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# The Influence of Propellant Loading Density on Computed Burn Rate in a Mini-Closed Bomb

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ARL-MR-404 August 1998

# Abstract

An investigation was conducted to determine what loading density should be used to calculate propellant thermochemical properties used in closed-chamber data analysis to minimize the differences in computed burn rates observed as the propellant loading density in the closed chamber varies. A comparison between the traditional loading density of 0.2 $g/cm^2$ and the actual propellant loading density was made. The traditional $r = bP^n$ burn rate law was used as the basis for the comparison.

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# 1. Introduction

In July 1990, a series of firings using M5, solid propellant lot RAD 64597-S, was performed using a mini-closed chamber (7.8 $cm^3$) to determine the burning characteristics of the propellant. The firings were conducted at the Advanced Ballistic Concepts Branch Closed-Chamber Facility at the U.S. Army Ballistic Research Laboratory.

Pressure data were recorded on a Nicolet (Model 4090) oscilloscope as voltage using a Kistler Model 607C4 pressure transducer mounted in the chamber wall. The data were converted to pressure units and reduced to burn rate using the closed-chamber data analysis program BRLCB (Oberle and Kooker 1993). Two sets of thermochemical properties were used for each burn rate analysis. First, properties calculated based on the loading density (ld) of that particular firing, and second, thermochemical calculations based on loading density of 0.2 $g/cm^3$ (the traditional value used for gun thermochemical calculations). Loading density is defined as the ratio of propellant mass to chamber volume.

The objective of this report is to investigate what loading density should be used to calculate propellant thermochemical properties used in closed-chamber data analysis to minimize the differences in computed burn rates observed as the propellant loading density in the closed chamber varies. Two different loading densities for the thermochemical calculation will be considered: (1) the traditional loading density of 0.2 $g/cm^3$ and (2) the actual propellant loading density used in the closed-chamber experiment. In the study, the traditional $r = bP^n$ burn rate law will be used as the basis for all comparisons.

# 2. Experimental Configuration

A series of seven firings in a 7.8-$cm^3$ closed chamber was made varying the propellant and igniter mass. Specific details for each firing are provided in Table 1. The loading density stated in the table is based on the ratio of propellant mass to chamber volume and does not include the igniter mass. The grain geometry of the propellant was a single-perforated cylinder. The grain dimensions, given in Table 2, were the same for all the firings in the series.

**Table 1. Mass Variation**

| Firing No. | Propellant Mass (g) | Igniter Mass (g) | Loading Density ($g/cm^3$) |
|---|---|---|---|
| 1 | 0.7875 | 0.1042 | 0.10 |
| 2 | 1.1827 | 0.1101 | 0.15 |
| 3 | 1.5590 | 0.1050 | 0.20 |
| 4 | 1.9454 | 0.1062 | 0.25 |
| 5 | 2.3431 | 0.1108 | 0.30 |
| 6 | 2.7285 | 0.1082 | 0.35 |
| 7 | 2.7342 | 0.1000 | 0.35 |

**Table 2. Grain Dimensions, Single Perf-Geometry**

| Parameter | Dimension (cm) |
|---|---|
| Length | 0.1028 |
| Outer Diameter | 0.1463 |
| Perf. Diameter | 0.0980 |
| Web | 0.02415 |

Table 3 lists the thermochemical properties for the propellant at various loading densities, as computed by the thermodynamic equilibrium code BLAKE (Freedman 1982). The density for the propellant is 1.59 $g/cm^3$.

**Table 3. Thermochemistry of M5**

| Thermochemical Value | Loading Density (g/cm$^3$) | | | | | |
|---|---|---|---|---|---|---|
| | 0.1 | 0.15 | 0.2 | 0.25 | 0.3 | 0.35 |
| Impetus (J/g) | 1075.87 | 1077.85 | 1079.28 | 1080.28 | 1081.04 | 1081.6 |
| Flame Temp (K) | 3249.0 | 3258.0 | 3264.0 | 3268.0 | 3272.0 | 3275.0 |
| Molecular Weight | 25.108 | 25.129 | 25.141 | 25.152 | 25.162 | 25.172 |
| Covolume (cm$^3$/g) | 1.0447 | 1.0248 | 1.0034 | 0.9811 | 0.9581 | 0.9347 |
| Gamma | 1.2284 | 1.2293 | 1.2308 | 1.2330 | 1.2358 | 1.2392 |

# 3. Results

The pressure-time curve for each firing is shown in Figures 1–7.

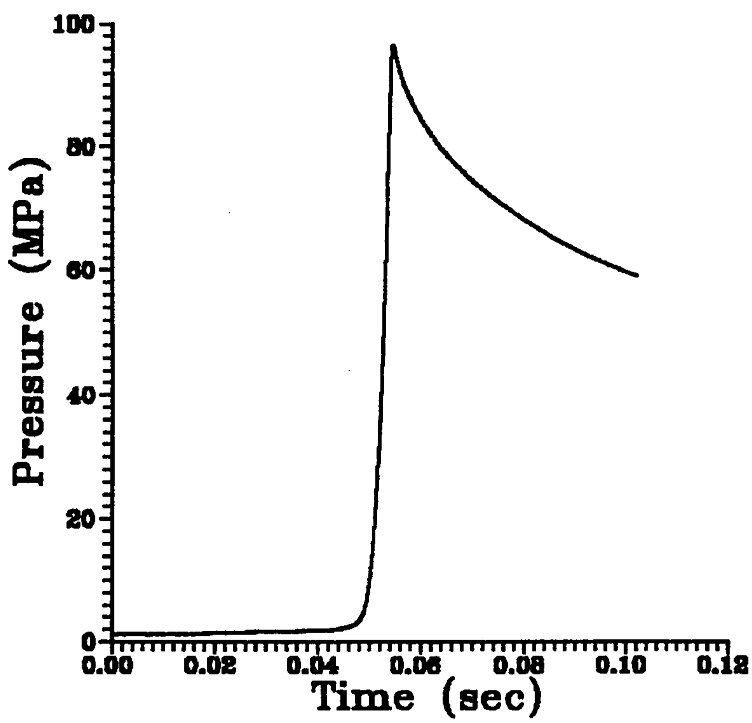


**Figure 1. Pressure-Time Profile, Firing 1, ld = 0.1 g/cm$^3$.**

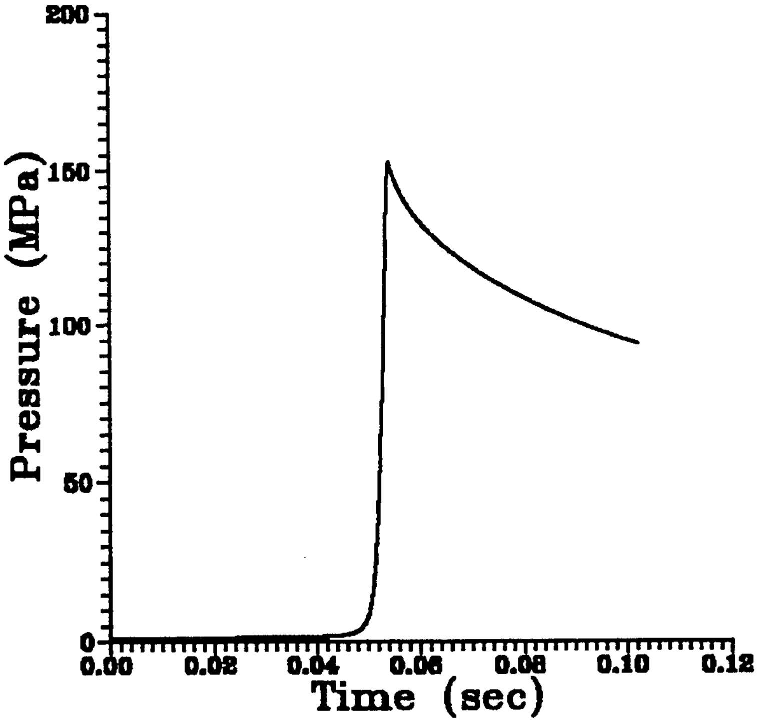


Figure 2. Pressure-Time Profile, Firing 2, ld = 0.15 g/cm$^3$.

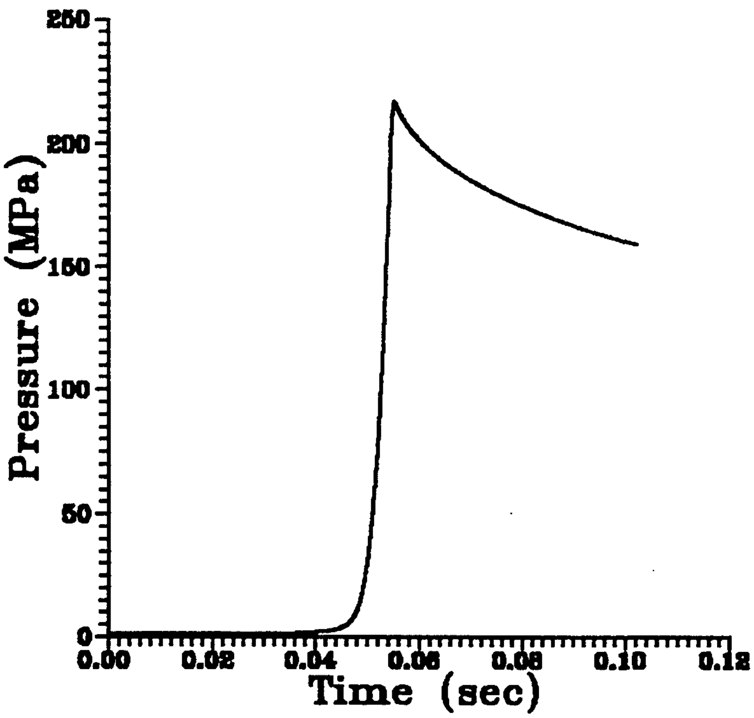


Figure 3. Pressure-Time Profile, Firing 3, ld = 0.2 g/cm$^3$.

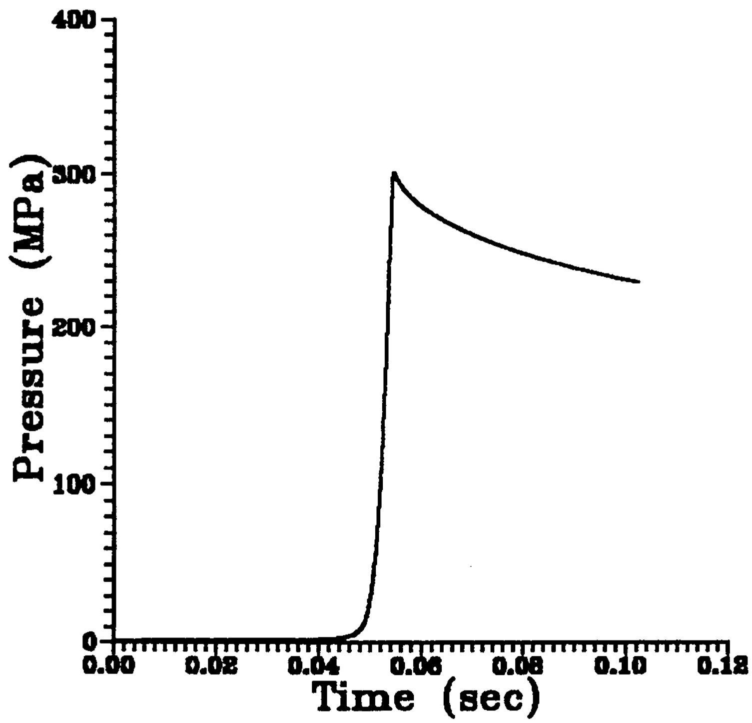


Figure 4. Pressure-Time Profile, Firing 4, ld = 0.25 g/cm$^3$.

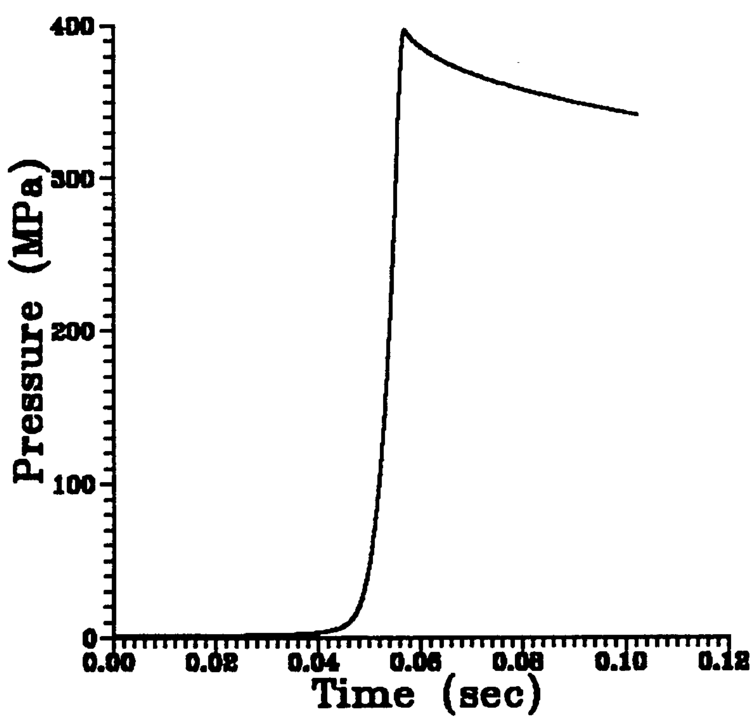


Figure 5. Pressure-Time Profile, Firing 5, ld = 0.3 g/cm$^3$.

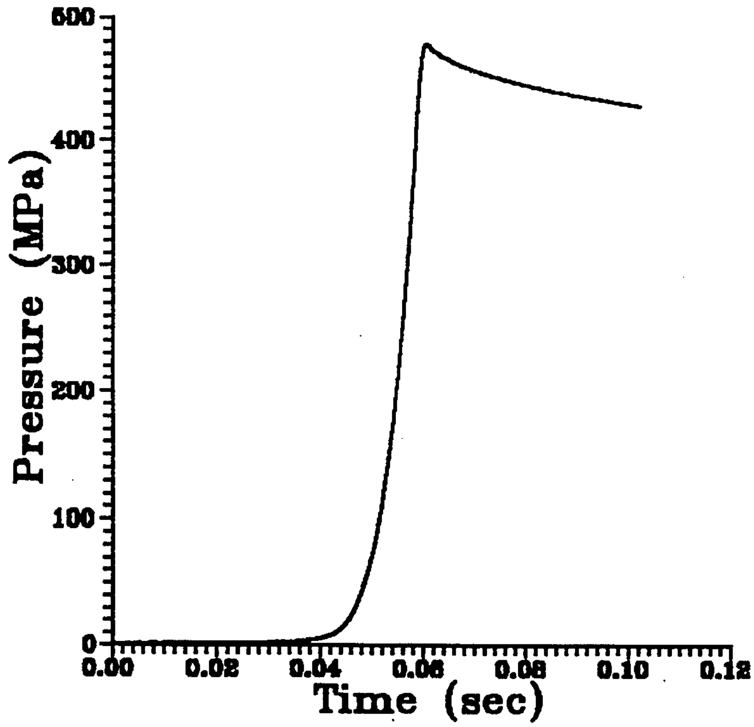


**Figure 6. Pressure-Time Profile, Firing 6, ld = 0.35 g/cm³.**

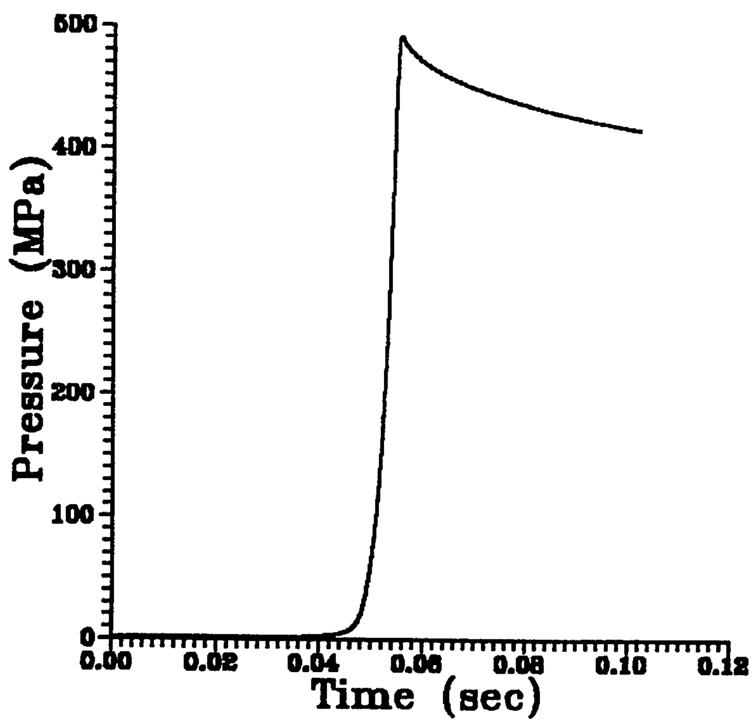


**Figure 7. Pressure-Time Profile, Firing 7, ld = 0.35 g/cm³.**

For each of the seven firings, the original voltage data were converted to pressure units and reduced to burn rate using BRLCB, Version 3, with two sets of thermochemical data as discussed earlier.

Tables 4–10 summarize the computed burn rate coefficient and exponent as well as theoretical and observed maximum pressures for each of the seven firings. The symbol ★ indicates the actual loading density of each experimental firing. The effect of using the actual loading density thermochemical properties vs. the traditional loading density (i.e., 0.2 g/cm$^3$) properties is represented as a percentage of change. The percentage of change is computed using the formula

$$\text{Percentage change} = \frac{\text{Value (ld = 0.2)} - \text{Value (ld = actual)}}{\text{Value (ld = actual)}} * 100$$

(The only exception being firing 3, which had an actual loading density of 0.2 g/cm$^3$.)

**Table 4. Results for Firing 1**

| Parameter | Loading Density | | Percentage of Change |
|---|---|---|---|
| | 0.1★ g/cm$^3$ | 0.2 g/cm$^3$ | |
| Coefficient (cm/s–MPa$^n$) | 0.074046 | 0.0731575 | -1.19 |
| Exponent | 0.9527990 | 0.9558150 | 0.32 |
| Theoretical Pmax (MPa) | 127.58150 | 127.35880 | -0.17 |
| Observed Pmax (MPa) | 96.33575 | | |

Figures 8–14 give the tradition plot of log burn rate vs. log pressure for each firing. It is shown from the overlay of the plot, in which the data reduction was performed using both the actual and traditional loading density, that there is no difference in the computed burn rate. This is due to the proportional relationship between the burning rate coefficient and the exponent. The maximum percentage change in this relationship is <1%.

**Table 5. Results for Firing 2**

| Parameter | Loading Density | | Percentage of Change |
|---|---|---|---|
| | 0.15★ g/cm$^3$ | 0.2 g/cm$^3$ | |
| Coefficient (cm/s-MPa$^n$) | 0.0637984 | 0.0631071 | -1.08 |
| Exponent | 0.9782990 | 0.9807700 | 0.25 |
| Theoretical Pmax (MPa) | 201.39180 | 200.85740 | -0.27 |
| Observed Pmax (MPa) | 152.6715 | | |

**Table 6. Results for Firing 3**

| Parameter | Loading Density |
|---|---|
| | 0.2★ g/cm$^3$ |
| Coefficient (cm/s-MPa$^n$) | 0.0213178 |
| Exponent | 1.0083580 |
| Theoretical Pmax (MPa) | 278.91750 |
| Observed Pmax (MPa) | 216.79180 |

**Table 7. Results for Firing 4**

| Parameter | Loading Density | | Percentage of Change |
|---|---|---|---|
| | 0.25★ g/cm$^3$ | 0.2 g/cm$^3$ | |
| Coefficient (cm/s-MPa$^n$) | 0.0316704 | 0.0324608 | 2.50 |
| Exponent | 0.9159250 | 0.9110420 | -0.53 |
| Theoretical Pmax (MPa) | 367.70480 | 370.21970 | 0.68 |
| Observed Pmax (MPa) | 301.2470 | | |

**Table 8. Results for Firing 5**

| Parameter | Loading Density | | Percentage of Change |
|---|---|---|---|
| | 0.3★ (g/cm$^3$) | 0.2 (g/cm$^3$) | |
| Coefficient (cm/s-MPa$^n$) | 0.0136179 | 0.0145765 | 7.04 |
| Exponent | 0.9388650 | 0.9260520 | −1.36 |
| Theoretical Pmax (MPa) | 469.78980 | 478.38410 | 1.83 |
| Observed Pmax (MPa) | 396.3794 | | |

**Table 9. Results for Firing 6**

| Parameter | Loading Density | | Percentage of Change |
|---|---|---|---|
| | 0.35★ g/cm$^3$ | 0.2 g/cm$^3$ | |
| Coefficient (cm/s-MPa$^n$) | 0.0068970 | 0.0078251 | 13.46 |
| Exponent | 0.9360540 | 0.9130430 | −2.46 |
| Theoretical Pmax (PMa) | 578.27390 | 598.95810 | 3.58 |
| Observed Pmax (MPa) | 478.0475 | | |

**Table 10. Results for Firing 7**

| Parameter | Loading Density | | Percentage of Change |
|---|---|---|---|
| | 0.35★ g/cm$^3$ | 0.2 g/cm$^3$ | |
| Coefficient (cm/s-MPa$^n$) | 0.0140839 | 0.0160551 | 14 |
| Exponent | 0.932685 | 0.908918 | −2.55 |
| Theoretical Pmax | 578.9294 | 599.67 | 3.58 |
| Observed Pmax (MPa) | 491.1205 | | |

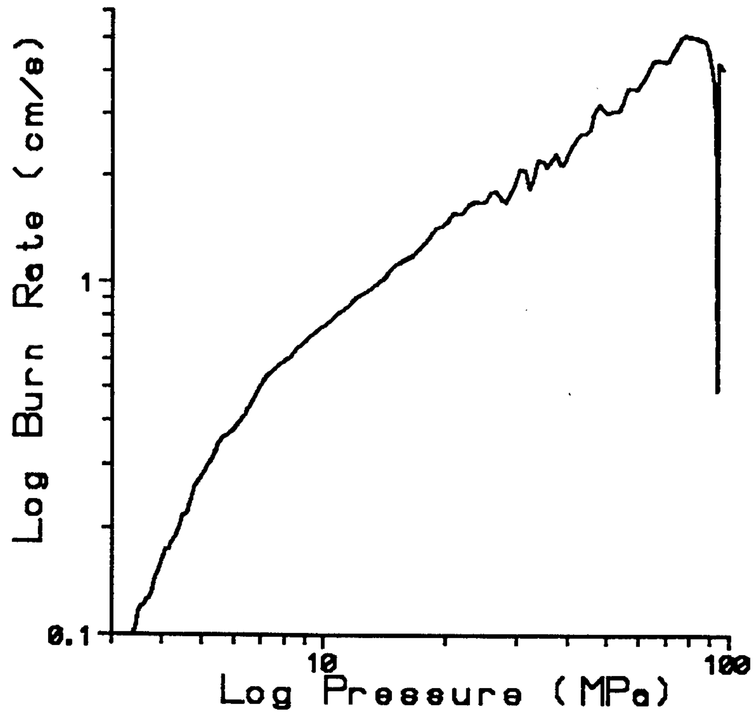


**Figure 8. Burn Rate vs. Pressure, Firing 1, ld = 0.1 vs. 0.2 g/cm³.**

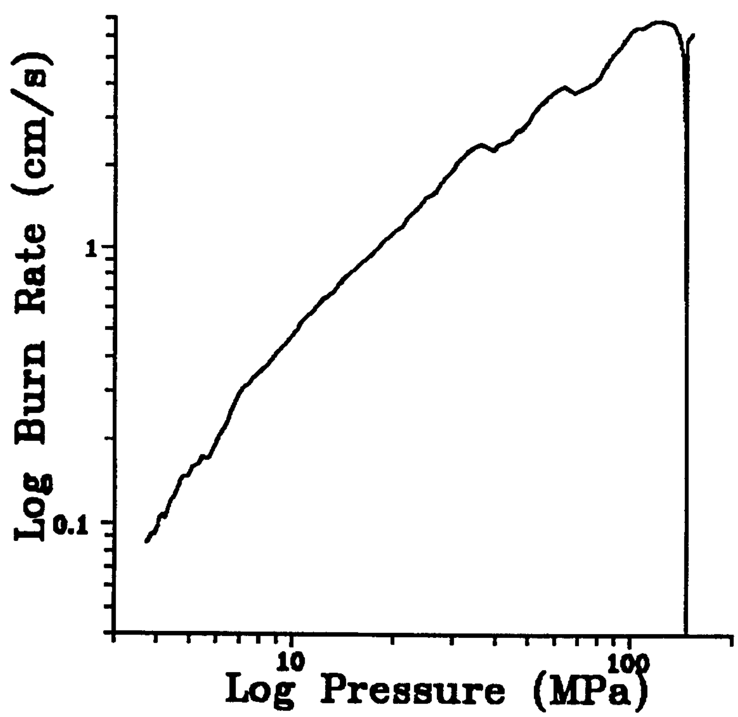


**Figure 9. Burn Rate vs. Pressure, Firing 2, ld = 0.15 vs. 0.2 g/cm³.**

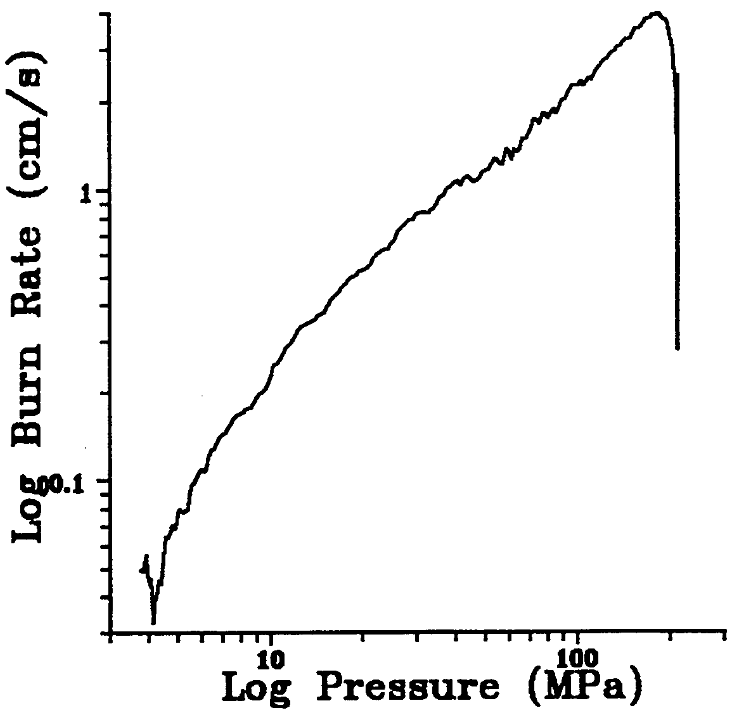


**Figure 10. Burn Rate vs. Pressure, Firing 3, ld = 0.2 g/cm$^3$.**

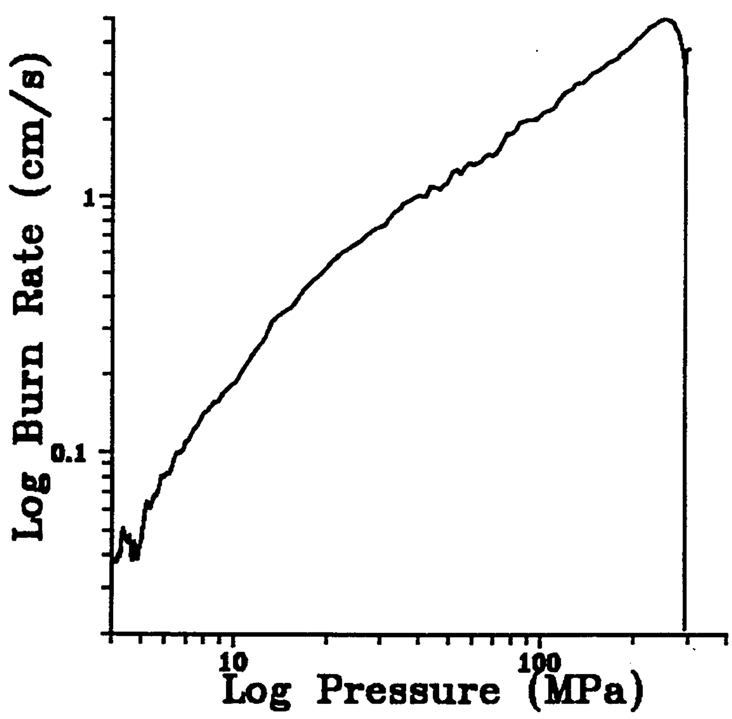


**Figure 11. Burn Rate vs. Pressure, Firing 4, ld = 0.25 vs. 0.2 g/cm$^3$.**

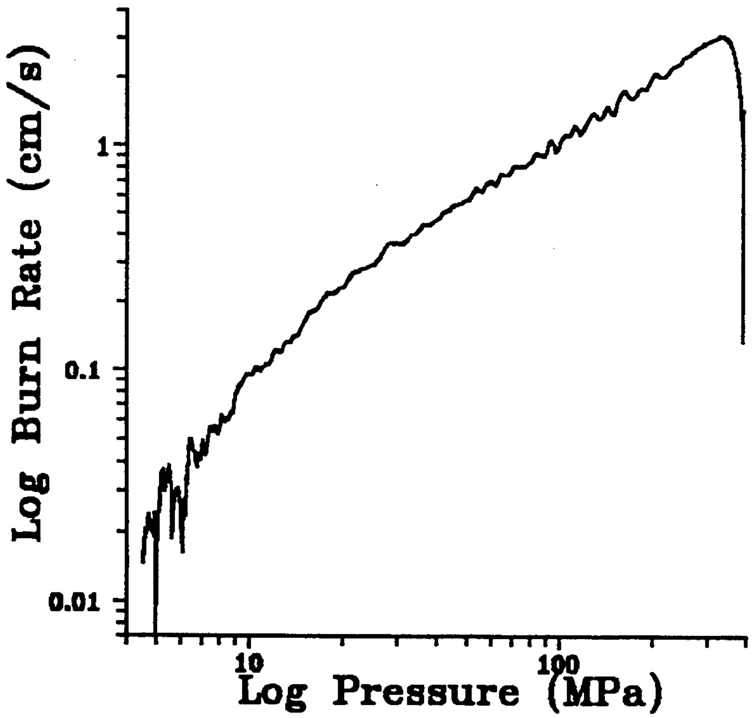


Figure 12. Burn Rate vs. Pressure, Firing 5, ld = 0.3 vs. 0.2 g/cm$^3$.

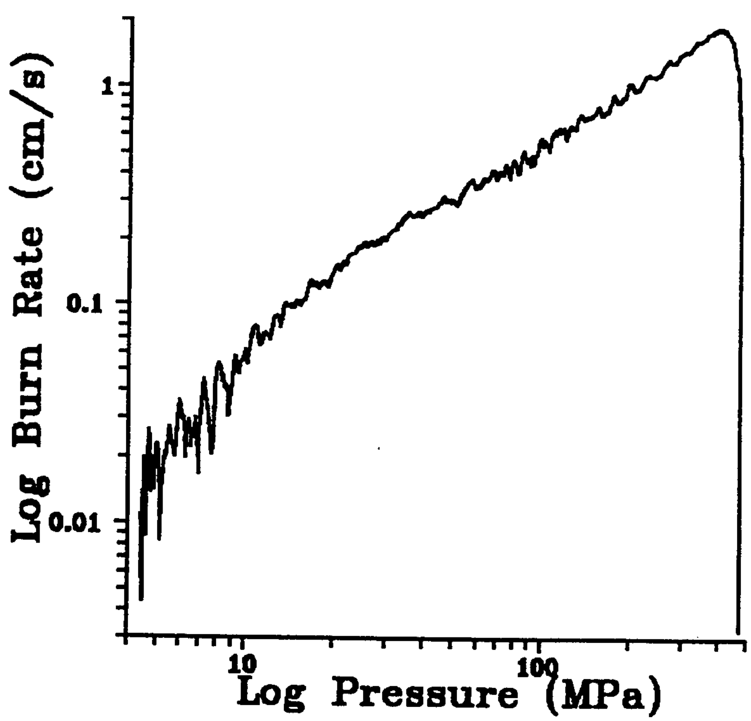


Figure 13. Burn Rate vs. Pressure, Firing 6, ld = 0.35 vs. 0.2 g/cm$^3$.

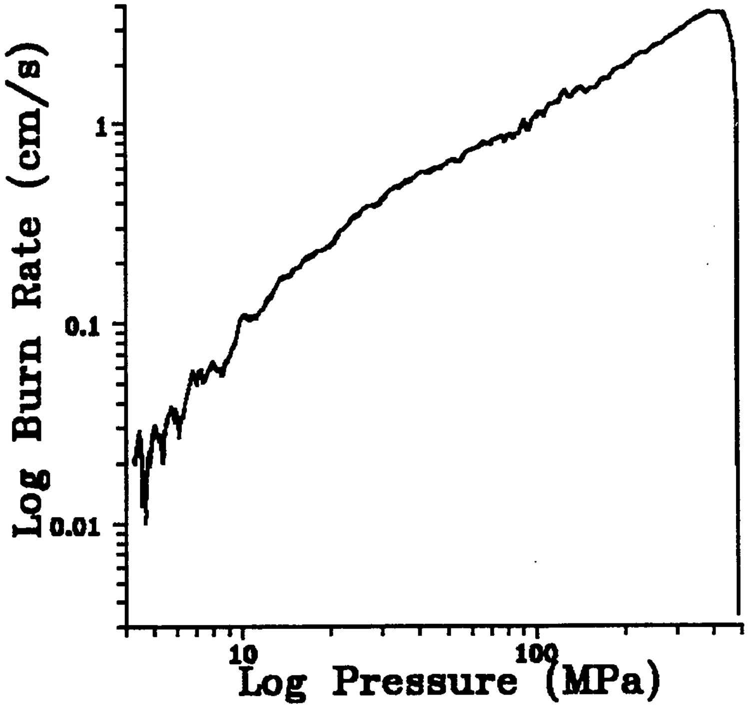


**Figure 14. Burn Rate vs. Pressure, Firing 4, ld = 0.35 vs. 0.2 g/cm$^3$.**

# 4. Discussion

In theory, the propellant burn rate is dependent only on pressure. Thus, the computed burn rates should be the same for all closed-chamber firings if the thermochemistry is handled properly. For the data reduction, values for the thermochemical properties are held constant based on not only the chemical composition of the propellant but also the user-selected loading density input to BLAKE. At first glance, it seems logical that using the actual propellant loading density is the correct choice. Unfortunately, this is not the case; BLAKE (and all thermochemical codes) compute the equilibrium thermochemical properties of the gas phase only, assuming total combustion of the propellant. In an actual closed-chamber experiment or gun firing, the loading density associated with the amount of propellant that has actually burned is continuously changing. For example, consider a 100-cm$^3$ closed chamber loaded with 35 g of propellant whose density is 1.6 g/cm$^3$. Then, the loading density of the propellant converted to gas (loading density of gas) as the propellant burns is given by:

$$\frac{\text{mass burned}}{\text{free volume}} = \frac{m}{100 - \frac{35}{1.6} + \frac{m}{1.6}} + \frac{1.6\ m}{125 + m},$$

where $m$ is the amount of propellant burned. Table 11 lists the loading density of the gas for various propellant amounts burned.

**Table 11. Gun Loading Density for Various Amounts of Propellant Burned**

| Amount Burned (g) | Loading Density (g/cm$^3$) |
|---|---|
| 5 | 0.06 |
| 10 | 0.12 |
| 15 | 0.17 |
| 20 | 0.22 |
| 25 | 0.27 |
| 30 | 0.31 |
| 35 | 0.35 |

The average gas loading density is:

$$\frac{\int_0^{35} \frac{1.6\ \mathrm{m}}{125 + \mathrm{m}}\, \mathrm{dm}}{35} = 0.1894\ \mathrm{g/cm^3}.$$

The situation for a gun firing is even more complicated since the volume changes as the projectile moves down the tube.

Based on the previous paragraph, it is clear that the correct approach should be to compute new thermochemical values at each step of the closed-chamber data reduction. Fortunately, results from studies (Robbins 1993; Wren and Oberle 1993) using such a coupled thermochemical and analysis (both closed-chamber and interior ballistic analysis codes) code approach have shown little difference between computations based on fixed thermochemical values provided:

- The same fixed thermochemical values are used in all the codes;

- The analysis is for conventional solid propellant performance (e.g., results are substantially different for electrothermal-chemical firings due to the large variation in thermochemical values, which are produced by the introduction of electrical energy).

Thus, from the point of view of what loading density to use to compute the values of the thermochemical properties used in the burn rate analysis, it appears that there is no one correct choice as long as the computed burn rates and thermochemical values are coupled in all applications in which the burn rate information is used. However, it has been observed (Robbins 1993; Oberle 1993) that for fixed thermochemical values computed with a loading density of 0.2 g/cm$^3$, 5–10% differences in computed burn rates result for closed-chamber experiments with different propellant loading densities. This is clearly evident in Figure 15, which shows the computed burn rate for the seven firings in the series with the data reduction performed with thermochemical values computed at the fixed loading density, 0.2 g/cm$^3$.

To determine which loading density to use in the thermochemical calculation, the root mean square (RMS) of the burn rate with mean removed will be used as the statistic. The RMS is given by the following equation

$$\mathrm{RMS} = \frac{1}{n} \sum_{i=1}^{n} (x_i - \overline{x})^2 ,$$

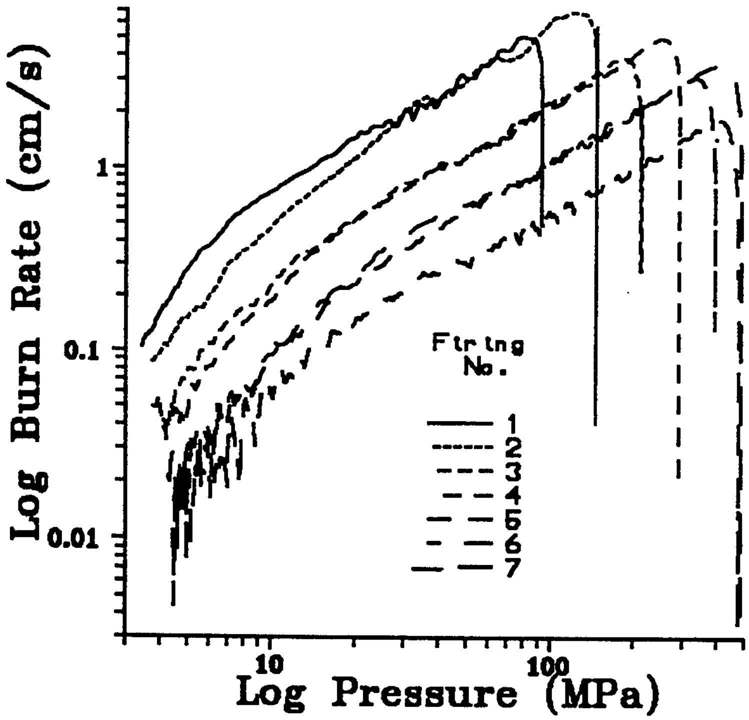


**Figure 15. Overlay of M5 Burn Rate, Thermochemistry With Fixed 1d = 0.2 g/cm$^3$.**

where $\bar{x}$ represents the average burn rate at each pressure. The following procedure will be used to compute the RMS for each loading density assumption:

- The computed burn rate law will be used to generate a table of pressure vs. burn rate for pressures from 50 MPa to 400 MPa in steps of 5 MPa.

- At each pressure, an average rate will be determined.

- The average rate will be subtracted from each rate with the result squared.

- The total RMS value for each loading density as well as the RMS for each firing is then computed.

Table 12 presents the RMS calculations that were computed using the program listed in the Appendix.

**Table 12. RMS Calculations**

| Firing No. | Total RMS Value | |
|---|---|---|
| | ld = 0.2 g/cm$^3$ | ld = propellant ld |
| 1 | 59.96557 | 59.03743 |
| 2 | 58.56320 | 58.06792 |
| 3 | 0.66977 | 0.65154 |
| 4 | 2.22200 | 2.14645 |
| 5 | 15.74655 | 15.57574 |
| 6 | 26.59130 | 26.43074 |
| 7 | 15.75257 | 15.60059 |
| Average RMS | 25.64442 | 25.35863 |

From Table 12, the RMS values are slightly lower using the actual loading density in BLAKE. However the difference is negligible. One obvious observation is the large RMS values, regardless of which loading density is used, in the thermochemical calculation for firings 1 and 2 (which correspond to actual loading densities of 0.1 and 0.15 g/cm$^3$, respectively). It also appears that firing 6 may be an outlier. Performing the RMS calculation deleting these three firings gives the results in Table 13.

As in Table 12, the results in Table 13 show little difference based on what loading density is used in the thermochemical code calculation, with results using the actual propellant loading density only slightly better.

Finally, this study also illustrates the importance of considering both the burn rate coefficient and exponent when trying to analyze differences in computed burn rates. For all seven firings, the computed RMS value for each firing is roughly the same regardless of which loading density is used

**Table 13. RMS Calculations Without Firings 1, 2, and 6.**

| Firing No. | Total RMS Value | |
|---|---|---|
| | ld = 0.2 g/cm$^3$ | ld = propellant ld |
| 3 | 3.05901 | 3.02844 |
| 4 | 1.15169 | 1.16501 |
| 5 | 1.98350 | 1.97697 |
| 7 | 1.98583 | 1.98589 |
| Average RMS | 2.04501 | 2.03908 |

to compute the thermochemistry. Thus, the computed burn rate for each firing is about the same; independent of the loading density used in the thermochemical calculation. However, from Tables 4–11, the percentage difference in the coefficients and exponents becomes quite large, up to 14%. Fortunately, the changes in coefficient and exponent are in opposite directions; change in the coefficient increases while the change in the exponent decreases, as summarized in Figure 16. Thus, roughly the same burn rate, over a reasonable pressure range, is computed with what are substantial changes in computed burn rate coefficients and exponents.

# 5. Conclusions

Based on results of this study, the following conclusions can be made within the context of the study parameters.

- There appears to be little dependence of computed burn rates on the loading density used to compute thermochemical propellant properties. Using the actual propellant loading density produces only slightly better results.

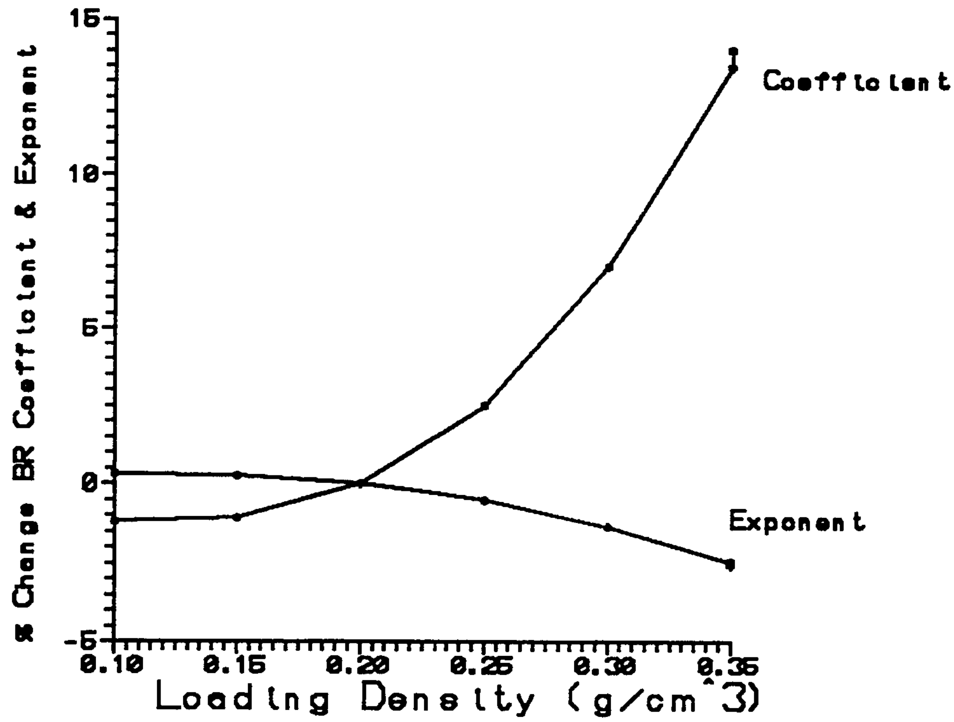


**Figure 16. Percentage Change vs. Actual Loading Density.**

- Low loading density (<1.5 g/cm$^3$) firings produce burn rate results that differ markedly from those of higher loading density firings. Thus, any burn rates computed based on such low loading densities should be used with caution. It is recommended that firings at these loading densities be avoided.

- Both changes in burn rate coefficient and exponent must be considered in evaluation changes in computed burn rates.

Finally, it is recommended that studies similar to this one be performed for a variety of closed-chamber volumes and propellant types to determine if the previous conclusions can be generalized.

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# 6. References


Oberle, W. F., and D. E. Kooker. "BRLCB: A Closed-Chamber Data Analysis Program, Part I-Theory and User's Manual." ARL-TR-36, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, January 1993.

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Wren, G., and W. Oberle. "A Coupled Thermochemistry - Interior Ballistic Model and Application to Electrothermal-Chemical (ETC) Guns." ARL-TR-63, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, February 1993.

Oberle, F. "Closed-Chamber Analysis of M5 Propellant Lot RAD-64597." ARL-MR-83, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, June 1993.

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# Appendix A:

# RMS Calculations

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```
      PROGRAM RMS
      DIMENSION A(72,8),C(7),E(7)
C***************** Burn Rate Data Is Read
****************************
      OPEN(UNIT=3,FILE='BR.DAT')
      DO 5 I=1,7
           READ(3,*)C(I),E(I)
 5    CONTINUE
      CLOSE(UNIT=3)
C***************** Rate Data For Each Firing Computed
****************
      DO 10 I=1,71
           P=5.*(I-1)+50.
           DO 10 J=1,7
                A(I,J)=C(J)*P**E(J)
 10   CONTINUE
C***************** Averages & Differences Squared Computed
***********
      DO 20 I=1,71
           SUM=0.0
           DO 30 J=1,7
                SUM=SUM+A(I,J)
 30        CONTINUE
           SUM=SUM/7.
           DO 40 J=1,7
                A(I,J)=(A(I,J)-SUM)**2.
 40        CONTINUE
 20   CONTINUE
C*****************  RMS Values Are Computed
*************************
      DO 50 I=1,8
           A(72,I)=0.0
 50   CONTINUE
      DO 60 J=1,7
      DO 60 I=1,71
           A(72,J)=A(72,J)+A(I,J)/71.
 60   CONTINUE
      DO 70 J=1,7
           A(72,8)=A(72,8)+A(72,J)/7.
 70   CONTINUE
C**************************** Output
**********************************
      OPEN(UNIT=3,FILE='RMS.OUT')
      DO 80 I=1,7
           WRITE(3,90)I,A(72,I)
 80   CONTINUE
 90   FORMAT(' The RMS value for firing ',I1,' is:',F10.5)
      WRITE(3,100)A(72,8)
 100  FORMAT(' The total RMS is: ',F10.5)
      CLOSE(UNIT=3)
      END
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**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
August 1998

**3. REPORT TYPE AND DATES COVERED**
Final, Jan - Dec 92

**4. TITLE AND SUBTITLE**
The Influence of Propellant Loading Density on Computed Burn Rate in a Mini-Closed Bomb

**5. FUNDING NUMBERS**
1L162618AH80

**6. AUTHOR(S)**
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**8. PERFORMING ORGANIZATION REPORT NUMBER**
ARL-MR-404

**9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)**

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

An investigation was conducted to determine what loading density should be used to calculate propellant thermochemical properties used in closed-chamber data analysis to minimize the differences in computed burn rates observed as the propellant loading density in the closed chamber varies. A comparison between the traditional loading density of 0.2 g/cm$^2$ and the actual propellant loading density was made. The traditional $r = bP^n$ burn rate law was used as the basis for the comparison.

**14. SUBJECT TERMS**
propellant, burn rate, loading density

**15. NUMBER OF PAGES**
30

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

NSN 7540-01-280-5500



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