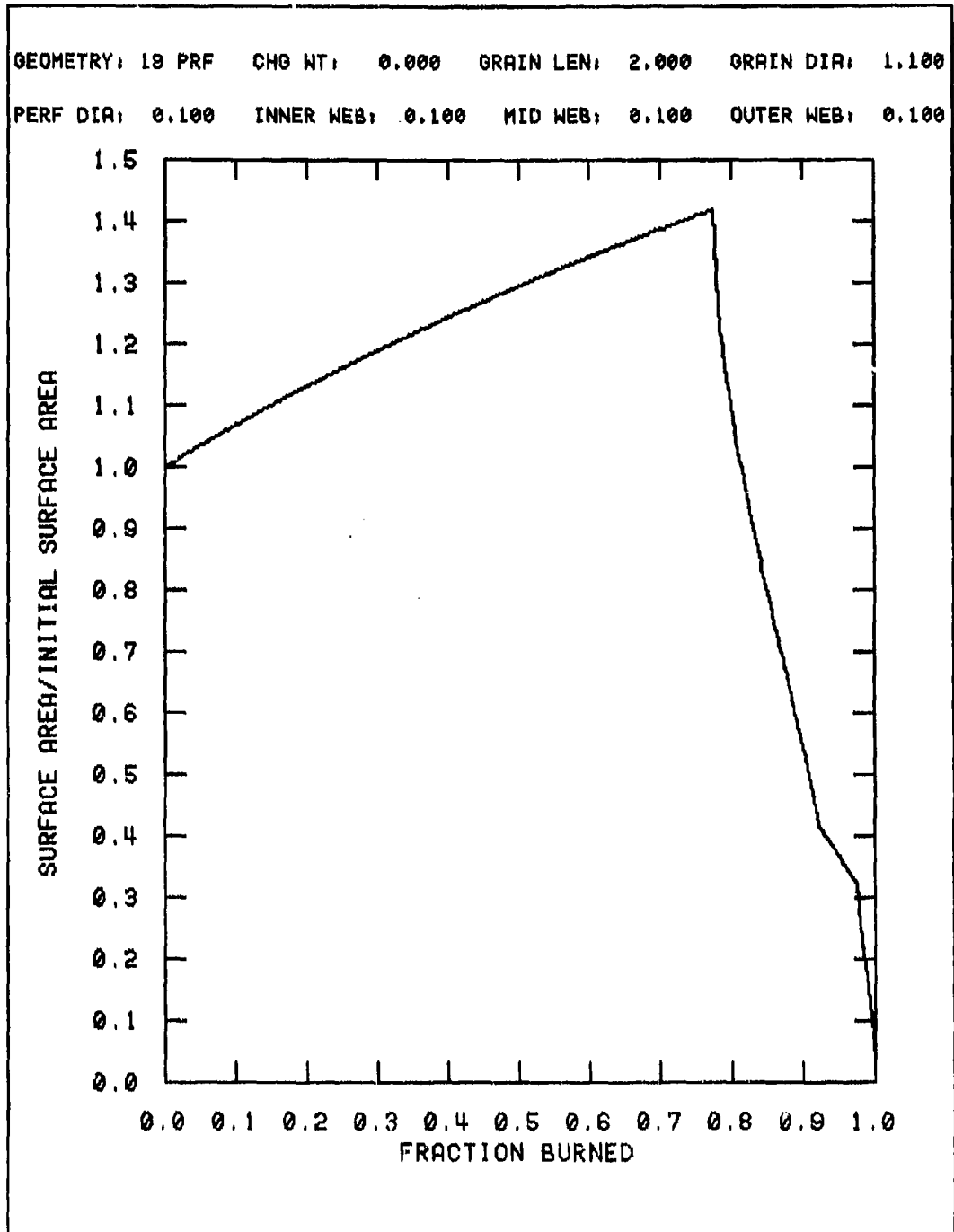


Figure 9. Surface Area Plot - Grain with Equal Webs

SAMPLE 19-PF PROPELLANT WITH DIFFERENT WEBS

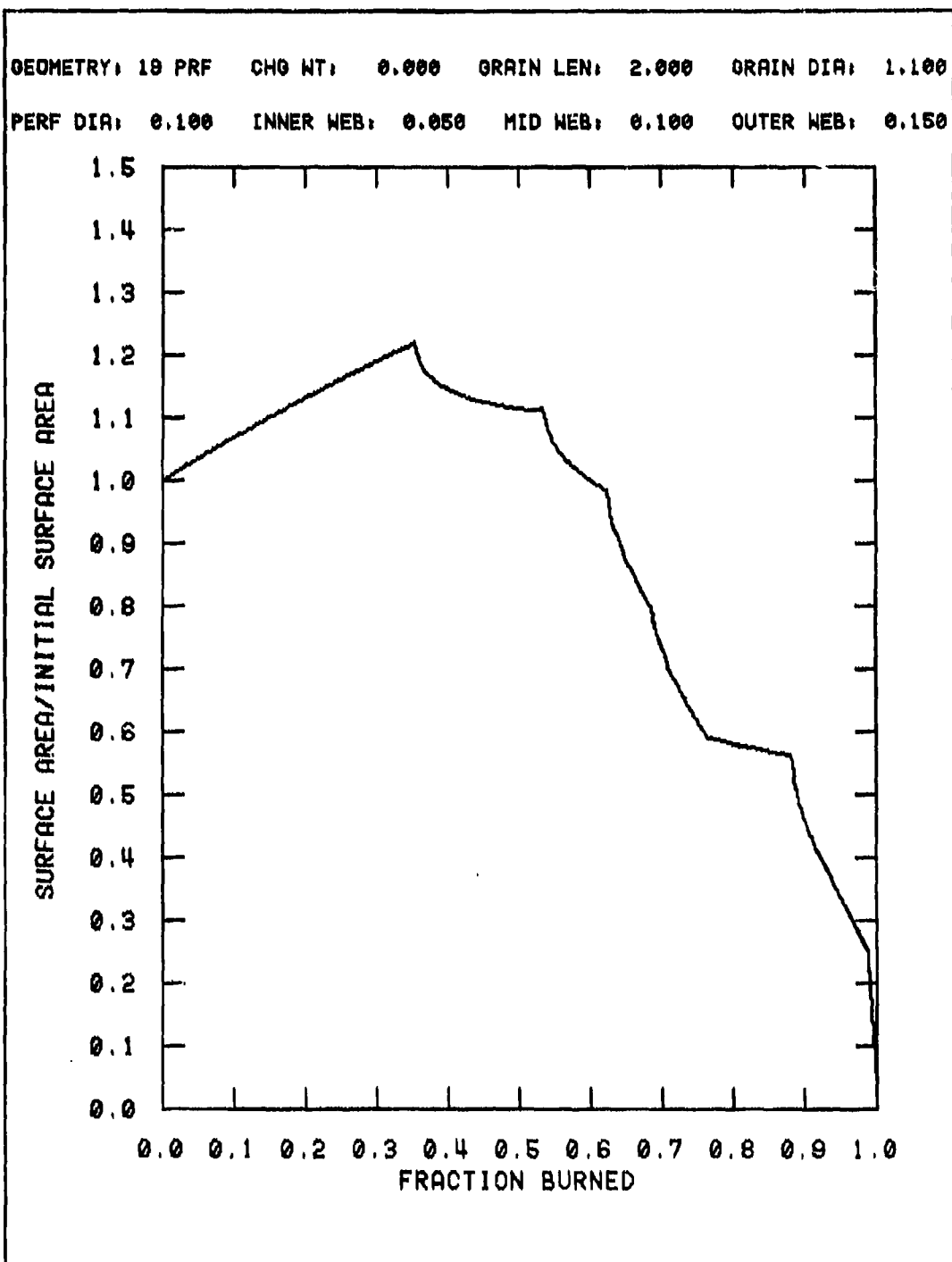


Figure 10 Surface Area Plot - Grain with Unequal Webs

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1. Corner, J., "Theory of the Interior Ballistics of Guns", John Wiley & Sons, New York, 1950, pp. 30-35.
2. Stals, J., "Form-Functions for Multicomponent Propellant Charges Including Inhibited Grains and Sliver Burn", MRL Technical Note 371, Materials Research Laboratories, Maribyrnong, Victoria, Australia, September 1975.

APPENDIX

LISTING OF SAMPLE PROGRAM FOR NINETEEN-PERFORATED GRAIN PLUS LISTINGS
OF SUBROUTINES "GENOS" AND "GENIS".

```

      C      SAMPLE PROGRAM EMPLOYING *GENOS* AND *GENIS*
      C      TO PRODUCE SURFACE & VOLUME FOR 19-PERFORATED
      C      GRAIN WITH THREE INDEPENDENT WEBS.
      C
0001      DIMENSION SIDE(3,4),ANGL(4,4),NCHECK(4)
0002      DATA NCHECK/4*-1/,IDONE/0/,PI/3.14159265/
      C
0003      TYPE 1030
0004      ACCEPT 1000,WI,WM,W0,PD,GL,DELTA
0005      D=5.*PD+2.*(WI+WM+W0)
      C
0006      SIDE(1,1)=WI+PD
0007      SIDE(2,1)=SIDE(1,1)
0008      SIDE(3,1)=SIDE(1,1)
      C
0009      SIDE(1,2)=.5*SQRT(3.*(WM+PD)**2 + (WI+PD)**2)
0010      SIDE(2,2)=SIDE(1,2)
0011      SIDE(3,2)=SIDE(1,1)
      C
0012      SIDE(1,3)=.5*(WI+WM)+PD
0013      SIDE(2,3)=SIDE(1,2)
0014      SIDE(3,3)=WM+PD
      C
0015      SIDE(1,4)=SIDE(1,3)
0016      SIDE(2,4)=2.*SIDE(1,3)
0017      SIDE(3,4)=SIDE(1,3)*SQRT(3.)
      C
0018      WEB=AMIN1(W0,WM,WI,.5*(WI+WM),SIDE(1,2)-PD,GL)
      C
0019      TYPE 1010,WI,WM,W0,PD,GL,DELTA
0020      JSTEP=0
0021      DEPTH=JSTEP*DELTA
0022      PRFD=PD+2.*DEPTH
0023      GRL=GL-2.*DEPTH
0024      RAD=.5*D-DEPTH
0025      IF(2.*DEPTH.GT.WEB) GOTO 200
      C
0027      TA=PI*(RAD**2-4.75*PRFD**2)
0028      SSUM=2.*TA+GRL*PI*(2.*RAD+19.*PRFD)
0029      VSUM=TA*GRL
0030      GOTO 300
      C
0031      200      IDONE=0
0032      SSUM=0.
0033      VSUM=0.
      C
0034      DO 250 I=1,2
0035      CALL GENIS(SIDE(1,I),ANGL(1,I),PRFD,GRL,NCHECK(I),TA,TV)
0036      SSUM=SSUM+6.*TA
0037      VSUM=VSUM+6.*TV
0038      IDONE=IDONE+NCHECK(I)

```



```
0039 250  CONTINUE
0040      CALL GENIS(SIDE(1,3),ANGL(1,3),PRFD,GRL,NCHECK(3),TA,TV)
0041      SSUM=SSUM+12.*TA
0042      VSUM=VSUM+12.*TV
      C
0043      CALL GENOS(SIDE(1,4),ANGL(1,4),PRFD,GRL,RAD,NCHECK(4),TA,TV)
0044      SSUM=SSUM+12.*TA
0045      VSUM=VSUM+12.*TV
0046      IDONE=IDONE+NCHECK(3)+NCHECK(4)
      C
0047 300  TYPE 1020,DEPTH,SSUM,VSUM
0048      IF(IDONE.EQ.4) GOTO 400
0050      JSTEP=JSTEP+1
0051      GOTO 100
      C
0052 400  STOP 'GRAIN EXTINGUISHED!'
      C
0053 1000  FORMAT(10E12.0)
0054 1010  FORMAT(/' INNER WEB = ',F10.4
      $    //' MIDDLE WEB= ',F10.4
      $    //' OUTER WEB = ',F10.4
      $    //' PERF DIAM = ',F10.4
      $    //' GRAIN LEN = ',F10.4
      $    //' BURN INCR = ',F10.4
      $    //' DEPTH BURNED    SURFACE AREA    VOLUME' /)
0055 1020  FORMAT(1X,F10.4,5X,F10.4,5X,F10.4)
0056 1030  FORMAT(' INNER,MIDDLE,OUTER WEBS,PERF DIAM',
      $    ',GRAIN LENGTH,DEPTH-BURNED INCREMENT ?')
0057      END
```

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```
0001      FUNCTION ACOS(U)
0002      ACOS=ATAN2(SQRT(1.-U**2),U)
0003      RETURN
0004      END
```

```

0001      SUBROUTINE GENOS(S,A,PRFD,GRL,RAD,IFLAG,SURF,VOL)
      C
      C      SUBROUTINE *GENOS*: CALCULATE SURFACE AREA AND VOLUME FOR A
      C      GENERAL OUTER SLIVER OF A BURNING GRAIN
      C      WITH LENGTH = GRL, RADIUS = RAD, AND
      C      PERF DIAM = PRFD.
      C
0002      DIMENSION S(3),A(4)
      C
0003      IF(IFLAG) 10,20,30
      C
      C      INITIAL PASS: IFLAG WAS SET NEGATIVE BY CALLING ROUTINE.
      C      STORE ANGLES A1,A2,A3 AND AREA OF TRIANGLE
      C      WITH SIDES S(1),S(2),S(3) INTO A(1),...,A(4)
      C
0004      10  A(1) = ACOS((S(2)**2+S(3)**2-S(1)**2)/(2.*S(2)*S(3)))
0005          A(2) = ACOS((S(1)**2+S(3)**2-S(2)**2)/(2.*S(1)*S(3)))
0006          A(3) = ACOS((S(1)**2+S(2)**2-S(3)**2)/(2.*S(1)*S(2)))
      C
0007          A(4) = .5*S(1)*S(3)*SIN(A(2))
      C
      C      ...AND SET FLAG TO ZERO TO BYPASS INITIALIZATION HEREAFTER.
      C
0008          IFLAG = 0
      C
      C      SUCCEEDING PASSES UNTIL BURNOUT: FIRST DETERMINE AUXILIARY ANGLES
      C
0009      20  TAU1 = ACOS(AMIN1(1.,(S(2)**2+RAD**2-.25*PRFD**2)/(2.*S(2)*RAD)))
0010          TAU2 = ACOS(AMIN1(1.,(S(3)**2+RAD**2-.25*PRFD**2)/(2.*S(3)*RAD)))
0011          TAU3 = ACOS(AMAX1(-1.,(S(2)**2-RAD**2+.25*PRFD**2)/(S(2)*PRFD)))
0012          TAU4 = ACOS(AMAX1(-1.,(S(3)**2-RAD**2+.25*PRFD**2)/(S(3)*PRFD)))
      C
0013          SIG = ACOS(AMIN1(1.,S(1)/PRFD))
      C
      C      ...THEN CHECK ERROR CONDITIONS...
      C
0014          IF(TAU3.LT.A(3) .OR. TAU4.LT.A(2)) STOP '*GENOS* ERROR1'
      C
      C      ...IF OK, BRANCH IF SLIVER FAILS BURNOUT CRITERIA.
      C
0016          IF(TAU1+TAU2.LT.A(1) .AND. GRL.GT.0.) GOTO 25
      C
      C      SLIVER JUST BURNED OUT: SET FLAG TO BYPASS AREA & VOLUME CALCULATIONS.
      C
0018          IFLAG = 1
0019          GOTO 30
      C
      C      SLIVER NOT BURNED OUT: DETERMINE END AREA, VOLUME, AND SURFACE AREA
      C
0020      25  E = .5*RAD*(S(2)*SIN(TAU1)+RAD*(A(1)-TAU1-TAU2)+S(3)*SIN(TAU2))
          S      -A(4)-.25*PRFD*(S(1)*SIN(SIG)+.5*PRFD*(TAU3+TAU4-2.*SIG)

```

```

      * -A(2)-A(3))
    C
0021 C   VOL = E*GRL
    C
0022 C   SURF = 2.*E+GRL*(RAD*(A(1)-TAU1-TAU2)+.5*PRFD*(TAU3+TAU4-2.*SIG
      * -A(2)-A(3))
    C
    C   ...AND RETURN.
    C
0023 C   RETURN
    C
    C   SLIVER IS BURNED OUT: RETURN WITH ZERO VOLUME AND SURFACE AREA.
    C
0024 C 30 VOL = 0.
0025 C   SURF = 0.
0026 C   RETURN
    C
0027 C   END

```

```

0001      SUBROUTINE GENIS(S,A,PRFD,GRL,IFLAG,SURF,VOL)
      C
      C      SUBROUTINE *GENIS*: CALCULATE SURFACE AREA AND VOLUME FOR A
      C      GENERAL INNER SLIVER OF A BURNING GRAIN
      C      WITH LENGTH = GRL & PERF DIAM = PRFD.
      C
0002      DIMENSION S(3),A(4)
0003      DATA PI2/ 1.5707963 /
      C
0004      IF(IFLAG) 10,20,30
      C
      C      INITIAL PASS: IFLAG WAS SET NEGATIVE BY CALLING ROUTINE.
      C      STORE ANGLES A1,A2,A3 AND AREA OF TRIANGLE
      C      WITH SIDES S(1),S(2),S(3) INTO A(1),...,A(4)
      C
0005      10  A(1) = ACOS((S(2)**2+S(3)**2-S(1)**2)/(2.*S(2)*S(3)))
0006          A(2) = ACOS((S(1)**2+S(3)**2-S(2)**2)/(2.*S(1)*S(3)))
0007          A(3) = ACOS((S(1)**2+S(2)**2-S(3)**2)/(2.*S(1)*S(2)))
      C
0008          A(4) = .5*S(1)*S(3)*SIN(A(2))
      C
      C      ...CHECK FOR ERROR CONDITION: FIND IF TRIANGLE ACCEPTABLE...
      C
0009          J = 0
0010          DO 15 I = 1,3
0011              IF(A(I).LT..5*PI2) J = J+1
0013      15  CONTINUE
0014          IF(J.GT.1) STOP '*GENIS* ERROR!'
      C
      C      IF OK, SET FLAG TO ZERO TO BYPASS INITIALIZATION HEREAFTER.
      C
0016          IFLAG = 0
      C
      C      SUCCEEDING PASSES UNTIL BURNOUT: FIND AUXILIARY ANGLES
      C
0017      20  TAU12 = ACOS(AMIN1(1.,S(3)/PRFD))
0018          TAU13 = ACOS(AMIN1(1.,S(2)/PRFD))
0019          TAU23 = ACOS(AMIN1(1.,S(1)/PRFD))
      C
      C      ...AND BRANCH IF SLIVER FAILS BURNOUT CRITERIA.
      C
0020          IF(TAU12+TAU13+TAU23.LT.PI2 .AND. GRL.GT.0.) GOTO 25
      C
      C      SLIVER JUST BURNED OUT: SET FLAG TO BYPASS AREA & VOLUME CALCULATIONS.
      C
0022          IFLAG = 1
0023          GOTO 30
      C
      C      SLIVER NOT BURNED OUT: DETERMINE END AREA, VOLUME, AND SURFACE AREA
      C
0024      25  E = A(4)-.25*PRFD*(S(1)*SIN(TAU23)+S(2)*SIN(TAU13))

```

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```
      *   +S(3)*GIN(TAU12)+PRFD*(PI2-TAU12-TAU13-TAU23))
0025 C      VOL = E*GRL
      C
0026 C      SURF = 2.*E+GRL*PRFD*(PI2-TAU12-TAU13-TAU23)
      C
      C      ...AND RETURN.
      C
0027 C      RETURN
      C
      C      SLIVER IS BURNED OUT: RETURN WITH ZERO VOLUME AND SURFACE AREA.
      C
0028 30 VOL = 0.
0029     SURF = 0.
0030     RETURN
      C
0031     END
```

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