CALCULATED GUN INTERIOR BALLISTIC EFFECTS
OF IN-DEPTH BURNING OF VHBR PROPELLANT

FREDERICK W. ROBBINS
DAVID L. KRUCZYNSKI

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Calculated Gun Interior Ballistic Effects of In-Depth Burning of VHBR Propellant

Very High Burning Rate (VHBR) propellants exhibit sufficiently high burning rates to motivate consideration of a charge consisting of single-perforated monolithic grain. If the outside surfaces, including the ends, of such a grain were inhibited, the result would be a highly progressive grain whose performance could be quite attractive.

The VHBR picture is complicated, however, by the fact that some of these propellants seem to burn not only on the surface but also at some depth into the surface, so that they have an extended reaction zone. This paper details the development of a lumped parameter interior ballistic code which permits an examination of the ballistic effects of in-depth propellant combustion. It is concluded that if in-depth burning occurs in a reproducible manner, and if the grain is properly designed so that it is fully burned at the time of shot ejection, then the performance improvement over that expected from a conventional charge for the same gun is significant.
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I. INTRODUCTION

A large single-perforated monolithic grain comprised of Very High Burning Rate (VHBR)\textsuperscript{1} propellant holds the promise of significant increases in performance in ballistic applications. It has been theorized by several researchers\textsuperscript{1,2} that propellants with very high burning rates may be exhibiting a phenomenon in which burning takes place at some depth into the propellant simultaneously with surface burning. This phenomenon, referred to as "porous burning", if real, could have a significant impact on the performance of this family of propellants.

This study attempts to quantify these effects by modifying a current interior ballistic code to include a representation of this porous burning effect. The code not only allows a representation of porous burning but is generic enough to simulate any condition in which additional surface area beyond that traditionally expected becomes available during the burning process. This could happen as a result of porous burning, surface cracks, bubbles, or other irregularities in the propellant. For this report, the term "in-depth" burning is used to describe this generic surface-increasing effect.

II. THEORY

Most lumped parameter interior ballistic computer codes require the mass of propellant burned as a function of time. Then using an equation of state to get the mean pressure and an analytic formulation to get the projectile base pressure from the mean pressure, the code calculates the inbore projectile acceleration, velocity, and distance traveled. One approach (and the one we will follow) is to get the time rate of change of the mass of propellant burned from $\dot{m} = \rho S \frac{dx}{dt}$ and integrate this numerically to get the mass of propellant burned. Here $\dot{m}$ is the time rate of change of the mass of propellant burned, $\rho$ is the density of the solid propellant (assumed constant), $S$ is the total surface area of the burning propellant, and $\frac{dx}{dt}$ is the linear burning rate of the propellant.

The modeling problem for in-depth burning is to find a way to represent the surface area involved in the volume associated with the in-depth burning as well as that which would normally be associated with burning normal to the propellant surfaces. In this paper we will get the total surface area from normal surface areas as well as the surface associated with a volume by assuming it can be modeled by $S = S_0 + S_a D M$. Here, $S$ is the total surface area. $S_0$ is the surface area associated with surface burning of the propellant. $S_0$ is defined to be the surface that would be determined from the grain geometry, with burning normal to all burning surfaces, for the current mass of propellant burned. $S_a D M$ is the surface area associated with the in-depth burning volume, and we shall call this surface area $S_v$. $D$ is the effective depth for which in-depth burning is hypothesized to occur and can be a function of any variable. In this paper, $D$ is considered constant during any computation. $S_a$ is the effective surface area such that the product of $S_a$ and $D$ is the volume in which in-depth burning is occurring. $M$ is the surface area.
per unit volume such that \( S_a \Delta M, S_a \), is the extra surface on which burning will occur within the in-depth burning volume. \( M \) may be thought of as the factor that describes the degree of porosity of the porous volume. \( M \) can also be a function of any variable, but for this paper, \( M \) will be kept constant.

All the subsequent calculations will be done for a single-perforated monolithic grain with the ends and lateral surfaces inhibited. The grain fills most of the gun chamber. For this geometry \( S_a \) can be defined in terms of the current perforation surface \( S_o \). It can be shown that \( S_a = S_o \frac{(D + 2R)}{(2R)} \), where \( S_a \) is the multiplier of the in-depth burning distance, \( D \), such that \( S_a \Delta D \) gives the volume undergoing in-depth burning, and \( R \) is the instantaneous radius of the perforation.

Figure 1 gives a graphic representation of some of the parameters discussed above.

### III. COMPUTATIONS

The lumped parameter interior ballistic code used for the following calculations is a version of IBRGA³ (which uses The Technical Cooperative Program (TTCP) model) modified for the above in-depth analysis (a listing, input, output, and a short description of the input are given in Appendices A, B, C, and D, respectively). The calculations are performed for a single-perforated monolithic grain which burns a) only on the perforation surface or b) on the perforation surface and in an in-depth volume which extends from the perforation surface. The purpose of the calculations will be to assess the geometric effects of in-depth burning on the progressive nature of an outside- and end-inhibited single-perforated monolithic grain. It is assumed that the burning rate of the propellant can be
controlled in manufacture such that for given grain and gun dimensions any desired maximum breech pressure can be achieved. That is, for any grain dimensions and in-depth burning, the burning rate will be varied to achieve the desired maximum breech pressure. The effects of in-depth burning will be assessed by comparing muzzle velocities for the same grain configuration with the same maximum breech pressure but with different effective in-depth burning depths ($D$) and surface areas per unit volume ($M$).

Data for the propellant used in all the calculations are given in Table 1. Information on the gun systems is given in Tables 2 and 3. The two gun systems were chosen to look at typical low and high ratios of propellant-charge-weight to projectile-weight.

The mass of the propellant grain was calculated to give one grain for each perforation diameter. The outside grain diameter was 15 cm for both gun systems. The calculations used the Lagrange gradient with nominal heat loss, no recoil, no resistive forces, a burning rate exponent of one, and all burning propellant surfaces burning at time zero at ambient pressure.

<table>
<thead>
<tr>
<th>Bore diameter</th>
<th>12.7 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel</td>
<td>457.2 cm</td>
</tr>
<tr>
<td>Projectile mass</td>
<td>9.796 kg</td>
</tr>
<tr>
<td>Propellant grain length</td>
<td>50.0 cm</td>
</tr>
<tr>
<td>Maximum breech pressure</td>
<td>517.0 MPa</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Bore diameter</th>
<th>15.64 cm</th>
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<tbody>
<tr>
<td>Travel</td>
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<tr>
<td>Projectile mass</td>
<td>43.54 kg</td>
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<td>Propellant grain length</td>
<td>109.22 cm</td>
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<tr>
<td>Maximum breech pressure</td>
<td>345.0 MPa</td>
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</table>

The effects of in-depth burning as modeled here will be caused by the decrease in surface area in the in-depth burning volume ($S_V$) as the in-depth burning volume intersects the outer grain surface and starts to get smaller. Figure 2 illustrates this effect where (a) shows the in-depth burning volume before intersection with the outer surface, (b) shows the increased in-depth burning volume just at its intersection with the outer surface and (c) shows the decrease in the in-depth volume some time after its intersection with the outer surface.
This is further illustrated in Figure 3 where the surface area of the perforation (S₀) and the surface associated with the in-depth burning volume (Sᵥ) versus distance burned into the grain is given for different effective in-depth burning depths. The curves were generated for no in-depth burning depth (D = 0), the in-depth burning depth set to half of the web (D = 3.25 cm) and for the in-depth burning depth set to the web (D = 6.5 cm).

Table 4 demonstrates the wide range of surface areas we get from different values of the surface area per unit volume (M) for different in-depth burning depths (D). To provide a physical comparison, the surface area in the in-depth burning volume (Sᵥ) is referenced to the perforation surface area (S₀). These calculations were done for an initial perforation diameter of 2 cm and a volume (M) of 50 m sq/m cu.
average perforation diameter of 9 cm, but the ratios do not change much for larger or smaller perforations.

If in-depth burning occurs, and if the increase in surface area in that in-depth burning volume is small, then the model predicts a degradation in velocity of only a few percent. For example, a 2-cm-diameter perforation in the small gun system with no in-depth burning gives a velocity of 1713 m/s. With \( M = 1 \text{ m}^2/\text{m}^3 \), so that \( \frac{S_v}{S_0} \) is very small, and with the burning depth \( (D) \) equal to the web, 6.5 cm, we get a velocity of 1648 m/s, a decrease of only 3.8 percent.

| Table 4. Ratio of In-depth Surface to Perforation Surface (Sv/So) |
|---------------------------------|----------|----------|----------|----------|
| In-depth Burning depth (D) (m) | Surface Volume Multiplier (M) | Surface Area Per Unit Volume (m sq/m cu) |
| 1 | 5 | 50 | 500 |
| 0.001 | 0.001 | 0.006 | 0.060 | 0.30 |
| 0.006 | 0.005 | 0.025 | 0.264 | 2.64 |
| 0.010 | 0.011 | 0.055 | 0.555 | 5.55 |
| 0.015 | 0.019 | 0.088 | 0.875 | 8.75 |
| 0.020 | 0.040 | 0.200 | 2.00 | 20.0 |

For \( M = 50 \text{ m}^2/\text{m}^3 \), so that \( \frac{S_v}{S_0} \) is about unity, the initial perforation diameter for which complete combustion of the propellant grain will occur becomes larger than 2 cm. As the depth of penetration of the in-depth burning increases there is an increase in the initial diameter of the perforation for which complete burnout of the propellant will occur. If the effective in-depth burning depth of the in-depth burning volume is made equal to the web of the propellant grain (the largest it can be), then the initial perforation diameter for which burnout will occur is 10.0 cm for the large gun system and 9.36 cm for the small gun system.

For \( M = 500 \text{ m}^2/\text{m}^3 \), so that \( \frac{S_v}{S_0} \) is larger than one, the perforation diameter for which burnout will occur when the depth of penetration of the in-depth burning is made equal to the web of the propellant grain is 11.7 cm for the large gun system and 11.3 for the small gun system.

A plot of the velocity versus the perforation diameter with no in-depth burning is shown for both the small and large gun systems in Figure 4. The optimal velocity for the systems is seen to be when the perforation diameter is small,

![Figure 4. Velocity vs. Perf Diameter (No In-depth Burn)](image-url)
about 1-2 cm. The smaller local maxima in velocity, seen for larger perforation diameters, occurs because of the constraint of having only one grain. With only one grain with a constant outer diameter, for a large perforation, the grain acts like a single-perforated monolithic stick configuration. With a large perforation diameter the progressivity is small, with the optimal velocity occurring for grains which burn out before muzzle exit. For small perforations, the surface area near maximum breech pressure increases nearly as fast as the volume is increasing, resulting in the pressure being near maximum breech pressure before and up to burnout.

Figure 5 is the same plot as Figure 4 of velocity versus perforation diameter with the in-depth burning depth (D) being 1.5 cm and the surface area per unit volume (M) being 50 m²/m³. The general shape and magnitude of the curves are about the same.

Table 5. Velocities and Burnout Conditions - Small Gun

<table>
<thead>
<tr>
<th>Surface Volume Multiplier - M</th>
<th>1</th>
<th>5</th>
<th>50</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-depth Burning Depth (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1713</td>
<td>1</td>
<td>1713</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1713</td>
<td>1</td>
<td>1713</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1713</td>
<td>1</td>
<td>1713</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>1712</td>
<td>1</td>
<td>1711</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>1712</td>
<td>1</td>
<td>1707</td>
<td>1</td>
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<tr>
<td>30</td>
<td>1708</td>
<td>1</td>
<td>1653</td>
<td>1</td>
</tr>
<tr>
<td>45</td>
<td>1686</td>
<td>1</td>
<td>1472</td>
<td>0.81</td>
</tr>
<tr>
<td>85</td>
<td>1648</td>
<td>1</td>
<td>1282</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Fraction Burned = fraction propellant burned at projectile exit
Cases where fraction is less than one are highlighted
Optimized velocity for a seven perforation granular charge using IBROA = 1531 m/s

Table 6. Velocities and Burnout Conditions - Large Gun

<table>
<thead>
<tr>
<th>Surface Volume Multiplier - M</th>
<th>1</th>
<th>5</th>
<th>50</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-depth Burning Depth (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1185</td>
<td>1</td>
<td>1185</td>
<td>1</td>
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<tr>
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<td>1</td>
<td>1088</td>
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<tr>
<td>85</td>
<td>1183</td>
<td>1</td>
<td>857</td>
<td>0.36</td>
</tr>
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Fraction Burned = fraction propellant burned at projectile exit
Cases where fraction is less than one are highlighted
Optimized velocity for a seven perforation granular charge using IBROA = 1074 m/s
The effects of in-depth burning on near-optimal grain configurations (2-cm initial perforation diameter) for the same maximum pressure are given in Tables 5 and 6. The calculations were performed by varying the burning rate to get a specified maximum breech pressure. It is seen that for small values of surface area per unit volume ($M$) that the velocity drops only a few percent with even large changes in the in-depth burning depth. For larger values of surface area per unit volume ($M$) the velocity still does not drop very much until all of the propellant does not bum up completely, as evidenced by the mass fraction burned at projectile exit being less than one.

<table>
<thead>
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<th>Indepth Burning Depth (m)</th>
<th>Surface Volume Multiplier</th>
<th>Pressure (Mpa)</th>
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<tr>
<td></td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>0.0</td>
<td>517</td>
<td>517</td>
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<tr>
<td>0.001</td>
<td>522</td>
<td>545</td>
</tr>
<tr>
<td>0.005</td>
<td>549</td>
<td>742</td>
</tr>
<tr>
<td>0.015</td>
<td>664</td>
<td>2359</td>
</tr>
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</table>

The effects of in-depth burning occurring for a designed grain with no expected in-depth burning (the burning rate of the propellent remains the same) are given in Table 7. There is a large effect on the maximum pressure for small increases in surface area in the in-depth burning volume.

The missing data in Table 7 are from cases when the pressure exceeded the limits of the equation of state.

IV. DISCUSSION

The incorporation of an in-depth burning model into the lumped parameter interior ballistic computer code was done such that the effective in-depth burning depth ($D$) could be varied as well as the surface area per unit volume ($M$). A time and a threshold pressure condition was also imposed, both of which must be exceeded, before in-depth burning commences. Also the burning rate for the in-depth burning volume may be different from the burning rate before in-depth burning starts. In all simulations reported, in-depth burning started at time zero and atmospheric pressure. During any single simulation, a constant effective in-depth burning depth and a constant surface area per unit volume were used. The burning rate for the surface in the in-depth burning volume ($S_v$) was the same as that before in-depth burning started. It is believed that this model, with the proper in-depth burning characteristics, will simulate, at least in direction and relative magnitude, most situations in which in-depth burning may occur (e.g., porous burning, rough burning surfaces, crack formation, and grain breakup).

The purpose of the calculations is to assess the geometric consequences of in-depth burning for a single-perforated outside- and end-inhibited monolithic grain. The calculations indicate that there are two major effects, assuming that the burning rate of the propellant can be adjusted to achieve a desired maximum breech pressure. These effects
are due to the decrease of the in-depth burning volume after its intersection with the outside of the grain and effects due to the grain's not burning out. If the burning rate is kept the same and in-depth burning occurs, then for a small increase in surface in the in-depth volume ($S_v$), there is a large increase in maximum breech pressure.

The interest in a large single-perforated monolithic grain which burns only on the perforation is evident when we compare the increase in velocity over that of an optimized 7-perforated granular charge. For the small gun system the velocity increase is from 1531 m/s to 1713 m/s, an increase of 11.9 percent, and for the large gun system the velocity increases from 1074 m/s to 1185 m/s, an increase of 10.3%. This large increase in velocity requires that the burning rate of the monolithic grain be two orders of magnitude larger (because of the small surface area of the grain) than the burning rate for normal propellant. This large burning rate induces a large sensitivity to small increases in burning surface area as can be seen in Table 5. This results in large increase in maximum breech pressure for small increases in the in-depth burning surface.

The effects of the in-depth volume's intersecting the outer surface of the grain and then the in-depth volume's decreasing along with its surface area (as long as burnout still occurs) result in a velocity decrease on the order of 4 percent. Even with this decrease, there would still be an increase in velocity over a standard 7-perforated granular charge.

A major drop in velocity is seen to occur (Tables 5 & 6) when the charge does not burn out completely. Burnout of the propellant does not occur because the burning rate must be lowered (to stay below a given maximum breech pressure) as surface area is increased in the in-depth burning volume. With this decreased burning rate, and for large in-depth burning depths, the surface area decreases after intersection with the outer diameter leading to lower mass generation. This effect is similar to the slivering event in multi-perforated granular propellant.

All of these effects from in-depth burning would suggest that the use of one large single-perforated outside- and end-inhibited monolithic grain would be viable even if in-depth burning occurs, if the burning rate can be controlled and the amount (if any) of in-depth burning is reproducible and definable.

V. CONCLUSIONS

There are three major consequences if in-depth burning is occurring in a large mono-perforated outside- and end-inhibited grain

- If the grain is properly designed, then little degradation in performance accompanies in-depth burning.
• For efficient grain design, the amount of in-depth burning must be small enough that grain burnout occurs.

• If the grain is designed for a given burning rate and more in-depth burning occurs than is designed for, then much larger than expected maximum breech pressures are probable.

A simple versatile model for in-depth burning has been incorporated into a standard lumped parameter interior ballistic code.
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ACKNOWLEDGMENTS

The authors wish to thank Mr. A.W. Horst, Dr. K. White, Dr. A. A. Juhasz, Dr. T. C. Minor, and Mr. R. Deas for helpful discussions and technical insight. We also wish to thank Mr. T. Raab and Ms. K. Cieslewicz for performing many computer runs and code modifications. Ms. K. E. Meyers is acknowledged for the preparation and editing of the technical drawings and manuscript.

REFERENCES


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program ibrqml
character bdfile*10,outfil*10
dimension br(10),trav(10),rp(10),tr(10),forcp(10),tempp(10),covp(10),
&grainn(10)
dimension chwp(10),rhop(10),gamap(10),nperfs(10),glenp(10),pdpi(10)
&dp(10),gdiap(10),dbpcp(10),alpha(10,10),beta(10,10),
&pres(10,10),tbo(10)
dimension a(4),b(4),ak(4),d(20),y(20),p(20),z(20),frac(10),surf(10)
&nbr(10),ibo(10),ipdb(10)
dimension nbrn(10)
&betan(10,10),alphan(10,10),presn(10,10),idbs(10),td(10),pdb(10),
&dpen(10),smult(10)
real lambda,jlzp,j2zp,j3zp,j4zp
dimension chdist(5),chdiam(5),bint(4)
data idbs/0,0,0,0,0,0,0,0,0,0/
call gettim(ihr,imin,isec,ihuns)
pi=3.141592654
write(*,15)
15   format(' input name of data file to be used as input ')
read(*,10)bdfile
10   format(al0)
onopen(unit=2,err=999,filesbdfile,status='old',iostat=ios)
write(*,25)
25   format(' input name of output file ')
read(*,10)outfil
open(unit=3,err=998,file=outfil,status='new')
write(3,2)bdfile
cformat(1x,' USING INPUT FILE ',a10)
read(2,*,end=20,err=30)cham,grve,aland,glr,twst,travp,igrad
if(igrad.gt.1)go to 51
write(3,55)
55   format(Ix,'using Lagrange pressure gradient')
go to 52
cdefine chambrage assumes nchpts=number of points to define
cchamber > or = 2 < or = 5 (?),chdiam(I) defines chamber diameter
cat chdist (I) chamber distance. chdiam(nchpts) is assumed to be
cthe bore diameter and chdist(1) is assumed to be 0, i.e. at the
cbreech. Assumes truncated cones.
write(3,47,err=30)
47   format(Ix,'Using chambrage pressure gradient')
read(2,*,end=20,err=30)nchpts,(chdist(I),chdiam(I),I=1,nchpts)
write(3,53,err=30)(chdist(I),chdiam(I),I=1,nchpts)
format(///,' chamber distance cm chamber diameter cm',/(5x,e14
&.6,5x,e14.6))
do 54  I=1,nchpts
chdist(I)=0.01*chdist(I)
54   chdiam(I)=0.01*chdiam(I)
calculate chamber integrals and volume
if(nchpts.gt.5) write(3,44,err=30)
44   format(1x,'use first 5 points')
if(nchpts.gt.5)nchpts=5
bore=chdiam(nchpts)
if(chdist(1).ne.0.0)write(3,45,err=30)
45   format(1x,' # points ? ')
chdist(1)=0.0
pi3=pi/3.0
b1=0.0
b2=0.0
b3=0.0
A-3
b4=0.0  
points=25.0  
56 points=points+points  
step=chdist(nchpts)/points  
zz=0.0  
bint(1)=0.0  
bint(3)=0.0  
bint(4)=0.0  
bvol=0.0  
r2=0.5*chdiam(1)  
k=1  
j=int(points+0.5)  
do 57 I=1,j  
zz=zz+step  
if(k.eq.nchpts-1)go to 46  
do 58 II=k,nchpts-1  
if(zz.gt.chdist(II).and. zz.lt.chdist(II+1))go to 59  
58 continue  
II=nchpts-1  
59 k=II  
46 diam=(zz-chdist(k))/(chdist(k+1)-chdist(k))  
diam=chdiam(k)+diam*(chdiam(k+1)-chdiam(k))  
rl=0.5*diam  
area=pi*(r1+r2)*(rl+r2)/4.  
bvol=bvol+step*pi3*(rl*rl+r1*r2+r2*r2)  
bint(1)=bint(1)+step*bvol/area  
bint(3)=bint(3)+step*area*bint(1)  
bint(4)=bint(4)+step*bvol*bvol/area  
57 r2=rl  
temp=abs(1.0-b1/bint(1))  
if(abs(1.0-b3/bint(3)).gt.temp)temp=abs(1.0-b3/bint(3))  
if(abs(1.0-b4/bint(4)).gt.temp)temp=abs(1.0-b4/bint(4))  
if(temp.le.0.001)go to 41  
b1=bint(1)  
b3=bint(3)  
b4=bint(4)  
      go to 56  
41 cham=bvol*1.e6  
c write(3,47,err=30)bint(1),bint(3),bint(4)  
c format(1x,'bint 1 = ',e14.6,' bint 3 = ',e14.6,' bint 4 = ',e14.6)  
c &6)  
chmlen=chdist(nchpts)  
52 write(3,40,err=30)cham,grve,aland,glr,twst,travp  
40 format(1x,'chamber volume cm**3',e14.6,' groove diam cm',e14.6,/  
&' land diam cm',e14.6,/ ' groove/land ratio',e14.6,/ ' twist turns  
&/caliber ',e14.6,/ projectile travel cm',e14.6///)  
cham=cham*1.e-6  
grve=grve*1.e-2  
aland=aland*1.e-2  
twst=twst*1.e-2  
read(2,*,end=20,err=30)prwt,iair,htfr,pgas  
write(3,50,err=30)prwt,iair,htfr,pgas  
50 format(1x,'projectile mass kg',e14.6,'/ switch to calculate energ  
&y lost to air resistance J',i2,'/ fraction of work against bore u  
&sed to heat the tube',e14.6/1x,' gas pressure Pa',e14.6)  
read(2,*,end=20,err=30)npts,(br(i),trav(i),i=1,npts)  
write(3,60,err=30)npts,(br(i),trav(i),i=1,npts)  
60 format(1x,'number barrel resistance points',i2,'/ bore resistance  
& MPa - travel cm'/(1x,e14.6,e14.6))
write(3,65)
do 62 i=1,npts
br(i)=br(i)*1.e6
trav(i)=trav(i)*1.e-2
continue
65 format(1x)
read(2,*,end=20,err=30)rcwt,nrp,(rp(i),tr(i),i=1,nrp)
write(3,70,err=30)rcwt,nrp,(rp(i),tr(i),i=1,nrp)
70 format(1x,' mass of recoiling parts kg','e14.6,'/ number of recoi
&1 point pairs',i2,' recoil force N','e14.6,'/ recoil time sec'/,(1x,e14 &.6,3x,e14.6))
write(3,65)
read(2,*,end=20,err=30)ho,tshl,cshl,thw1,thw2,rcuentes
write(3,75,err=30)ho,tshl,cshl,thw1,thw2,rcuentes
75 format(1x,' free convective heat transfer coefficient w/cm**2 k', &e14.6,/ chamber wall thickness cm','e14.6,/ heat capacity of st &eel of chamber wall j/g k','e14.6,/ initial temperature of chamb &r wall k','e14.6,/ heat loss coefficient','e14.6,/ density of ch &amber wall steel g/cm**3','e14.6//)
ho=ho/1.e-4
tshl=tshl*1.e-2
cshl=cshl*1.e+3
rcuentes=rcuentes*1.e-3/1.e-6
read(2,*,end=20,err=30)forcig,covigen,thw1,thw2,rcuentes
write(3,85,err=30)forcig,covigen,thw1,thw2,rcuentes
85 format(1x,' impetus of igniter propellent J/g','e14.6,/ c &ovolume & of igniter cm**3/g','e14.6,/ adiabatic flame temperature of igni &ter propellent K','e14.6,/ initial mass of igniter kg','e14.6,/ r &atio of specific heats for igniter','e14.6//)
forcig=forcig*1.e+3
covigen=covigen*1.e-6/1.e-3
read(2,*,end=20,err=30)nprop
tmpi=0.0
do 99 i=1,nprop
read(2,*,end=20,err=30)idbs(i),forcp(i),tempf(i),cwpf(i), &rhop(i),gamap(i),nperfs(i),glenp(i),pdp(i),pdpo(i),gdiap(i),dbpc &p(i),ingc
write(3,95,err=30)i,forcp(i),tempf(i),cwpf(i), &rhop(i),gamap(i),nperfs(i),glenp(i),pdp(i),pdpo(i),gdiap(i),dbpc &p(i)
95 format(' for propellant number ',i2,' impetus of propellent J/g &','e14.6,/ adiabatic temperature of propellent K','e14.6,/ c &ovolume of propellant cm**3/g','e14.6,/ initial mass of propellant kg &','e14.6,/ density of propellant g/cm**3','e14.6,/ ratio of specifi &c heats for propellant','e14.6,/ number of perforations of propell &ant',i2,' length of propellant grain cm','e14.6,/ diameter of inn &er perforation in propellant grains cm','e14.6,/ diameter of outer &perforation of propellant grains cm','e14.6,/ outside diameter of &propellant grain cm','e14.6,/ distance between perf centers cm','e1 &4.6//)
if(INGC.ne.1)go to 191
if(nperfs(i).ne.-1)go to 191
chwp(i)=pi*(gdiap(i)**2-pdpo(i)**2)/4.0*glenp(i)*rhop(i)/1000.
write(3,192)chwp(i)
192 format(1x,'propellant wt changed to ',e14.6,' kg')
191 if(idbs(i).eq.0)go to 96
read(2,*,end=20,err=30)td(i),pdb(i),dpen(i),smult(i)
write(3,98,err=30)td(i),pdb(i),dpen(i),smult(i)
98 format(' IN DEPTH BURNING WILL OCCUR WHEN TIME IS GREATER THAN ',e &14.6,' MSEC/' AND PRESSURE IS GREATER THAN ',E14.6,'MPA/' INITI
&AL DEPTH BURNT PENETRATION mm ,e14.6,/ AND INITIAL SURFACE AREA/
&UNIT VOLUME m**2/m**3 ,e14.6,/)

forcp(i)=forcp(i)*1.e+3
covp(i)=covp(i)*1.e-6/1.e-3
rhop(i)=rhop(i)*1.e-3/1.e-6
td(i)=td(i)*0.001
pdb(i)=pdb(i)*1.e6
dpen(i)=dpen(i)*0.001
glenp(i)=glenp(i)*0.01
pdpi(i)=pdpi(i)*0.01
pdpo(i)=pdpo(i)*0.01
gdiap(i)=gdiap(i)*0.01
dbcp(i)=dbcp(i)*0.01
tmpi=tmpi+chwp(i)

if(nperfs(i).eq.-1)go to 91
if(nperfs(i).eq.-1) go to 92
call prf017(pdpo(i),pdpi(i),gdiap(i),dbcp(i),glenp(i),
& surf(i),frac(i),0.0,nperfs(i) ,u)
go to 93

91 call mono(pdpo(i),gdiap(i),glenp(i),surf(i),frac(i),0.0,u)
go to 93

92 call cig(gdiap(i),glenp(i),surf(i),frac(i),0.0,u)

93 grainn(i)=chwp(i)/(rhop(i)*u)
write(3,94,err*30)l,grainn(i)

94 format(' the calculated number of grains for propellant ',i2,
& ' is ',e14.6)

99 continue
tmpi=tmpi+chwi
do 97 j=1,nprop
read(2,*,end=20,err=30)nbr(j),(alpha(j,i),beta(j,i),pres(j,i).
& i=1,nbr(j))
write(3,110,err=30)j,nbr(j),(alpha(j,i),beta(j,i),pres(j,i) ,t=1,
& nbr(j))

110 format(1x,' for propellant ',i2,' the number of burning rate point
&s is ',i2/3x,' exponent',8x,' coefficient',10x,' pressure'/5x,'-
&.15x,'cm/sec-mpa**a','10x,'mpa',/(1x,e14.6,5x,e14.6,15x,e14.6))
if(idbs(j).eq.0)go to 111
read(2,*,end=20,err=30)nbrn(j),(alphan(j,i),betan(j,i),presn(j,i),
& i=1,nbrn(j))
write(3,116,err=30)nbrn(j),(alphan(j,i),betan(j,i),presn(j,i) ,t=1,
& nbrn(j))

116 format(' THE INTERIOR BURNING SURFACE FOR IN-DEPTH BURNING WILL RE
&GRESS ACCORDING TO '/' number of burning rate points',i2/3x,' expo
&nent',8x,' coefficient',10x,' pressure'/5x,'-',15x,'cm/sec-mpa**a
&i',10x,'mpa',/(1x,e14.6,5x,e14.6,15x,e14.6))

111 do 112 i=1,nbr(j)
beta(j,i)=beta(j,i)*1.e-2
betan(j,i)=betan(j,i)*1.e-2
pres(j,i)=pres(j,i)*1.e6
presn(j,i)=presn(j,i)*1.e6

112 continue

97 continue
write(3,65)
read(2,*,end=20,err=30)deltat,deltap,tstop
write(3,120,err=30)deltat,deltap,tstop

120 format(1x,'time increment msec',e14.6,' print increment msec',e14.
&.6/1x,'time to stop calculation msec ',e14.6)
write(*,130)
deltat=deltat*0.001
deltap=deltap*0.001
tstop=tstop*.001

130 format(1x,'normal end')
if(igrad.gt.1)go to 131
bore=(glr*grve*grve+aland*aland)/(glr+1.)
bore=sqrt(bore)

131 areab=pi*bore*bore/4.
lambda=1.>((13.2+4.*log10(100.*bore))**2)
pmaxm=0.0
pmaxbr=0.0
pmaxba=0.0
tpmaxm=0.0
tpmaxbr=0.0
tpmaxba=0.0
tpmax=0.0
a(1)=0.5
a(2)=1.-sqrt(2.)/2.
a(3)=1.+sqrt(2.)/2.
a(4)=1./6.
b(1)=2.
b(2)=1.
b(3)=1.
b(4)=2.
ak(1)=0.5
ak(2)=a(2)
ak(3)=a(3)
ak(4)=0.5
vp0=0.0
tr0=0.0
tcw=0.0
ipdbm=0
ipdbc=0
do 5 i=1,nprop
ipdb(i)=0
ibo(i)=0
tbo(i)=0
5 vp0=chwp(i)/rhop(i)+vp0
volgi=cham-vp0-chwi*covi
pmean=forcig*chwi/volgi
volg=volgi
volg=volgi+vp0
wallt=twal
ptime=0.0
ibrp=8
IMF=IBRP+NPROP
z(3)=1.
y(3)=0.
ngrain=0.
nde=ibrp+nprop+NPROP
write(3,132)areab,pmean,vp0,volgi
132 format(1x,'area bore m^2 ',e16.6,/
&'pressure from ign pa',e16.6,/
&'volume of unburnt prop m^3 ',e16.6,/'init cham vol-cov ign m
&'3 ',e16.6)
write(3,6)
6 format(1x,'time     acc     vel     dis     mpress
&   pbase       pbrch')
iswl=0
continue
do 11 J=1,4
c FIND BARREL RESISTANCE
do 201 k=2,npts
if(y(2)+y(7).ge.trav(k))go to 201
  go to 203
201  continue
  k=npts
203  resp=(trav(k)-y(2)-y(7))/(trav(k)-trav(k-1))
  resp=br(k)-resp*(br(k)-br(k-1))
  c  FIND MASS FRACTION BURNING RATE
  do 211 k=1,nprop
    if(ibo(k).eq.1)goto211
    if(nperfs(k).eq.-1)go to 71
    if(nperfs(k).eq.-11)go to 72
    go to 73
71    continue
    if(idbs(k).eq.0)go to 74
    if(td(k).gt.t) go to 74
    if(ipdb(k).eq.1) go to 76
    if(pdb(k).gt.pmean)go to 74
    ipdb(k)=1
76    pddb=sqrt(gdiap(k)**2-4.*(chwp(k)-y(imf+k))/rhop(k)/grainn(k)/pi/ &glenp(k))
    diastb=(pddb-pdpo(k))/2.
    call mono(pdpo(k),gdiap(k),glenp(k),surf(k),frac(k),distsb,u)
    if(dpen(k).gt.(gdiap(k)-pddf)/2.)dpen(k)=(gdiap(k)-pddf)/2.
    sa=(1.0+dpen(k)/pddf)
    surf=surf(k)*sa*dpen(k)*smult(k)+ & surf(k)
    z(imf+k)=grainn(k)*rhop(k)*surf+surfz(ibrp+k)
    write(3,204)pddb,distsb,dpen(k),surf,k,sa
    c204 format(x,' perf diameter during in-depth burning',el4.6 /' distan
    c &ce burnt into grain perf ',el4.6/' depth of penetration',el4.6,' t
    c total surface',el4.6/' surface of perf',el4.6,' surface multiplier'
    c &el4.6)
    if(surf(k).gt.1.e-10) go to 211
    ibo(k)=1
    tbo(k)=y(3)
    go to 211
74    call mono(pdpo(k),gdiap(k),glenp(k),surf(k),frac(k),y(ibrp+k),u)
    z(imf+k)=grainn(k)*rhop(k)*surf+surfz(ibrp+k)
    write(3,204)pddb,distsb,dpen(k),surf,k,sa
    if(surf(k).gt.1.e-10) go to 211
    ibo(k)=1
    tbo(k)=y(3)
    go to 211
72    continue
    if(idbs(k).eq.0)go to 77
    if(td(k).lt.y(3)) go to 77
    if(ipdb(k).eq.1) go to 78
    if(pdb(k).lt.pmean)go to 77
    ipdb(k)=1
78    dblnth=(chwp(k)-y(imf+k))*4./gdiap(k)/gdiap(k)/pi/rhop(k)
    distsb= glnep(k)-dblnth
    call cig(gdiap(k),glenp(k),surf(k),frac(k),distsb,u)
    if(dpen(k).gt. bdlnth) dpen(k)=bdlnth
    surf=surf(k)*dpen(k)*smult(k)+ & surf(k)
    z(imf+k)=grainn(k)*rhop(k)*surf+surfz(ibrp+k)
    if(surf(k).gt.1.e-10) go to 211
    ibo(k)=1
    tbo(k)=y(3)
    go to 211
A-8
call cig(gdiap(k),glenp(k),surf(k),frac(k),y(ibrp+k),u)
  z(imf+k)=grainn(k)*rhop(k)*surf(k)*z(ibrp+k)
if(surf(k).lt.1.e-10) ibo(k)=1
  go to 211

    call prfo17(pdpo(k),pdpi(k),gdiap(k),dbpcp(k),glenp(k),surf(k),frac(k),y(ibrp+k),nperfs(k),u)
  z(IMF+K)=GRAINN(K)*RHOP(K)*SURF(K)*Z(IBRP+K)
if(surf(k).gt.1.e-10) go to 211
  ibo(k)=1
tbo(k)=y(3)
211  continue

  c ENERGY LOSS TO PROJECTILE TRANSLATION
  elpt=prwt*y(1)*y(1)/2.
  c ENERGY LOSS DUE TO PROJECTILE ROTATION
  elpr=pi*pi*prwt*y(1)*y(1)/4.*twst*twst
  c ENERGY LOSS DUE TO GAS AND PROPELLANT MOTION
if(igrad.le.1)go to 214
pt=y(2)+y(7)
vzp=bvol+areab*pi
j4zp=biint(4)+((bvol+areab*pi)**3-bvol**3)/3./areab/areab
elgpm=tmpi*y(1)*y(1)*areab*areab*j4zp/2./vzp/vzp/vzp
go to 216
214  elgpm=tmpi*y(1)*y(1)/6.
  c ENERGY LOSS FROM BORE RESISTANCE
216  elbr=y(4)
  c ENERGY LOSS DUE TO RECOIL
  elrc=rcwt*y(6)*y(6)/2.
  c ENERGY LOSS DUE TO HEAT LOSS
  areaw=cham/areab*pi*bore+2.*areab+pi*bore*(y(2)+y(7))
  avden=0.0
  avc=0.0
  avcp=0.0
  z18=0
  z19=0
do 213 k=1,nprop
  z18=forcp(k)*gamap(k)*(Y(IMF+K)/(gamap(k)-1.))/temp(k)+z18
  z19=Y(IMF+K)+z19
  avden=avden+Y(IMF+K)
213  continue
  avcp=(z18+forcig*gamai*chi/(gamai-1.))/tempi)/(z19+chwi)
  avden=(avden+chwi)/(volg+covl)
  avvel=.5*y(1)
  htns=lambda*avcp*avden*avvel+ho
  z(5)=areaw*htns*(tgas-wallt)*hl
  elht=y(5)
  wallt=(elht+htfr*elbr)/cshl/rhocs/areaw/tshl+twal
  c write(3,*)lambda,avcp,avden,avvel,ho,areaw,htns,tgas,wallt,hl,z(5)
  c &elht
  c ENERGY LOSS DUE TO AIR RESISTANCE
  a=r=iair
  z(8)=y(1)*pgas*air
  elar=areab*y(8)
  c RECOIL
  z(6)=0.0
if(pbrch.le.rp(1)/areab)go to 221
rfor=rp(2)
if(y(3)-tr0.ge.tr(2))go to 222
rfor=(tr(2)-(y(3)-tr0))/(tr(2)-tr(1))
rfor=rp(2)-rfor*(rp(2)-rp(1))
222 \( z(6) = \text{areab}/\text{rcwt} \times (\text{pbrch} - \text{rfor}/\text{areab} - \text{resp}) \).  
\( \text{if} (y(6) \leq 0.0) y(6) = 0.0 \)  
\( z(7) = y(6) \)  
goto 223  
221 \( \text{tr0} = y(3) \)  
223 continue  
c CALCULATE GAS TEMPERATURE  
eprop = 0.0  
rprop = 0.0  
do 231 k=1,nprop  
eprop = eprop + forcp(k) \times Y(IMF+K)/(\text{gamap}(k) - 1.)  
rprop = rprop + forcp(k) \times Y(IMF+K)/(\text{gamap}(k) - 1.)/\text{temp}(k)  
continue  
tenergy = elpt + elpr + elgpm + elbr + elrc + elbt + elar  
tgas = (eprop + forcp*chwi/(\text{gamai} - 1.) - elpt - elpr - elgpm - elbr - elrc - elbt & - elar)/(rprop + forcp*chwi/(\text{gamai} - 1.)/\text{temp}(k))  
c FIND FREE VOLUME  
v1 = 0.0  
cov1 = 0.0  
do 241 k=1,nprop  
v1 = (\text{CHWP}(K) - Y(IMF+K))/\text{RHOP}(K) + V1  
cov1 = cov1 + covp(k)*Y(IMF+K)  
continue  
fwrl = volgi + areab* \( (y(2) + y(7)) - v1 \)  
if (cov1 \leq fwrl) goto 194  
write(3,193)  
193 format(Ix,'\text{mass prop*covolume gt free volume}')  
stop  
194 volg = volgi + areab* \( (y(2) + y(7)) - v1 - cov1 \)  
c CALCULATE MEAN PRESSURE  
r1 = 0.0  
do 251 k=1,nprop  
r1 = r1 + forcp(k) \times Y(IMF+K)/\text{temp}(k)  
continue  
pmean = tgas/volg*(r1 + forcp*chwi/\text{temp}(k))  
resp = resp + pgas*air  
if (igrad \leq 1.0) goto 252  
if (iswl \neq 0.0) goto 253  
pbase = pmean  
pbrch = pmean  
if (pbase \lt \text{resp} + 1.) iswl = 1  
go to 257  
c USE CHAMBRAGE PRESSURE GRADIENT EQUATION  
j1zp = bint(1) + (bvol*pt + areab/2.*pt*pt)/areab  
j2zp = (bvol + areab*pt)**2/areab/areab  
j3zp = bint(3) + areab*bint(1)*pt + bvolf+pt*pt/2. + areab*pt*pt/6.  
a2t = -tmpi*areab*areab/\text{prwt}/vzp/vzp  
alf = 1. - a2t*j1zp  
alt = tmpi*areab* \( (areab*y(1)*y(1)/vzp + areab*resp/\text{prwt})/vzp/vzp \)  
bt = tmpi*y(1)*y(1)/vzp*areab/2./vzp/vzp/vzp  
bata = alt*j1zp - bt*j2zp  
gamma = alf + a2t*j3zp/vzp  
delta = bata + alf*j3zp/vzp + bt*j4zp/vzp  
c calculate base pressure  
pbase = (pmean - delta)/gamma  
c calculate breech pressure  
pbrch = alf*pbase + bata  
go to 254  
c USE LAGRANGE PRESSURE GRADIENT EQUATION  
252 if (iswl \neq 0.0) goto 256
if (pmean .lt. resp) resp = pmean

C CALCULATE BASE PRESSURE
256 pbase = (pmean + tmpi * resp / 3. / prwt) / (1. + tmpi / 3. / prwt)
if (pbase .gt. resp + 1.) iswl = 1

C CALCULATE BREECH PRESSURE
pbrch = pbase + tmpi / 2. / prwt * (pbase - resp)

C CALCULATE PROJECTILE ACCELERATION
254 z(1) = areab * (pbase - resp) / prwt
if (z(1) .lt. 0.0) go to 257
257 go to 258
if (iswl .eq. 0) z(1) = 0.0
258 if (y(1) .lt. 0.0) y(1) = 0.0
z(2) = y(1)

C GET BURNING RATE
do 254 m = 1, nprop
z(ibrp + m) = 0.0
if (ibo(m) .eq. 1) go to 254
if (ipdb(m) .eq. 1) go to 256
262 continue
k = nbr(m)
263 z(ibrp + m) = beta(m, k) * (pmean * 1.e-6) ** alpha(m, k)
go to 264
266 do 257 k = 1, nbr(m)
if (pmean .gt. pres(m, k)) go to 267
267 continue
k = nbr(m)
268 z(ibrp + m) = beta(m, k) * (pmean * 1.e-6) ** alphan(m, k)
264 continue
do 21 i = 1, npe
d(i) = (z(i) - b(j) * p(i)) * a(j)
y(i) = deltat * d(i) + y(i)
p(i) = 3. * d(i) - ak(j) * z(i) + p(i)
21 continue
11 continue
t = t + deltat
if (pmaxm .gt. pmean) go to 281
pmaxm = pmean
tpmaxm = y(3)
281 if (pmaxba .gt. pbase) go to 282
pmaxba = pbase
tpmaxba = y(3)
282 if (pmaxbr .gt. pbrch) go to 283
pmaxbr = pbrch
tpmaxbr = y(3)
283 continue
if (y(3) .lt. ptime) go to 272
ptime = ptime + deltapt
write (3, 7) y(3), y(1), y(2), pmean, pbase, pbrch
7 format (lx, 7ell. 4)
316 format (lx)
272 continue
if (t .gt. tstop) go to 200
if (y(2) .gt. travp) go to 200
rmvelo = y(1)
tmvelo = y(3)
disto = y(2)
go to 19
200 write(3,311)t,y(3)
311 format(1x,' deltat t', el4.6, ' intg t',el4.6)
write(3,312) pmaxm, tpmxmxm
312 format(1x,' pmaxm Pa ',el4.6, ' time at pmaxm sec ',el4.6)
write(3,313) pmaxba, tpmxmba
313 format(1x,' pmaxba Pa ',el4.6, ' time at pmaxba sec ',el4.6)
write(3,314) pmaxbr, tpmxbr
314 format(1x,' pmaxbr Pa ',el4.6, ' time at pmaxbr sec ',el4.6)
if(y(2).le.travp) go to 303
dfract=(travp-dist0)/(y(2)-dist0)
rmvel=(y(1)-rmvelo)*dfract+rmvelo
tmvel=(y(3)-tmvelo)*dfract+tmvelo
write(3,318) rmvel, tmvel
318 format(1x,' muzzle velocity m/s ',el4.6, ' time of muzzle velocity s &sec ',el4.6)
goto 319
303 write(3,327)y(1),y(3)
goto 319
327 format(1x,' velocity of projectile m/s ',el4.6, ' at this time msec & ',el4.6)
319 efi=chwi*forcig/(gamai-1.)
efp=0.0
do 315 i=1,nprop
efp=efp+chwp(i)*forcp(i)/(gamap(i)-1.0)
315 continue
tenerg=efi+efp
write(3,317)tenerg
317 format(1x,' total initial energy available J = ',el4.6)
tengas=chwi*forcig*tgas/(gamai-1.)/tempi
do 135 i=1,nprop
tengas=(y(IMF+I)*forcp(i)*tgas/tempp(i)/(gamap(i)-1.))+teng
&as write(3,137)i,frac(i),tbo(i)
137 format(' FOR PROPELLANT ',I2,' MASS FRAC BURNT IS',el4.6,' AT TIME & ',el4.6)
135 continue
write(3,136)tengas
316 format(1x,' total energy remaining in gas J = ',el4.6)
write(3,320)elpt
320 format(1x,' energy loss from projectile translation J = ',el4.6)
write(3,321)elpr
321 format(1x,' energy loss from projectile rotation J = ',el4.6)
write(3,322)elgpm
322 format(1x,' energy lost to gas and propellant motion J = ',el4.6)
write(3,323)elbr
323 format(1x,' energy lost to bore resistance J = ',el4.6)
write(3,324)elrc
324 format(1x,' energy lost to recoil J = ',el4.6)
write(3,325)elht
325 format(1x,' energy loss from heat transfer J = ',el4.6)
write(3,326)elar
326 format(1x,' energy lost to air resistance J = ',el4.6)
c call gettim(ihro, imino, iseco, ihunso)
c time=(ihro-ihr)*3600.+(imino-imin)*60.+(iseco-isec)+(ihunso-ihuns)
&/100.
c write(3,*) time
stop
20 write(*,140)
140 format(1x,'end of file encounter')
stop
30  write(*,150)
999  continue
998  continue
150  format(1x,'read or write error')
stop
end

SUBROUTINE PRF017(P,P1,D,D1,L,SURF,MASSF,X,NP,u)
IMPLICIT REAL*4(A-Z)

C
C  P=OUTER PERF DIA
C  P1=INNER PERF DIA
C  D=OUTER DIA
C  D1=DISTANCE BETWEEN PERF CENTRES
C  L=GRAIN LENGTH
C  NP=NUMBER OF PERFS
C
C  SURF=OUTPUT SURFACE AREA
C  MASSF=OUTPUT MASS FRACTION OF PROPELLANT BURNER
C
C  W=WEB BETWEEN OUTER PERFS
C  W0=OUTER WEB
C  W1=WEB BETWEEN OUTER AND INNER PERFS
C  W4=MINIMUM WEB
C  U=INITIAL VOLUME OF 1 GRAIN
C
INTEGER ITYM,NP
DATA PI,SQRT3/3.141592654,1.732050808/,
DATA ITYM/0/
DATA HAFPI,PIFOR,TWOPI/1.570796327,.785398164,6.283185308/

C
IF(ITYM.GT.0)GO TO 10
P1SQ=P1*P1
D1SQ=D1*D1
PSQ=P*P
DSQ=D*D
D1SQ3=D1*SQRT3
02SQ3=D1SQ*SQRT3
IF(NP.EQ.0)GO TO 2000
IF(NP.EQ.1)GO TO 3000
IF(NP.NE.7)GO TO 60
IF(P1.GT.(P+D1*(SQRT3-1))) GO TO 60
IF(D.GE.D1*(SQRT3+1.)-P)GO TO 130
60 WRITE(6,90)
90  FORMAT(1X,'UNACCEPTABLE GRANULATION')
STOP
130 W=D1-P
IF(W.LT.0)GO TO 60
W0=(D-P-2.*D1)/2.
IF(W0.LT.0.)GO TO 60
W1=(2.*D1-P-P1)/2.
IF(W1.LT.0.)GO TO 60
X1=(P1SQ-PSQ+4.*D1SQ-2.*P1*D1SQ3)/4./(D1SQ3+P-P1)
X2=(4.*D1SQ+D*D-2.*D*D1SQ3-PSQ)/4.(-D1SQ3+P+D)
A=PI*L*(D+P1+6.*P)+HAFPI*(DSQ-P1SQ-6.*PSQ)
U=PI*L/4.*(DSQ-P1SQ-6.*PSQ)
W4=AMIN1(W,W0,W1)
10 MASSF=0.
TWOX=X+X
XSQ=X*X
PIP2X=P1+TWOX
PP2X=P+TWOX
```
DM2X=D-TWOX
LM2X=L-TWOX
P12XSQ=P1P2X*P1P2X
PP2XSQ=PP2X*PP2X
DM2XSQ=DM2X*DM2X
IF(NP.EQ.0)GO TO 2000
IF(NP.EQ.1)GO TO 3000
IF(LM2X.GT.0)GO TO 340
SURF=0.
V=0.
GO TO 850
340 S0=PI*LM2X*(D+P+12.*X)+HAPPI*(DM2X*DM2X
1-P1P2X*P1P2X-6.*PP2X*PP2X)
V0=PI*FOR*LM2X*(DM2X*DM2X-P1P2X*P1P2X-6.*PP2X*PP2X)
IF(X.GT.W4/2.)GO TO 360
MASSF=-TWOX/L/(DSQ-P1SQ-6.*PSQ)
MASSF=MASSF*(24.*XSQ+(24.*P+4.*P1+4.*D-12.*L)*X+P1SQ
1+6.*PSQ-2.*L*D-2.*P1*L-12.*L*P-DSQ)
SURF=S0
RETURN
360 IF(X.GT.W5/2.)GO TO 390
F2=0.
L2=0.
A3=0.
A4=0.
GO TO 460
390 Z=(2.*D1+P+P1+4.*X)/4.
B3=((P1-P)*(P1+P+4.*X)+4.*D1SQ)/4./D1/P1P2X
A3=ATAN(SQRT(1.-B3*B3)/B3)
B4=((P-P1)*(P+P+4.*X)+4.*D1SQ)/4./D1/PP2X
A4=ATAN(SQRT(1.-B4*B4)/B4)
1-SQRT(Z*(Z-D1)*(2.*Z-P-TW0X)*(2.*Z-P1-TW0X))
L2=LM2X*(A4*PP2X+A3*P1P2X)
460 IF(X.GT.W6/2.)GO TO 490
F3=0.
L3=0.
A5=0.
GO TO 530
490 B5=D1/PP2X
A5=ATAN(SQRT(1.-B5*B5)/B5)
F3=(A5*PP2XSQ-D1*SQRT(PP2XSQ-D1SQ))/2.
L3=2.*A5*LM2X*PP2X
530 IF(X.GT.W7/2.)GO TO 560
F1=0.
L1=0.
A1=0.
A2=0.
GO TO 650
560 Y=(2.*D1+P+D)/4.
B1=((D+P)*(D-P-4.*X)-4.*D1SQ)/4./D1/PP2X
A1=ATAN(SQRT(1.-B1*B1)/B1)
IF(A1.GT.0.)GO TO 610
A1=PI+A1
610 B2=((D+P)*(D-P-4.*X)+4.*D1SQ)/4./D1/DM2X
A2=ATAN(SQRT(1.-B2*B2)/B2)
F1=A1/4.*PP2XSQ-A2/4.*DM2XSQ+SQRT(Y*(Y-D1)
1*(2.*Y-P-TWOX)*(2.*Y-D-TWOX))
L1=LM2X*(A1*PP2X+A2*DM2X)
650 IF(X.GT.W8/2.)GO TO 690
```
SURF=S0+12.*(F1+F2+F3)-6.*(L1+L2+L3)
V=V0+6.*(F1+F2+F3)*LM2X
GO TO 850
690 IF(X.LT.X1)GO TO 730
S1=0.0
V1=0.0
GO TO 760
730 S1=3.*D2SQ3-PI*PP2XSQ-HAFPI*P12XSQ
$ +6.*F3+12.*F2
S1=S1+LM2X*(2.*(PI-3.*A5-3.*A4)*PP2X+(PI-6.*A3)
$ *P1P2X)
V1=LM2X/2.*(3.*D2SQ3-PI*PP2XSQ
$ -HAFPI*P12XSQ+6.*F3+12.*F2)
760 IF(X.LT.X2) GO TO 800
S2=0.0
V2=0.0
GO TO 830
800 S2=HAFPI*DM2XSQ-3.*D2SQ3-TWOPI*PP2XSQ
$ +12.*F1+6.*F3
S2=S2+LM2X*((PI-6.*A2)*DM2X+2.*(TWOPI-3.*A1-3.*A5)
$ *PP2X)
V2=LM2X/2.*(HAFPI*DM2XSQ-3.*D2SQ3-TWOPI
$ *PP2XSQ+12.*F1+6.*F3)
830 SURF=S1+S2
V=V1+V2
850 MASSF=1.-V/U
RETURN
C
C ZERO PERF CALCULATIONS START HERE.
C
2000 if (d-2*x.le.0.0) go to 2001
twox-x+x
xsq=x*x
MASSF=twox*(DSQ+2.*L*D-4.*X*D-TWOX*L+4.*XSQ)/(DSQ*L)
u=dsq*l*pi/4.
SURF=PI*(DSQ/2.-4.*D*X-TWOX*L+D*L+6.*XSQ)
RETURN
2001 surf=0.0
massf=1.0
u=dsq*l*pi/4.
return
C
C ONE PERF CALCULATIONS START HERE.
C
3000 if (d-4.*x.le.0.0) goto 3001
twox=x+x
MASSF=twox*(DSQ+2.*L*D-4.*X*D-PSQ+2.*P*L-4.*P*X)
$ /(DSQ*L-PSQ*L)
u=dsq*l*pi/4.-psq*l*pi/4.
SURF=PI*(DSQ/2.-4.*D*X-4.*X*P+D*L+P*L-PSQ/2.)
RETURN
3001 surf=0.0
massf=1.0
u=dsq*l*pi/4.-psq*l*pi/4.
return
END
SUBROUTINE MONO(PD, GD, GL, SURF, FRAC, X, VOL0)
DATA ITYM/0/, PI/3.141592654/

C PD = PERF DIAMETER

A-15
C GD = GRAIN DIAMETER  
C GL = GRAIN LENGTH  
C SURF = INSTANTANEOUS SURFACE AREA  
C FRAC = MASS FRACTION BURNT  
C VOL = INSTANTANEOUS VOLUME REMAINING  
C X = DEPTH BURNT  
C VOL0 = INITIAL VOLUME  
C ASSUMES END AND LATERAL SURFACES UNLIMITED  
C
VOLO=PI*(GD*GD/4.-PD*PD/4.)*GL
SURF=PI*PD*GL
FRAC=0.0
IF(ITYM.NE.0)GO TO 10
ITYM=1
RETURN
10 IF(X.GE.(GD-PD)/2.)GO TO 20
IF(X.GE.GL/2.)GO TO 20
VOL=PI*(GD*GD/4.-(PD+2.*X)**2/4.)*GL
FRAC=1.-VOL/VOLO
SURF=PI*(PD+2.*X)*GL
RETURN
C BURNOUT
20 FRAC=1.0
SURF=0.0
RETURN
END

C SUBROUTINE CIG(GD,GL,SURF,FRAC,X,VOLO)
DATA ITYM/0/,PI/3.141592654/
C
C GD = GRAIN DIAMETER  
C GL = GRAIN LENGTH  
C SURF = INSTANTANEOUS SURFACE (CONSTANT)  
C VOL = INSTANTANEOUS VOLUME REMAINING  
C FRAC = FRACTION OF PROPELLANT BURNT  
C X = DEPTH BURNT  
C VOL0 = INITIAL VOLUME  
C
C ASSUMES BURNS ON ONE END SURFACE ONLY  
C
VOLO=PI*GD*GD/4.*GL
SURF=PI*GD*GD/4.
FRAC=0.0
IF(ITYM.NE.0)GO TO 10
ITYM=1
RETURN
10 IF(X.GE.GL)GO TO 20
VOL=PI*GD*GD/4.**(GL-X)
FRAC=1.-VOL/VOLO
RETURN
C BURNOUT
20 FRAC=1.0
SURF=0.0
RETURN
END
APPENDIX B
Listing of Input Data
IBM1
INTENTIONALLY LEFT BLANK.
9832.2384  12.7  12.7  1.0  0.0  457.2  1
9.796  0.0  0.0
5  0.0  0.0  0.0  0.6  0.0  1.3  0.0  300.0  0.0  457.
1.e20  2  3.0e+4  0.0  8.0e+5  0.2
.001135  .01143  .46028  273.1  7.8612
84.5535  .9755  294.7  .004712  1.4
1
1  1160.0  3141.1  1.12  11.3557  1.53  1.23  -1  50.0  0.936  15.0  0.1
0.0  .1  7.0
1  1.0  2.69  689.476
1  1.0  2.69  689.476
.005  .05  30.
APPENDIX C
Listing of Output
USING INPUT FILE ibml
using Lagrange pressure gradient
chamber volume cm**3  0.983224E+04
groove diam cm  0.127000E+02
land diam cm  0.127000E+02
groove/land ratio  0.100000E+01
twist turns/caliber  0.000000E+00
projectile travel cm  0.457200E+03

projectile mass kg  0.979600E+01
switch to calculate energy lost to air resistance J 0
fraction of work against bore used to heat the tube  0.000000E+00
gas pressure Pa  0.000000E+00
number barrel resistance points 5
bore resistance MPa - travel cm
0.000000E+00  0.000000E+00
0.000000E+00  0.600000E+00
0.000000E+00  0.130000E+01
0.000000E+00  0.300000E+03
0.000000E+00  0.457000E+03

mass of recoiling parts kg  0.100000E+21
number of recoil point pairs 2
recoil force N  recoil time sec
0.300000E+05  0.000000E+00
0.800000E+06  0.200000E+00

free convective heat transfer coefficient w/cm**2 k  0.113500E-02
chamber wall thickness cm  0.114300E-01
heat capacity of steel of chamber wall j/g k  0.460280E+00
initial temperature of chamber wall k  0.273000E+03
heat loss coefficient  0.100000E+01
density of chamber wall steel g/cm**3  0.786120E+01

impetus of igniter propellent J/g  0.845535E+02
covolume of igniter cm**3/g  0.975500E+00
adiabatic flame temperature of igniter propellent k  0.294000E+03
initial mass of igniter kg  0.471200E-02
ratio of specific heats for igniter  0.140000E+01

for propellant number 1
impetus of propellant J/g  0.116000E+04
adiabatic temperature of propellant K  0.314100E+04
covolume of propellant cm**3/g  0.112000E+01
initial mass of propellant kg  0.113557E+02
density of propellant g/cm**3  0.153000E+01
ratio of specific heats for propellant  0.123000E+01
number of perforations of propellant-1
length of propellant grain cm  0.500000E+02
diameter of inner perforation in propellant grains cm  0.000000E+00
diameter of outer perforation of propellant grains cm  0.936000E+01
outside diameter of propellant grain cm  0.150000E+02
distance between perf centers cm  0.000000E+00
propellant wt changed to 0.825482E+01 kg
IN DEPTH BURNING WILL OCCUR WHEN TIME IS GREATER THAN 0.000000E+00 MSEC
AND PRESSURE IS GREATER THAN 0.100000E+00MPa
INITIAL DEPTH BURN PENETRATION m 0.720000E+01
AND INITIAL SURFACE AREA/UNIT VOLUME m**2/m**3 0.000000E+00

the calculated number of grains for propellant 1 is 0.100000E+01
for propellant 1 the number of burning rate points is 1
exponent 0.100000E+01
coefficient 0.269000E+01
pressure mpa 0.689476E+03

THE INTERIOR BURNING SURFACE FOR IN-DEPTH BURNING WILL REGRESS ACCORDING TO
number of burning rate points 1
exponent 0.100000E+01
coefficient 0.269000E+01
pressure mpa 0.689476E+03

time increment msec 0.500000E+02 print increment msec 0.500000E+01
time to stop calculation msec 0.300000E+02
area bore m^2 0.126677E+01 pressure from ign pa 0.898888E+05
volume of unburnt prop m^3 0.539531E-02 init cham vol-cov ign m^3 0.9

time acc vel dis mpress pbase pbrch
0.5000E-05 0.9194E+01 0.4557E-03 0.1117E-08 0.9108E+05 0.7110E+05 0.1011E+06
0.5500E-04 0.1046E+03 0.5358E-02 0.1438E-06 0.1036E+06 0.8089E+05 0.1150E+06
0.1050E-03 0.1191E+06 0.1094E-01 0.5463E-06 0.1180E+06 0.9209E+05 0.1310E+06
INITIAL DEPTH BURN PENETRATION m 0.720000E+01
0.1205E-03 0.1341E+06 0.1241E+00 0.1047E+06 0.1480E+06
0.1250E-03 0.1341E+06 0.1241E+00 0.1047E+06 0.1480E+06
0.1305E-03 0.1563E+06 0.2451E-01 0.1521E+06 0.1680E+06
0.1500E-03 0.1719E+06 0.3269E-01 0.1723E+06 0.1912E+06
0.1550E-03 0.1966E+06 0.4194E-01 0.1947E+06 0.2161E+06
0.1600E-03 0.2217E+06 0.5323E-01 0.2196E+06 0.2437E+06
0.1650E-03 0.2459E+06 0.6415E-01 0.2471E+06 0.2742E+06
0.1700E-03 0.2801E+06 0.7737E-01 0.2775E+06 0.3079E+06
0.1750E-03 0.3138E+06 0.9221E-01 0.3108E+06 0.3449E+06
0.1550E-03 0.3506E+06 0.1048E+00 0.3474E+06 0.3855E+06
0.6050E-03 0.3909E+06 0.1273E+00 0.3873E+06 0.4298E+06
0.6550E-03 0.4349E+06 0.1480E+00 0.4306E+06 0.4781E+06
0.7050E-03 0.4826E+06 0.1709E+00 0.4781E+06 0.5106E+06
0.7500E-03 0.5344E+06 0.1963E+00 0.5294E+06 0.5578E+06
0.8050E-03 0.5906E+06 0.2244E+00 0.5850E+06 0.6025E+06
0.8500E-03 0.6513E+06 0.2554E+00 0.6452E+06 0.6492E+06
0.9050E-03 0.7168E+06 0.2996E+00 0.7101E+06 0.6719E+06
0.9500E-03 0.7876E+06 0.3427E+00 0.7802E+06 0.6958E+06
0.1005E-02 0.8639E+06 0.3684E+00 0.8558E+06 0.7198E+06
0.1055E-02 0.9462E+06 0.4137E+00 0.9373E+06 0.7447E+06
0.1105E-02 0.1035E+06 0.4632E+00 0.1025E+07 0.8002E+06 0.1138E+07
0.1155E-02 0.1130E+06 0.5173E+00 0.1120E+07 0.8741E+06 0.1243E+07
0.1205E-02 0.1233E+06 0.5763E+00 0.1222E+07 0.9537E+06 0.1356E+07
0.1255E-02 0.1344E+06 0.6407E+00 0.1332E+07 0.1040E+07 0.1478E+07
0.1305E-02 0.1464E+06 0.7109E+00 0.1450E+07 0.1132E+07 0.1609E+07
0.1355E-02 0.1593E+06 0.7873E+00 0.1578E+07 0.1232E+07 0.1751E+07
0.1405E-02 0.1732E+06 0.8703E+00 0.1716E+07 0.1339E+07 0.1904E+07
0.1455E-02 0.1882E+06 0.9606E+00 0.1864E+07 0.1455E+07 0.2069E+07
0.1505E-02 0.2044E+06 0.1059E+01 0.2025E+07 0.1581E+07 0.2247E+07
0.1555E-02 0.2219E+06 0.1165E+01 0.2198E+07 0.1716E+07 0.2439E+07
0.1605E-02 0.2407E+06 0.1281E+01 0.2385E+07 0.1861E+07 0.2646E+07
0.1655E-02 0.2616E+06 0.1406E+01 0.2586E+07 0.2019E+07 0.2870E+07
0.1705E-02 0.2831E+06 0.1542E+01 0.2808E+07 0.2189E+07 0.3112E+07
0.1755E-02 0.3068E+06 0.1690E+01 0.3039E+07 0.2373E+07 0.3373E+07
0.1805E-02 0.3325E+06 0.1849E+01 0.3294E+07 0.2571E+07 0.3655E+07
0.1855E-02 0.3602E+06 0.2022E+01 0.3568E+07 0.2785E+07 0.3960E+07
0.7905E-02 0.2010E+06 0.1356E+04 0.2611E+01 0.1991E+09 0.1554E+09 0.2209E+09
0.7955E-02 0.1947E+06 0.1366E+04 0.2679E+01 0.1929E+09 0.1506E+09 0.2141E+09
0.8005E-02 0.1888E+06 0.1376E+04 0.2748E+01 0.1870E+09 0.1460E+09 0.2075E+09
0.8055E-02 0.1831E+06 0.1385E+04 0.2817E+01 0.1814E+09 0.1416E+09 0.2013E+09
0.8105E-02 0.1777E+06 0.1394E+04 0.2886E+01 0.1761E+09 0.1374E+09 0.1954E+09
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deltat t 0.925000E-02 intg t 0.925000E-02
pmaxm Pa 0.465884E+09 time at pmaxm sec 0.623000E-02
pmaxba Pa 0.163673E+09 time at pmaxba sec 0.623000E-02
pmaxbr Pa 0.516989E+09 time at pmaxbr sec 0.623000E-02
muzzle velocity m/s 0.154614E+04 time of muzzle velocity sec 0.924611E-02
total initial energy available J = 0.416340E+08
FOR PROPELLANT 1 MASS FRAC BURNT IS 0.100000E+01 AT TIME 0.690250E-02
total energy remaining in gas J = 0.253339E+08
energy loss from projectile translation J = 0.117148E+08
energy loss from projectile rotation J = 0.000000E+00
energy lost to gas and propellant motion J = 0.329245E+07
energy lost to bore resistance J = 0.000000E+00
energy lost to recoil J = 0.224172E-11
energy loss from heat transfer J = 0.129901E+07
energy lost to air resistance J = 0.000000E+00

C-7
Intentionally left blank.
IBRGA relies on an input data base consisting of all numerical parameters essential for running the code. All values are in metric units. Below is a compilation of a typical IBRGAM data base showing the name and location of each input parameter. The names for the numerical values are prefixed with an alphabetical designator corresponding to the position at which the data is to appear, that is, from left to right. The data may be separated by blanks or commas. The units are shown to the right of each input.

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<th>H</th>
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**record 1**

A. - chamber volume (cm$^3$)
B. - groove diameter (cm)
C. - land diameter (cm)
D. - groove/land ratio (none)
E. - twist (turns/caliber)
F. - projectile travel (cm)
G. - gradient switch (1 = Lagrange, 2 = chambrage)

**record 1a** (Read only if gradient switch = 2)

A. - number of points to describe chamber (I $\leq$ 10)
B. - initial distance from breech (must be 0.0 cm)
C. - diameter at 0 (cm)

Ith distance from breech (position of base of projectile (cm))
Ith diameter at Ith distance (used to calculate bore area (cm))

**record 2**

A. - projectile mass (kg)
B. - switch to calculate energy lost to air resistance
C. - fraction of work done against bore to heat tube
D. - gas pressure in front of projectile (Pa)

**record 3**

A. - number of barrel resistance points (J $\leq$ 10)
B. - bore resistance (MPa)
C. - travel (cm)

Jth bore resistance (MPa)
Jth travel (cm)

**record 4**

D-3
A. - mass of recoiling parts (kg)
B. - number of recoil point pairs (2)
C. - recoil force (N)
D. - recoil time (s)
E. - recoil force (N)
F. - recoil time (s)

record 5
A. - free convective heat transfer coefficient (W/cm²·K)
B. - chamber wall thickness (cm)
C. - heat capacity of steel of chamber wall (J/g·K)
D. - initial temperature of chamber wall (K)
E. - heat loss coefficient
F. - density of chamber wall steel (g/cm³)

record 6
A. - impetus of igniter propellant (J/g)
B. - covolume of igniter (cm³/g)
C. - adiabatic flame temperature of igniter propellant (K)
D. - initial mass of igniter (kg)
E. - ratio of specific heats for igniter

record 7
A. - number of propellants (K<10)

record 8
A. - switch for in-depth burning (0 none)
B. - impetus of propellant (J/g)
C. - adiabatic temperature of propellant (K)
D. - covolume of propellant (cm³/g)
E. - initial mass of propellant (kg)
F. - density of propellant (g/cm³)
G. - ratio of specific heats for propellant
H. - number of perforations of propellant (may be 0, 1, 7, -1 or -11 only)
   (-1 for single perf outside inhibited grain,
    -11 for cigarette burner)
I. - length of propellant grain (cm)
J. - diameter of inner perforations in propellant grains (cm)
K. - diameter of outer perforations of propellant grains (cm)
   (used for single perforation grain)
L. - outside diameter of propellant grain (cm)
M. - distance between perf centers (cm)
N. - switch to change mass to one single perforated grain (1=yes)

record 8a
( read only if in-depth burning switch is not 0)
A. - time after in-depth burning may start (msec)
B. - pressure which must be exceeded before in-depth burning may start (MPa)
C. - in-depth burning depth (mm)
D. - in-depth burning volume multiplier (m²/m³)
(Kth propellant)
A. - switch for in-depth burning (0 none)
B. - impetus of propellant (J/g)
C. - adiabatic temperature of propellant (K)
D. - covolume of propellant (cm³/g)
E. - initial mass of propellant (kg)
F. - density of propellant (g/cm³)
G. - ratio of specific heats for propellant
H. - number of perforations of propellant (may be 0, 1, 7, -1 or -11 only)
   (-1 for single perf outside inhibited grain,
   -11 for cigarette burner)
I. - length of propellant grain (cm)
J. - diameter of inner perforations in propellant grains (cm)
K. - diameter of outer perforations of propellant grains (cm)
   (used for single perforation grain)
L. - outside diameter of propellant grain (cm)
M. - distance between perf centers (cm)
N. - switch to change mass to one single perforated grain (1=yes)

record 8k (read only if in-depth burning switch is not 0)
A. - time after in-depth burning may start (msec)
B. - pressure which must be exceeded before in-depth burning may start (MPa)
C. - in-depth burning depth (mm)
D. - in-depth burning volume multiplier (m²/m³)

record 9
A. - number of surface burning rate points (J<10) for propellant 1
B. - exponent
C. - coefficient (cm/s MPa^i)
D. - pressure (MPa)

Jth exponent
Jth coefficient
Jth pressure

record 9a (Read only if in-depth burning switch is not 0)
A. number of in-depth burning surface area burning rate points (M<=10) for propellant 1
B. exponent
C. coefficient (cm/s MPa^i)
D. pressure (MPa)

Mth exponent
Mth coefficient
Mth pressure
A. number of surface burning rate points (L<=10) for propellant K
B. exponent
C. coefficient (cm/s MPa^a)
D. pressure (MPa)

Lth exponent
Lth coefficient
Lth pressure

record 9a  (Read only if in-depth burning switch is not 0)
A. number of in-depth burning surface area burning rate points (N<=10) for propellant K
B. exponent
C. coefficient (cm/s MPa^a)
D. pressure (MPa)

Nth exponent
Nth coefficient
Nth pressure

record 10
A. time increment (ms)
B. print increment (ms)
C. time to stop calculation (ms)
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