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COMBUSTION PROCESSES IN CONSOLIDATED PROPELLANTS

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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The use of consolidated or compacted conventional gun propellants offers the ballistician the opportunity for significant performance increases through effective use of very high loading densities on the order of 1.2 g/cm^3. Such loading densities will only be effective, however, if accompanied by an increase in surface area progressivity. We report the results of an experimental program surveying the effects of ignition stimulus and compaction density on the combustion of simple wafers of consolidated charges of single and double base propellants. We have found that sample confinement, surface inhibition, and grain

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) geometric factors, have significant effects on charge break-up and propellant mass burning rate. In effect, the samples can behave with strong surface area progressivity. With a knowledge of the base grain propellant linear burning rate, independently arrived at, we have extracted instantaneous surface area profiles for burning consolidated propellants. The progressive character of the gas generation rate from burning consolidated charge samples can be explained on the basis of "macroscopic progressivity" defined as the controlled release of surface area through a continuous deconsolidation process.

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1. INTRODUCTION

The quest for higher muzzle velocities in gun propulsion has led to the exploration of consolidated or compacted propellants as a means of increasing the charge-to-projectile mass ratio (c/m) for a given chamber volume. Typical high performance gun systems operate with propelling charge loading densities of about 0.9 g/cm^3. Mechanical compaction of granular propellants allows loading densities as high as 1.25 g/cm^3, with a resulting 40-percent increase in c/m. In certain cases, such as reported by Fortino[1], velocity increases of up to 13 percent have been achieved with consolidated charges without a significant increase in peak pressure.

Conventional interior ballistic theory, as shown by Witt[2] and Grollman[3], requires, however, enhanced progressive burning of a propelling charge in order to obtain velocity increases at very high loading densities. A propelling charge burns progressively if the mass burning rate, $\dot{m}$, increases with projectile velocity. In conventional guns progressivity is usually enhanced through surface area modification or chemical tailoring of the propellant's linear burning rate, r. The common multi-perforated propellant geometry used in large caliber systems and the deterred propellants used in small arms are typical examples. In a consolidated charge the objective is to enhance these methods using <u>macroscopic progressivity</u> which we define as a controlled release of surface area, S, through a continuous deconsolidation process.

The basic combustion law of interior ballistic theory is stated as:

$$dm/dt = \dot{m} = \rho \cdot r \cdot S$$

where ρ is the propellant density. Hence, the overall mass burning rate, $\dot{m}$, is proportional to the product of the instantaneous linear burning rate and the available burning surface area. In granular charges, surface area progressivity is obtained by choice of propellant geometry. Figure 1 illustrates the surface area enhancement, S/S_o, as a function of mass fraction burned obtainable with multiperforated grain geometries, where S_o is the initial propellant surface area. In consolidated charges enhanced progressivity results from surface area increases as the compacted charge burns through or fractures into smaller aggregates along natural stress lines in the charge. This breakup is aided by external or internal pressurization. There are some penalties to be paid in consolidating propellants, however. The compaction process may destroy or substantially

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[1] *F.E. Fortino, "Improved Ballistic Performance for 30-mm Ammunition Using Consolidated Charges", Frankford Arsenal TR-76064, September 1976.*

[2] *W. Witt, E. Melchior, "Thermodynamisches Modell der Innenballistik", Wehrtechnik, Juni [1974] 222.*

[3] *B.B. Grollman, P.G. Baer, "Theoretical Studies of the Use of Multi-Propellants in High Velocity Guns", Ballistic Research Laboratory, Report No. R-1411, August 1968.*

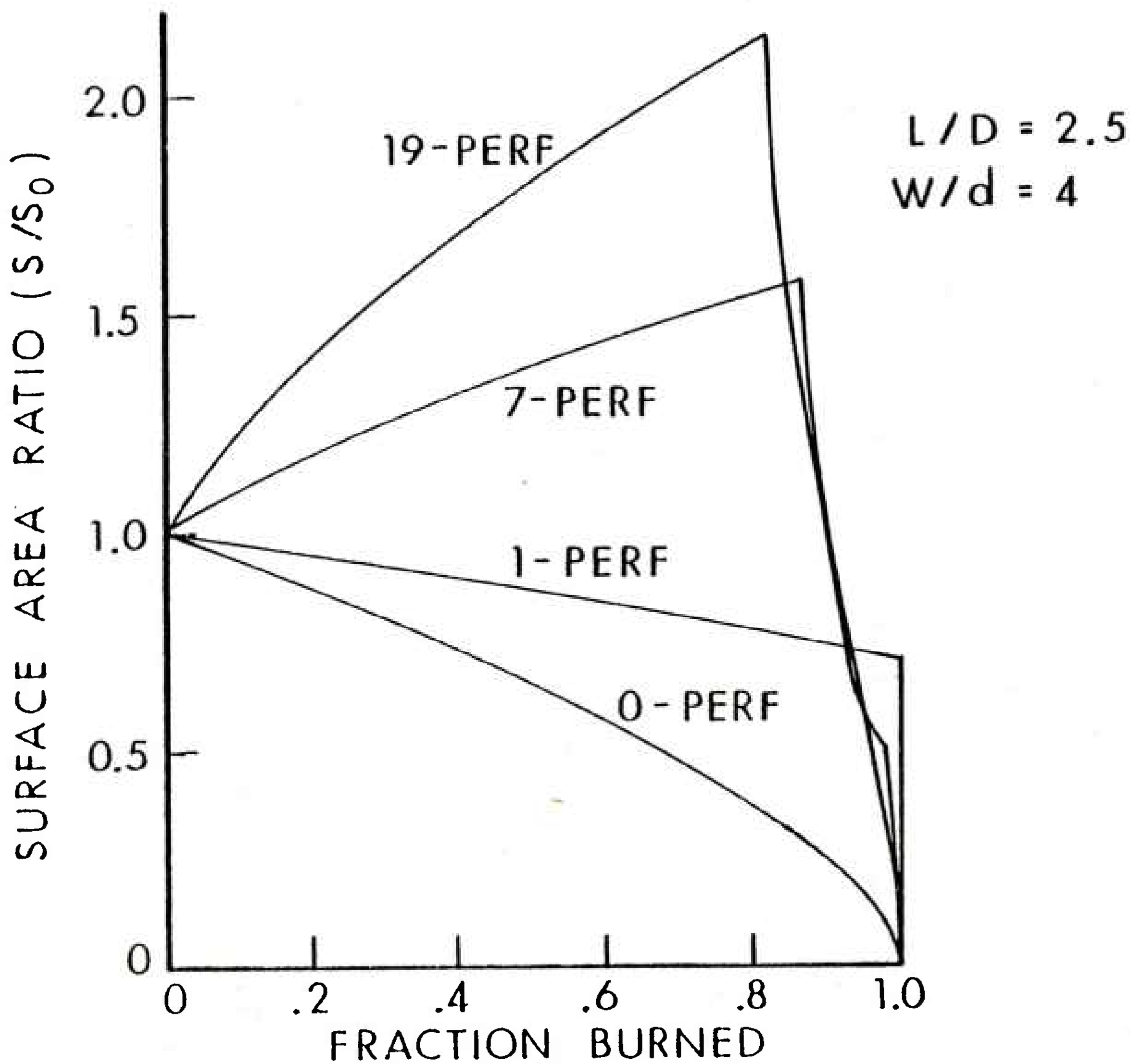

Figure 1. Geometric Progressivity of Multi-Perforated Propellant Grains

modify the original grain geometry. This may result in reduced single grain progressivity as well as a lower initial single grain surface area. One significant observation made in studies to date has been that, operating at a peak chamber pressure equivalent to that obtained with granular propellant, requires the use of faster burning propellants to compensate for the reduced surface area. It becomes important, therefore, to determine the overall or macroscopic progressivity for a consolidated propelling charge.

Although the development of the propelling charge surface area profile is a dominant factor of interest in conventional interior ballistic theory, other factors are also important and necessary for a more complete one-dimensional, two-phase flow, fluid dynamic modeling of the process. The details of flame propagation through a porous bed and of the eventual transition to a fluidized bed are also necessary. Such modeling of granular propelling charge performance has been quite successful recently[4]. It would be a significant advantage if such models could be applied to describing the functioning of consolidated charges. Details such as grain breakup, gas permeability, and gas flow resistance, are largely unknown and quite difficult to pin down for consolidated charges, as indicated in a previous study by Juhasz[5]. Yet, if quantitative measurements can be made of the qualitative phenomenology of consolidated charge functioning, the development of a successful consolidated charge design methodology, using a combined experimental and theoretical approach, would be greatly enhanced.

2. RATIONALE AND TEST PLAN

The basic purpose of our experiments was to extract quantitative information about the burning surface area development in consolidated charge combustion in an environment devoid of the complications of a moving projectile boundary. Previous work[5] indicated that a systematic survey of the effects of compaction density, ignition stimulus, and propellant composition on macroscopic progressivity is a necessary first step towards a generalized description of S/S_o for consolidated charges. Fortino[6] recently reported some experiments directed at a similar goal. Given a general surface area progressivity relationship, useful a priori interior ballistic performance predictions are then possible. Of further interest in our study is the effect of these parameters on the variability of combustion behavior. Unacceptably large ballistic variability has been a major reason for the failure of consolidated propelling charges to find

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[4] *A.W. Horst, T.C. Minor, "Ignition-Induced Flow Dynamics in Bagged-Charge Artillery", 4th International Symposium on Ballistics, Monterey, California, October 1978.*

[5] *A.A. Juhasz, I.W. May, "The Effects of Consolidation on the Burning of Gun Propellants", 15th JANNAF Combustion Meeting, Chemical Propulsion Information Agency, Laurel, MD, Publication 297, December 1978.*

[6] *F.E. Fortino, "Effect of Consolidation Parameters on the Burning of Consolidated Propellant Charges", 1979 JANNAF Propulsion Meeting, Anaheim, California, March 1979.*

their way into fielded gun systems. It must be noted at this point that the parameters studied here are by no means all inclusive. Process variables in the manufacture of consolidated propellants loom as serious complicating factors which may severely restrict any generalizations of our results.

3. EXPERIMENTAL DETAILS

In this study we restricted the scope to a consideration of two generic propellant compositions, compacted by one consolidation technique at several densities, and with two different igniters. Table 1 summarizes the test matrix.

3.1. Propellants

Available, single-perforated, undeterred, single base (SB) and double base (DB) propellants were chosen to be consolidated. Table 2 lists the basic compositions and grain dimensions. There is nothing unusual about their chemistry and they should, therefore, be considered as typical single and double base compositions. The webs and, perhaps more importantly, the grain length-to-diameter ratios (L/D), are quite different. The single base propellant with a L/D of 4.24 can be expected to consolidate somewhat differently from the double base propellant with an L/D of 1.18.

3.2. Consolidation Process

The propellants chosen for this study were consolidated under Contract DAAK11-77-C-0031 to BRL by Hercules, Inc.*[7] The process is depicted schematically in Figure 2. The propellant surface is softened by a vapor solvation process before compacting and drying to the original presolvated weight. It is unlikely that the basic chemistry has changed significantly because of the consolidation process. Grain surface hardness changes are likely, however, with possible effects on ignitability and low pressure burning rates. The samples are molded into simple wafers with a diameter of nearly 40 mm and a length of 25 mm. The wafers were circumferentially inhibited with EA-946†. The coating covered the exposed outermost surface of the propellant grains, but did not penetrate into the consolidated charge. The samples were cemented into thin steel cylinders with fast acting epoxy. This procedure prevents flamespread down the cylinder walls of the wafers. Experimentally, it results in a more nearly one-dimensional flame propagation.

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[7] *L. Scott, "Consolidated Propellant Charge Investigation," Volume 1: Preparation of Consolidated Charge Increments," Ballistic Research Laboratory, Contract Report ARBRL-CR-00408, November 1979.* (AD #B043967L)

* *Contract DAAK11-77-C-0031*

† *A product of the Hysol Division, Bendix Corporation.*

TABLE 1. TEST MATRIX

COMPOSITION	SINGLE BASE M1 SP	DOUBLE BASE HES 8567.11E SP
COMPACTION DENSITIES	1.10 g/cm^3 1.25 1.35	1.15 g/cm^3 1.25
IGNITERS	"SOFT" (Atlas M100 Match plus 1.0 g FFFG Black Powder)	"HARSH" (M52 Primer plus 1.0 g FFFG Black Powder)
	"HARSH"	"SOFT"

TABLE 2. PROPELLANTS

INGREDIENTS (% Weight)	M1 SINGLE BASE Lot No. RAD 68108	DOUBLE BASE Lot No. HES 8567.11E
Nitrocellulose	83.1	83.55
% Nitration	13.5	13.25
Dinitrotoluene	9.99	----
Nitroglycerine	-----	10.76
Dibutylphthalate	5.04	3.23
Diphenylamine	1.01	0.57
Total Volatiles	0.86	0.85
Potassium Nitrate	-----	1.02
Graphite	-----	0.02
DIMENSIONS: (mm)		
Web	0.343	0.935
Length	5.05	2.76
Diameter	1.19	2.33

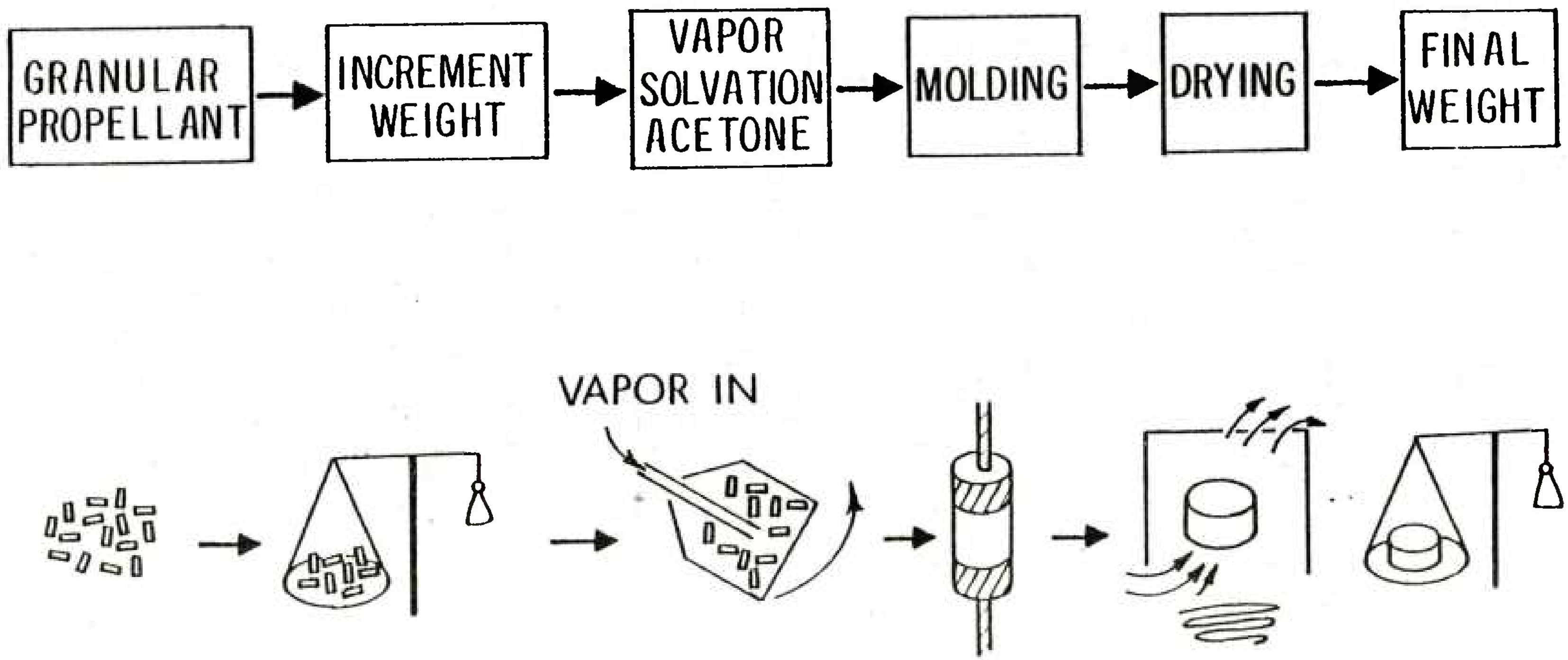

Figure 2. Typical Process for Consolidating Propellants

3.3. Igniters

The two igniter configurations were chosen to give what was felt to be a reasonable, though not overpowering difference in output characteristics. The M52 primer with 1 g of FFFG black powder results in substantially more rapid pressurization of the closed vessel than the relatively slow electric match with the same amount of black powder. The differences are readily apparent in Figure 3 which shows pressure-time characteristics of the two igniters only. The closed vessel was filled with an appropriate amount of inert filler. The "harsh" ignition obtained with the M52 primer results also in a higher final ignition pressure, and shorter igniter functioning time.

3.4. Test Device and Measurements

A closed vessel, illustrated in Figure 4, with an internal diameter of 40 mm was designed and built for this study. The steel-sleeved samples were slipped into the vessel and cemented in place to prevent movement during the experiment. A Kistler 607C piezoelectric gage was used to measure pressure versus time. The data were acquired digitally on a laboratory minicomputer, smoothed, and differentiated to obtain a basic data file of pressure, dp/dt, and time.

3.5. Data Reduction

The data obtained from an experiment are analyzed using a computer program, CBRED II. The program described previously by Price[8] and Juhasz[9] for the extraction of linear burning rates was modified to allow the inverse process of extracting surface area given linear burning rate information. The problem is, therefore, reduced to determining the linear burning rate of the unconsolidated propellant using the same closed vessel. The assumption is then made that the consolidation process has not significantly affected the chemistry and hence the burning rate. Finally the linear burning rate is then used to extract surface area profiles, S/S_0, as a function of the fraction of propellant burned, z, using CBRED II. This information can then be used directly in a suitable gun interior ballistics model.

4. RESULTS

In the data to follow, it is important to keep in mind that in the

[8] *Price, C.F., Juhasz, A.A., "A Versatile User-Oriented Closed Bomb Data Reduction Program (CBRED)", Ballistic Research Laboratory R-2018, September 1977.* (AD #A049465)

[9] *Juhasz, A.A., Price, C.F., "The Closed Bomb Technique for Burning Rate Measurement at High Pressure", Experimental Diagnostics in Combustion of Solids, ed. T.L. Boggs and B.T. Zinn, Vol. 63, Progress in Astronautics and Aeronautics, [1978] 129.*

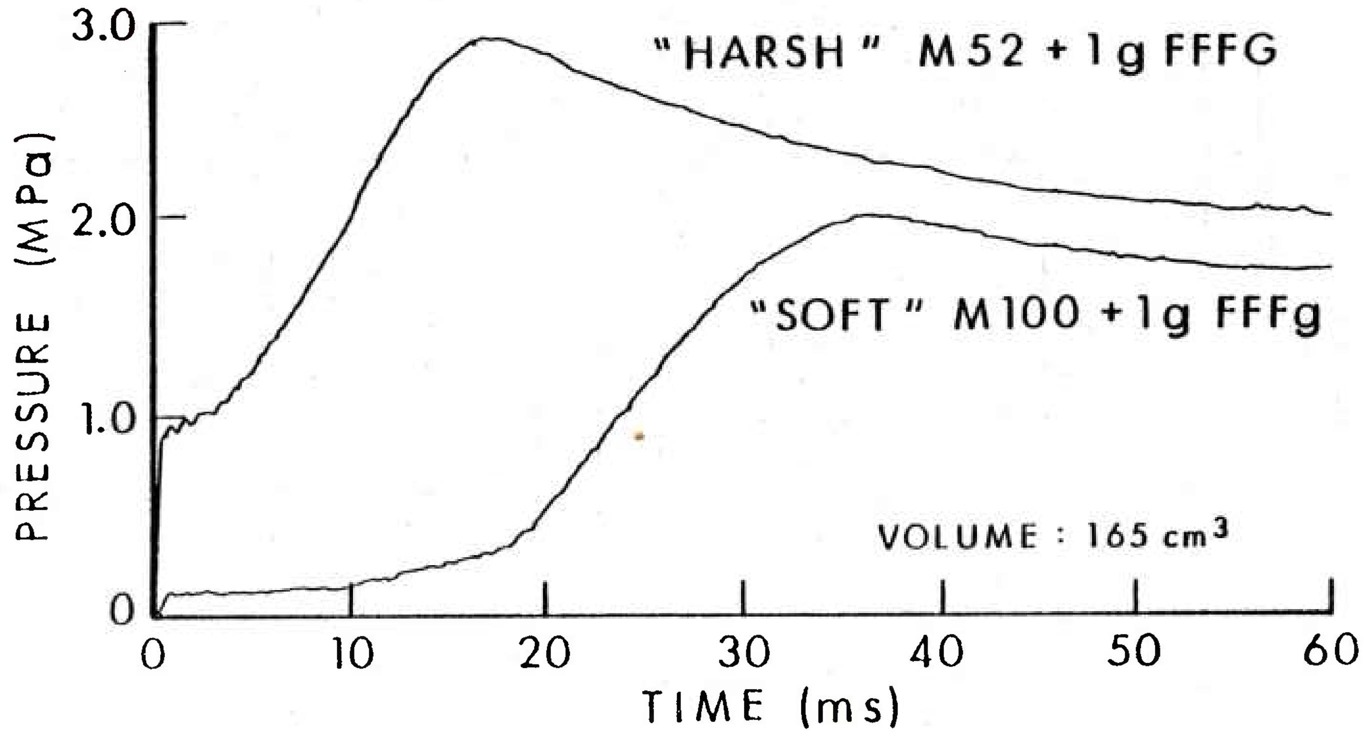

Figure 3. Pressure-Time Profiles for the Two Igniters

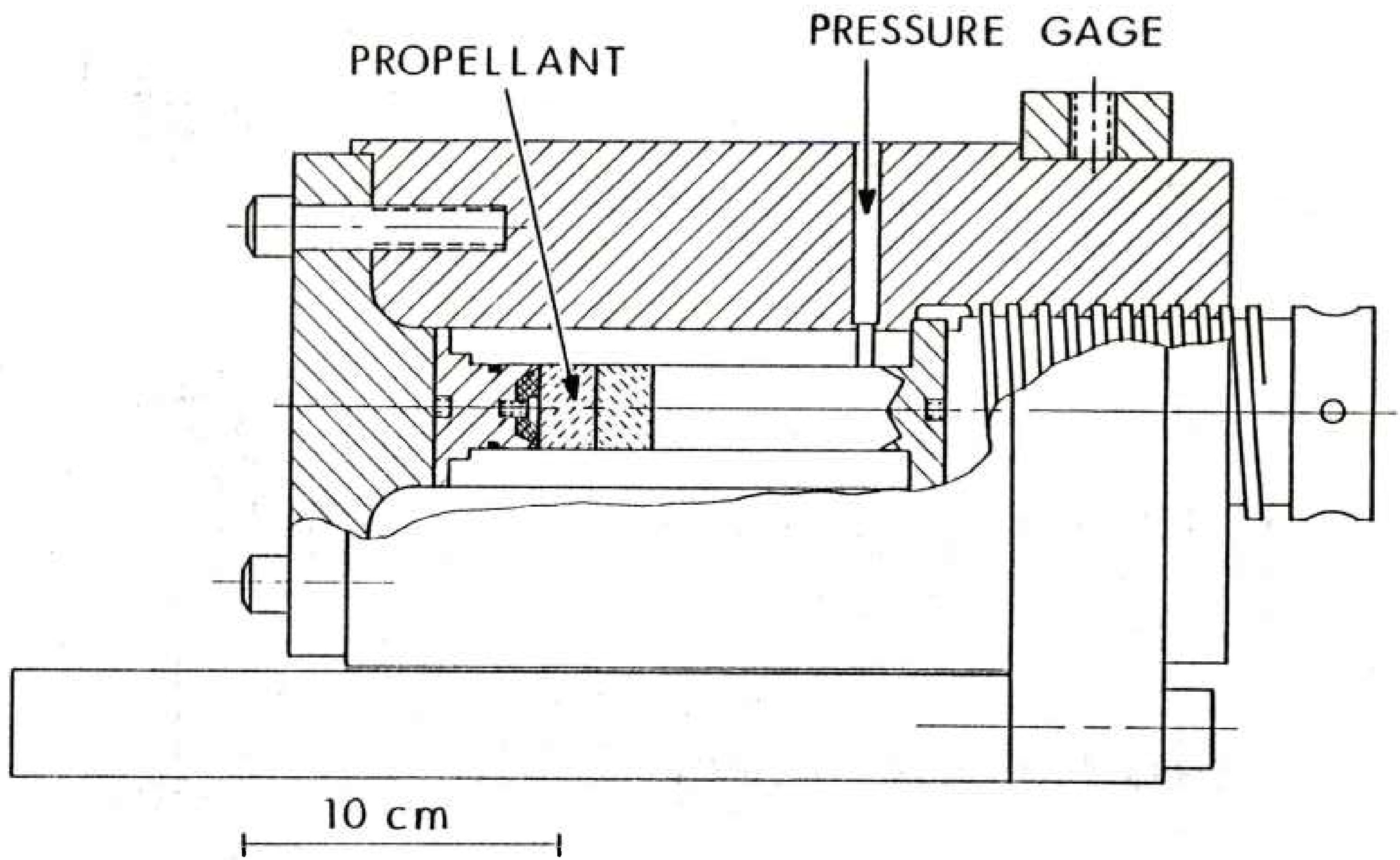

Figure 4. Closed Vessel Test Device

figures showing the surface area ratio, S/S_0, as a function of the fraction of propellant burned, S_0 represents the initial surface area for the equivalent amount of loose, granular propellant.

4.1. Baseline Propellant Burning Rates

The results from standard closed vessel experiments on granular M1 and HES propellants are shown in Figure 5. Each propellant was burned at 21°C with excellent reproducibility down to nearly 3 MPa. Burning rate variability at low pressures is not at all uncommon for closed vessel burning rate tests. It is usually ascribed to ignition and flamespread variability. It should also be noted that the burning rate curves for both propellants are linear only above 40 MPa. As expected the more energetic double base propellant also burns substantially faster. For each of the propellants an average burning rate table was constructed for use in the surface-area ratio analysis.

To test the internal consistency of the surface-area extraction routine in CBRED II, S/S_0 was computed for the loose propellant data from which the burning rate table was constructed. The results are shown in Figures 6 and 7. Superimposed on the "inverse" experimental curves is the ideal, single-perforated grain progressivity curve obtained from purely geometric considerations. The agreement from 10 to 80 percent of the fraction burned is pleasing. Again, ignition and flamespread effects as well as imperfect grain geometries are sufficient to explain the discrepancies in the extremes. From this exercise it should be obvious that the experimental variability for consolidated charges can only be greater.

4.2. Grain Deformation

The effect of the mechanical deformation of the single grain geometry is of interest. Figures 8 and 9 show samples of the base grain, the consolidated wafer, and mechanically broken-apart consolidated wafers. The single base propellant (RAD 68108) was not graphited, the double base propellant (HES 8567.11E) had a 0.02 percent graphite coating. Sample deconsolidation was done by placing single wafers between the plateus of a hydraulic press and pressing till initial wafer fracture took place. The differences in the grain break-up characteristics between the single and double base propellants are immediately apparent. Not so obvious, although of perhaps greater significance, is the observation of much less grain deformation with the lower L/D (1.18) DB propellant than with the high L/D (4.24) SB propellant. Physically, the single base wafers are stronger, presumably because of the greater intertwining of the longer grains. Of interest also, is the observation that the mechanical deconsolidation process results in granular aggregates of many different sizes. Some grain fracture is also observed. For the M1 propellant grains, collapse of the perforation is quite common. This is in distinct contrast with the double base propellant.

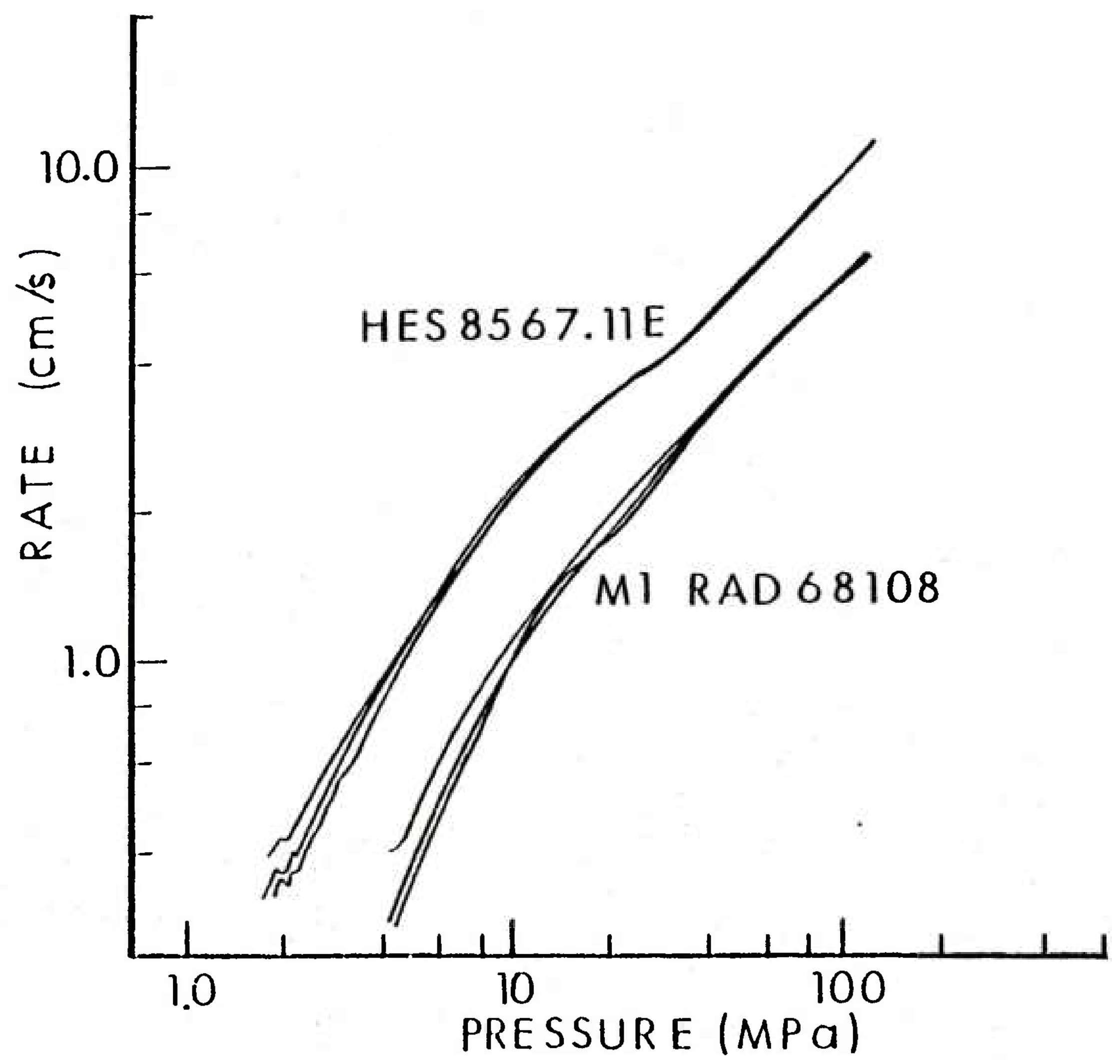

Figure 5. Baseline Propellant Burning Rates

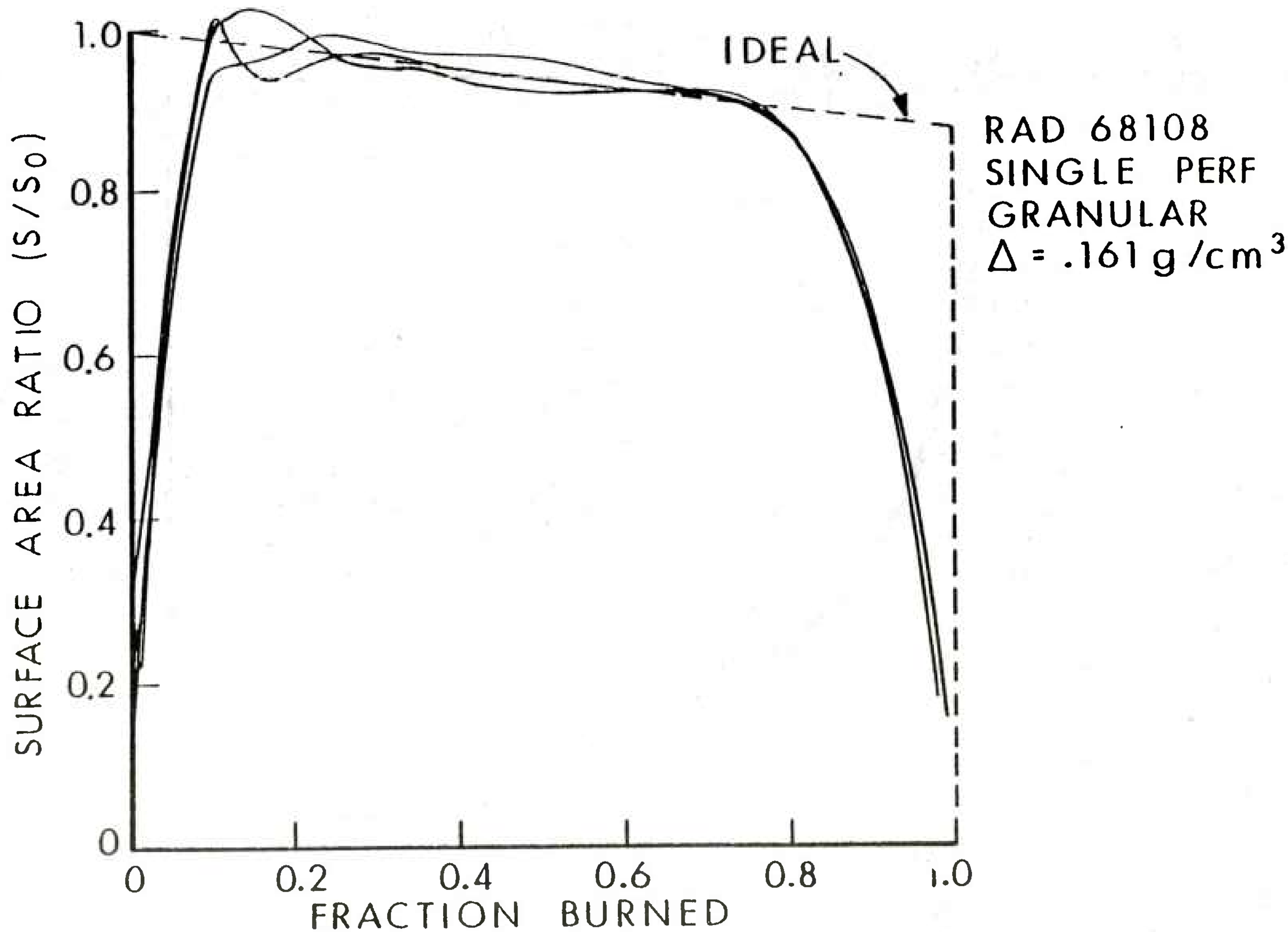

Figure 6. Inverse Reduction of Single Base Propellant Data

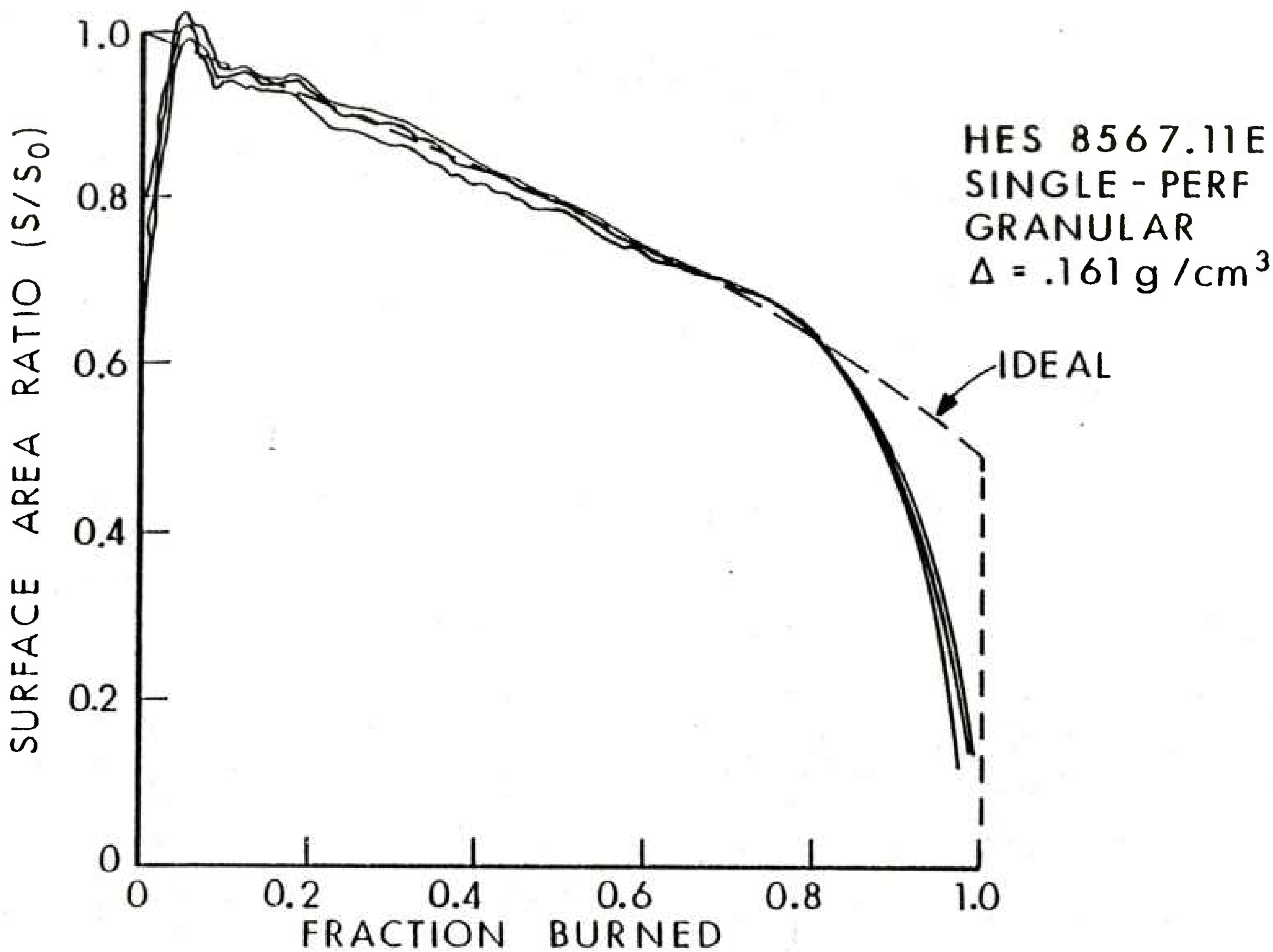

Figure 7. Inverse Reduction of Double Base Propellant Data

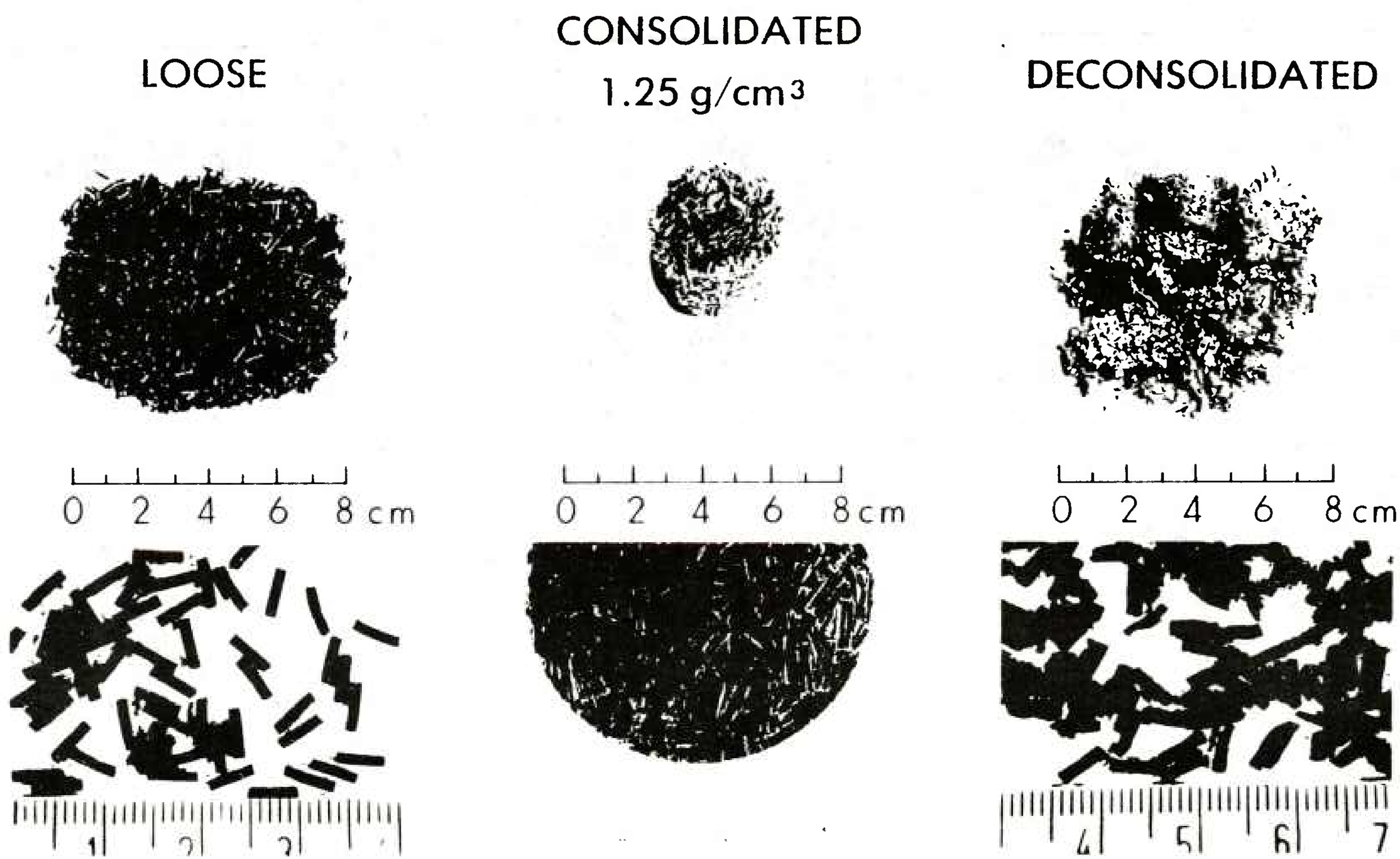

Figure 8. Single Base Propellant, M1 RAD 68108, Used in this Study

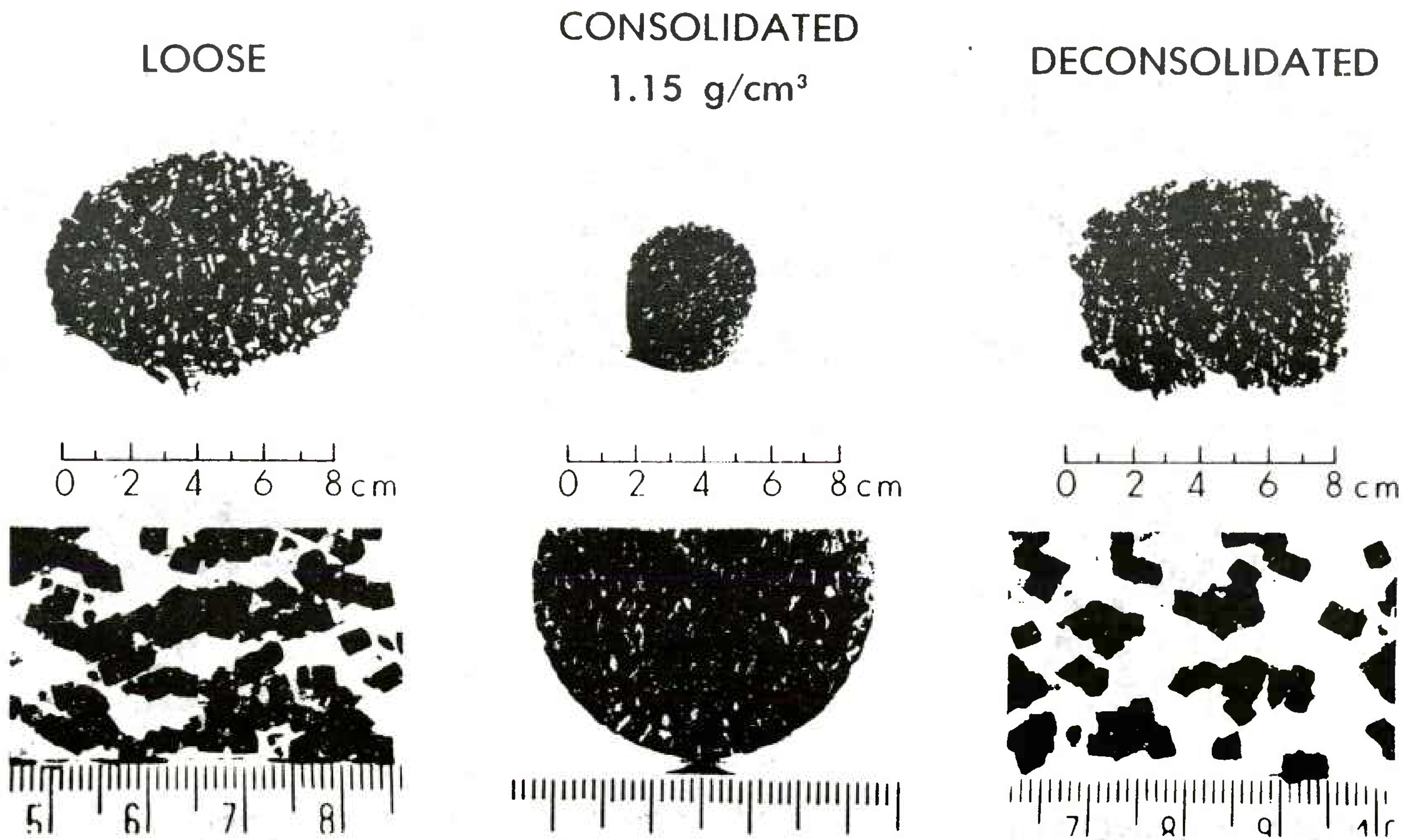

Figure 9. Double Base Propellant, HES 8567.11E, Used in this Study

Deconsolidated, whole, single grains were collected for standard closed vessel experiments. Assuming no geometry changes, pseudo-burning rates were then extracted as shown in Figures 10 and 11. For the M1 propellant, for which substantial perforation collapse is observed, the compaction process has a noticeable effect on the pseudo-burning rate. This is in distinct contrast to the double base propellant for which little change is noted. Our interpretation is that the greater single base grain L/D ratio is largely responsible for this effect, rather than any intrinsic composition effects. For comparison, pseudo-burning rates assuming perfect single grain geometry are shown in Figure 12 for consolidated double base wafers. The reduction in apparent burning rate due to the much lower burning surface area in the consolidated propellant is dramatic. To maintain ballistic equivalency in a gun firing, an approximately 50 percent reduction in web would be required in this particular case to compensate for the reduced surface area.

4.3. Reproducibility

Experimental variability of consolidated charges appears to be quite strongly correlated with compaction density. Figure 13 shows very poor reproducibility is obtained for the low compaction density samples. At high compaction densities much better reproducibility is observed as shown in Figure 14. We speculate that the higher strength wafers are much less susceptible to variations in igniter-induced grain break-up.

4.4. Compaction Density

Several trends emerge from the representative runs for the M1 propellant shown in Figure 15. The low density runs show a degressive behavior that is similar to the single grain surface profile although at a substantially reduced surface area. The high density (1.35 g/cm^3) surface area profile gives strong evidence of enhanced progressivity if S_o is redefined to be the initial surface area of the wafer at the end of the ignition-flame-spread phase. The intermediate density results fall in between the extremes. For the double base propellant data shown in Figure 16, the trends are not as clear. While the surface area decreases with increasing compaction density for the M1 propellant, as one would expect, the double base wafers show no such clear trend. With some imagination, the trend towards more progressivity with increased compaction density may, however, still be discerned. The concept of a macroscopic progressivity for consolidated propellants appears to be valid.

4.5. Ignition Effects

At the high compaction densities it was not possible to discern any substantial igniter-related effects. Apparently, if the wafers are strong enough to withstand a given ignition pulse, little changes in the combustion behaviors are to be expected. A modest, though not well understood, effect is, however, seen in the low density double base experiments shown

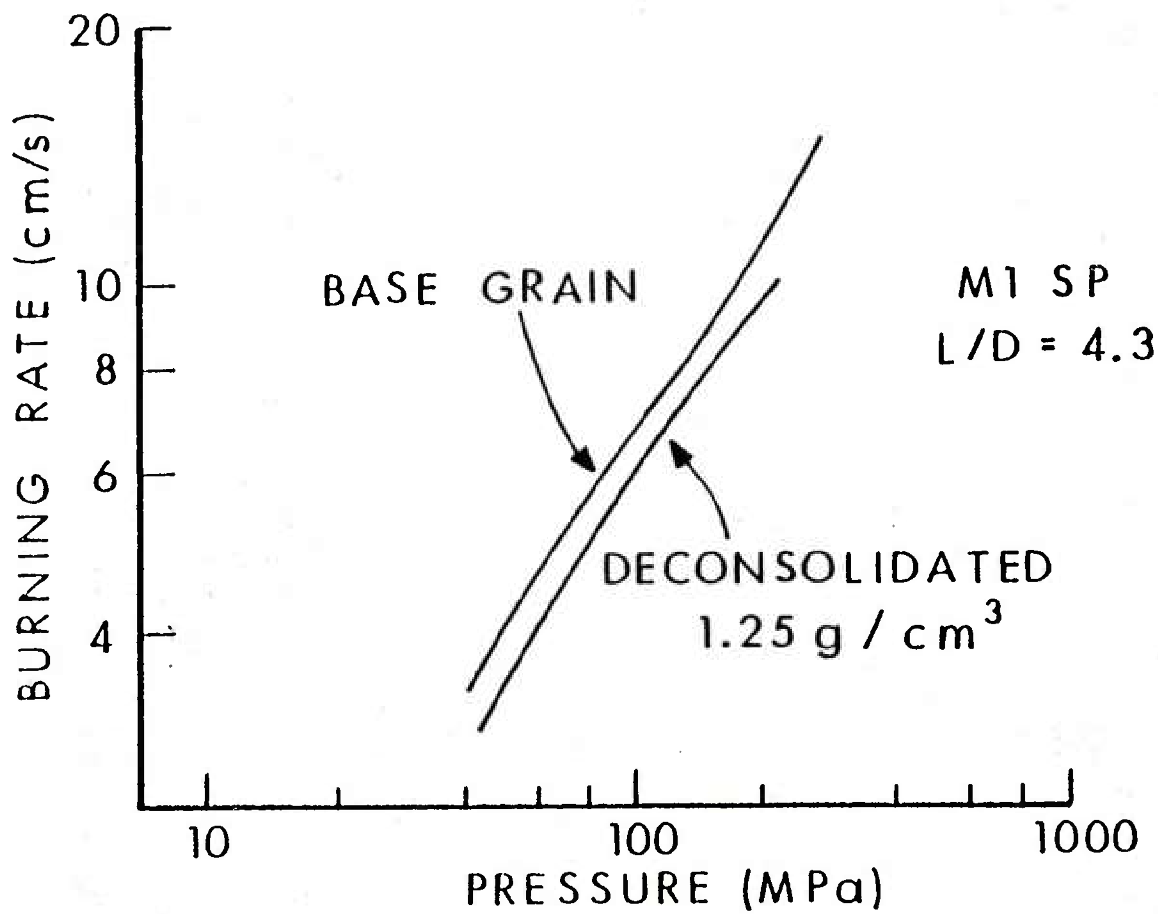

Figure 10. Pseudo-Burning Rate for Deformed Single Base Propellant Grains

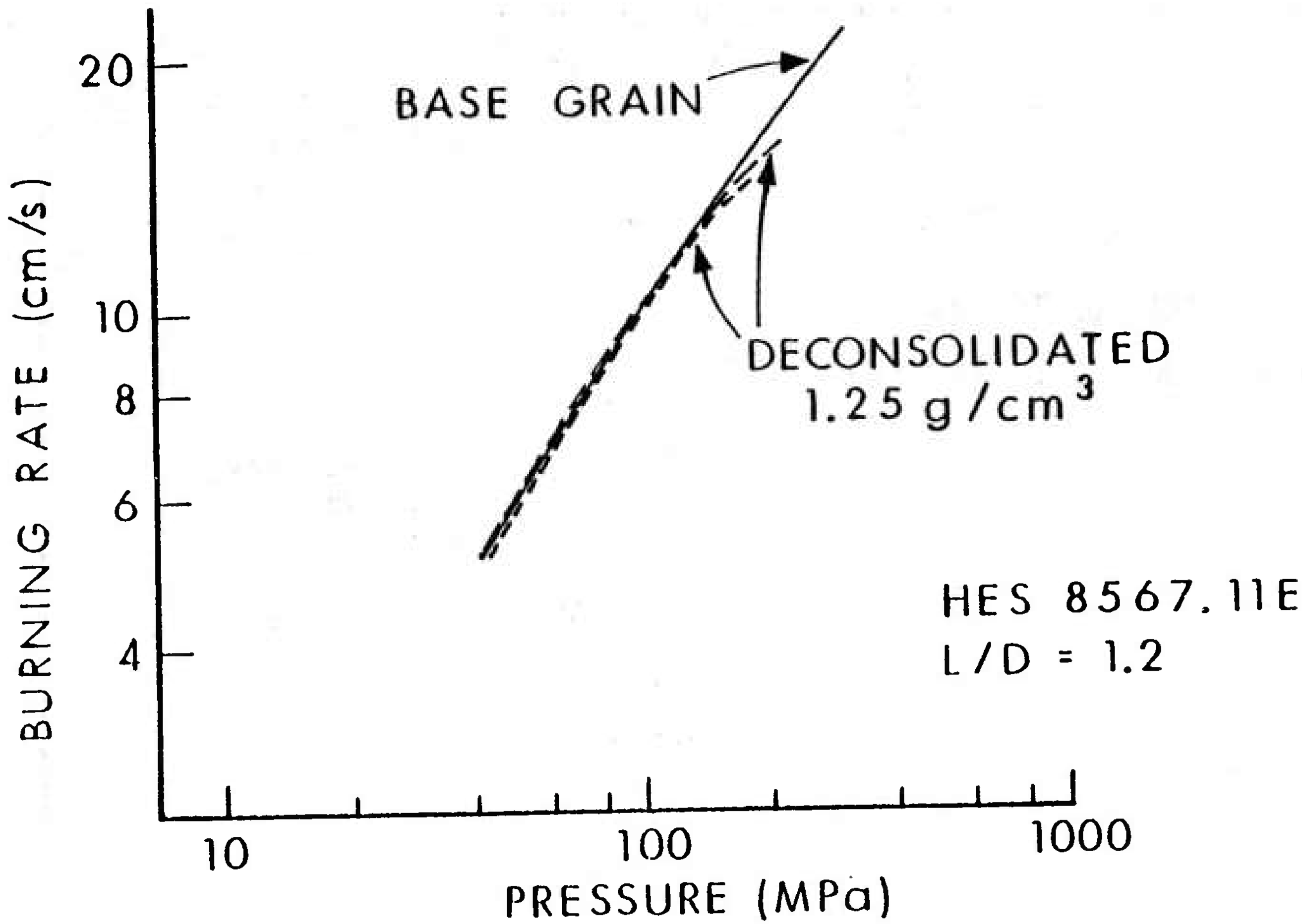

Figure 11. Pseudo-Burning Rate for Deformed Double Base Propellant Grains

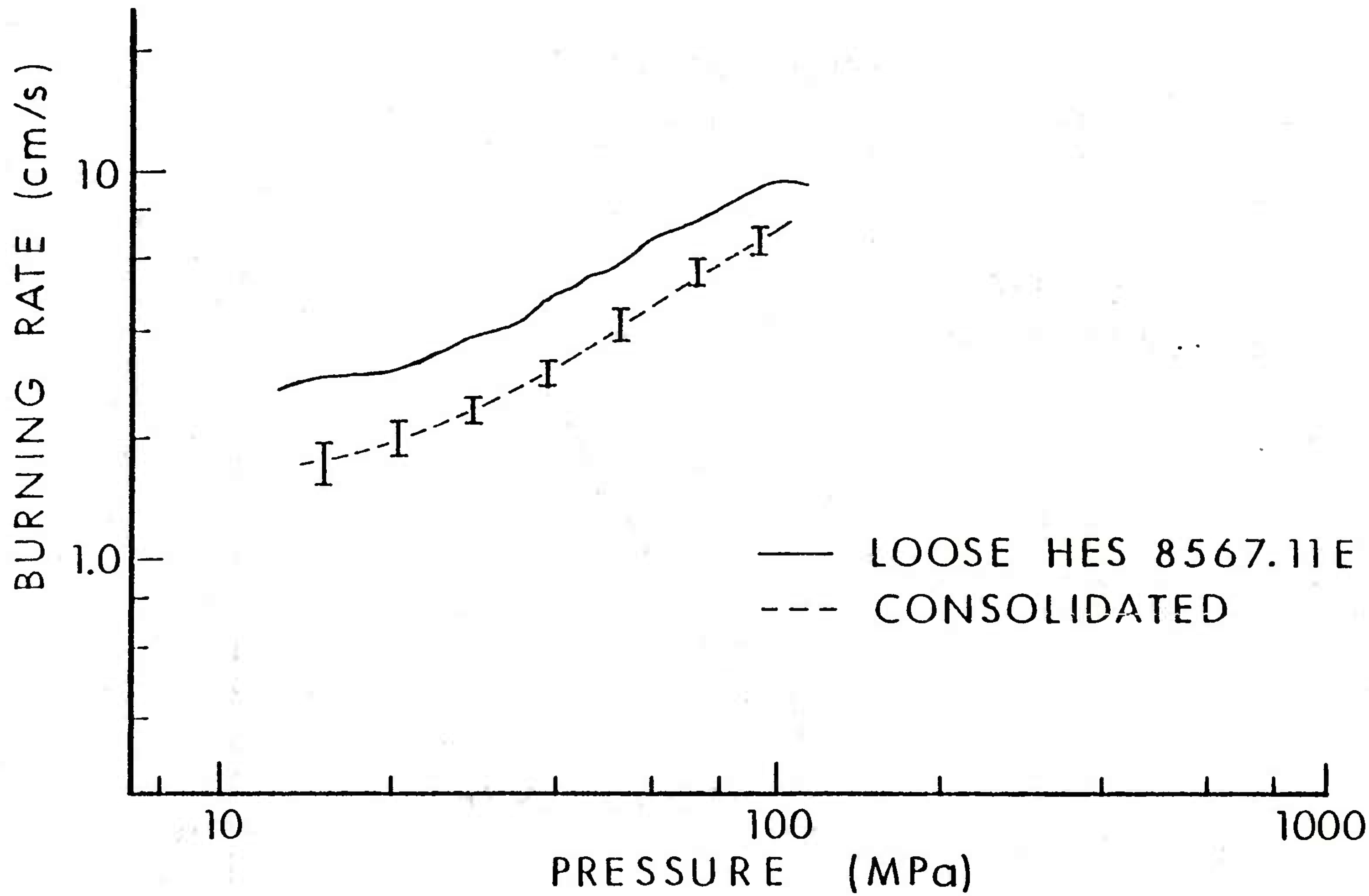

Figure 12. Pseudo-Burning Rate for Whole, Consolidated, Double Base Propellant Wafer (Reduction Assumed Perfect Single Grain Geometry)

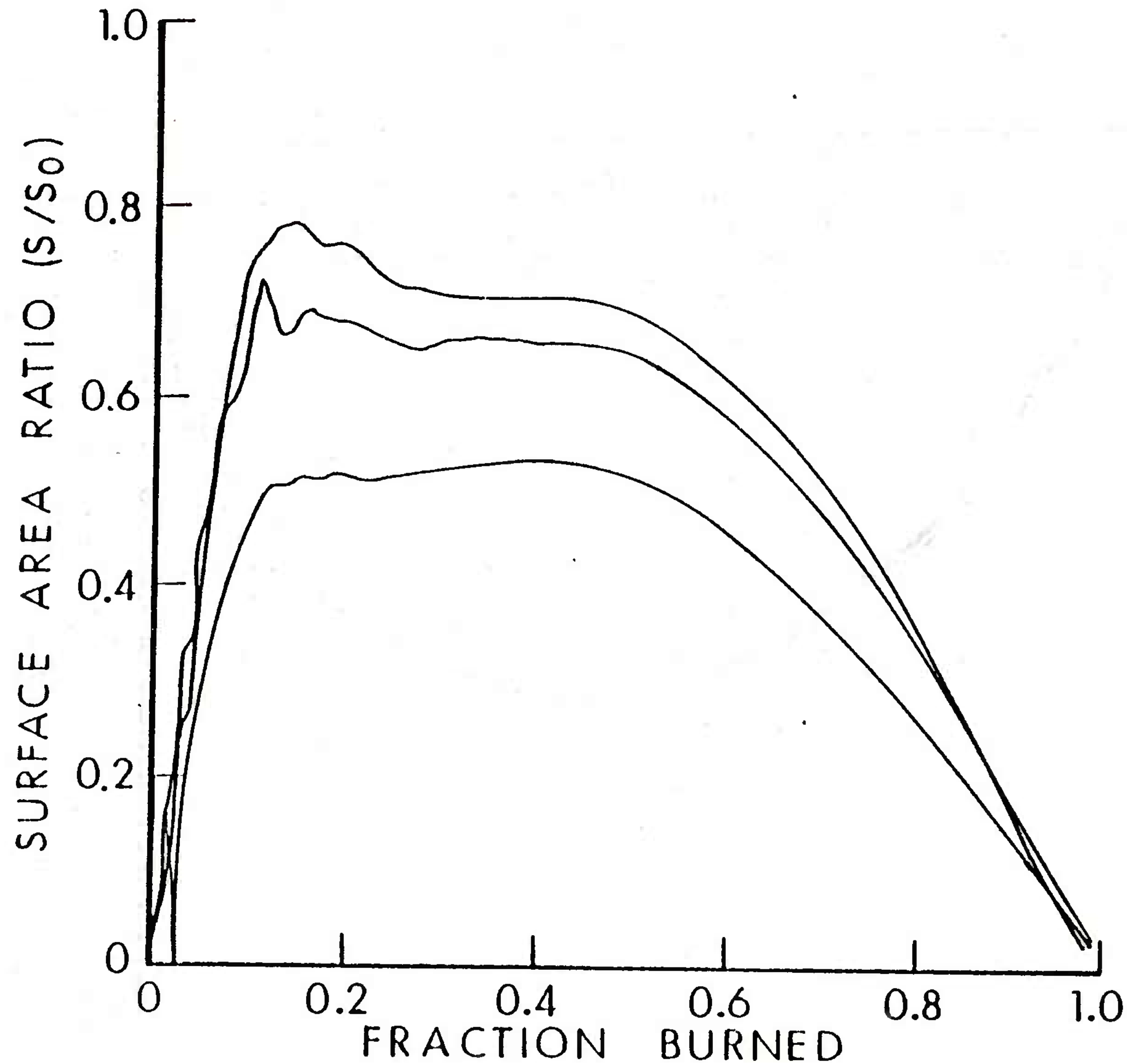

Figure 13. Reproducibility of Low Density Consolidated Wafers (M1, RAD 68108, 1.10 g/cm^3, "Soft" Ignition).

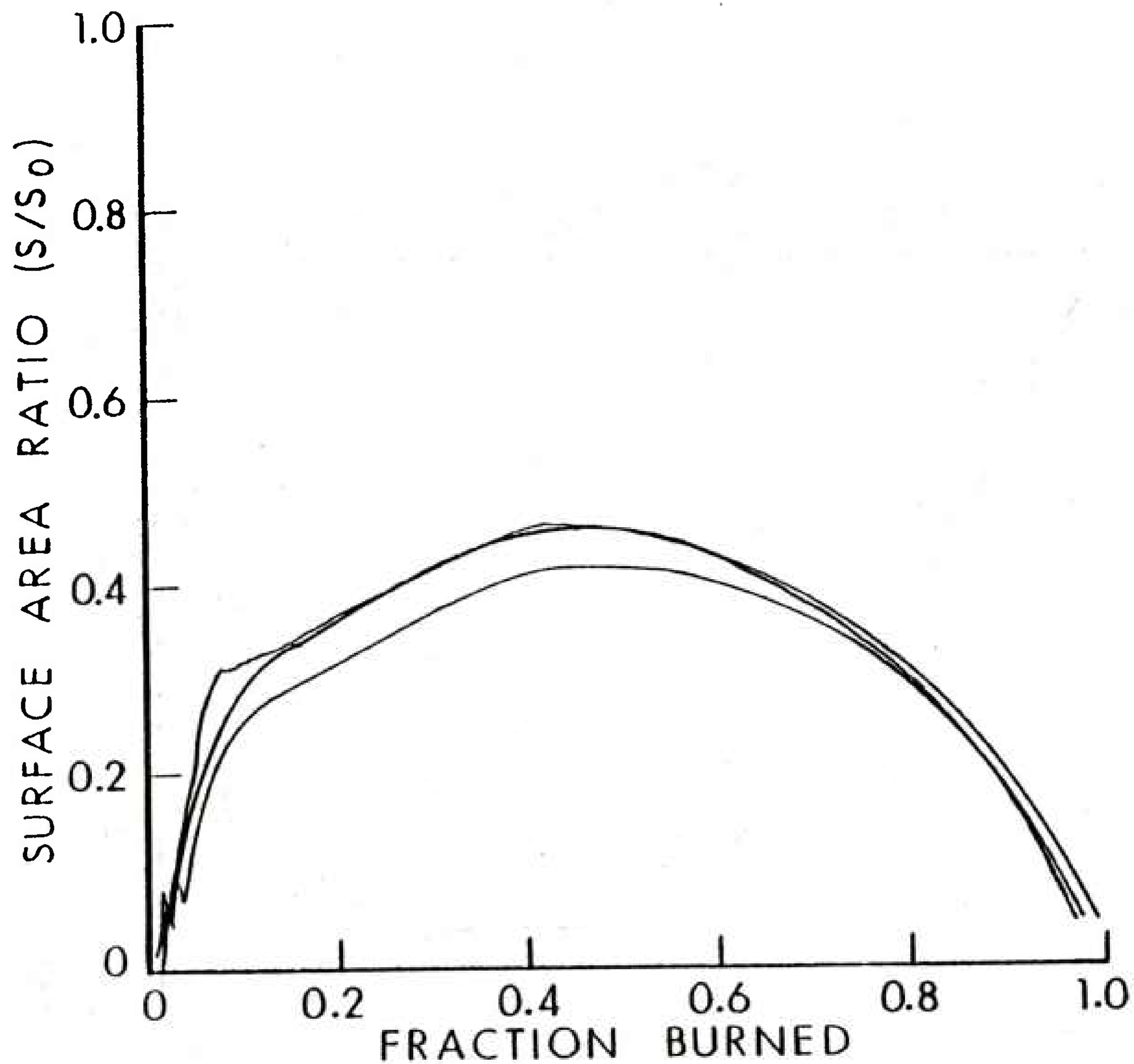

Figure 14. Reproducibility of High Density Consolidated Wafters (M1, RAD 68108, 1.35 g/cm^3, "Soft" Ignition)

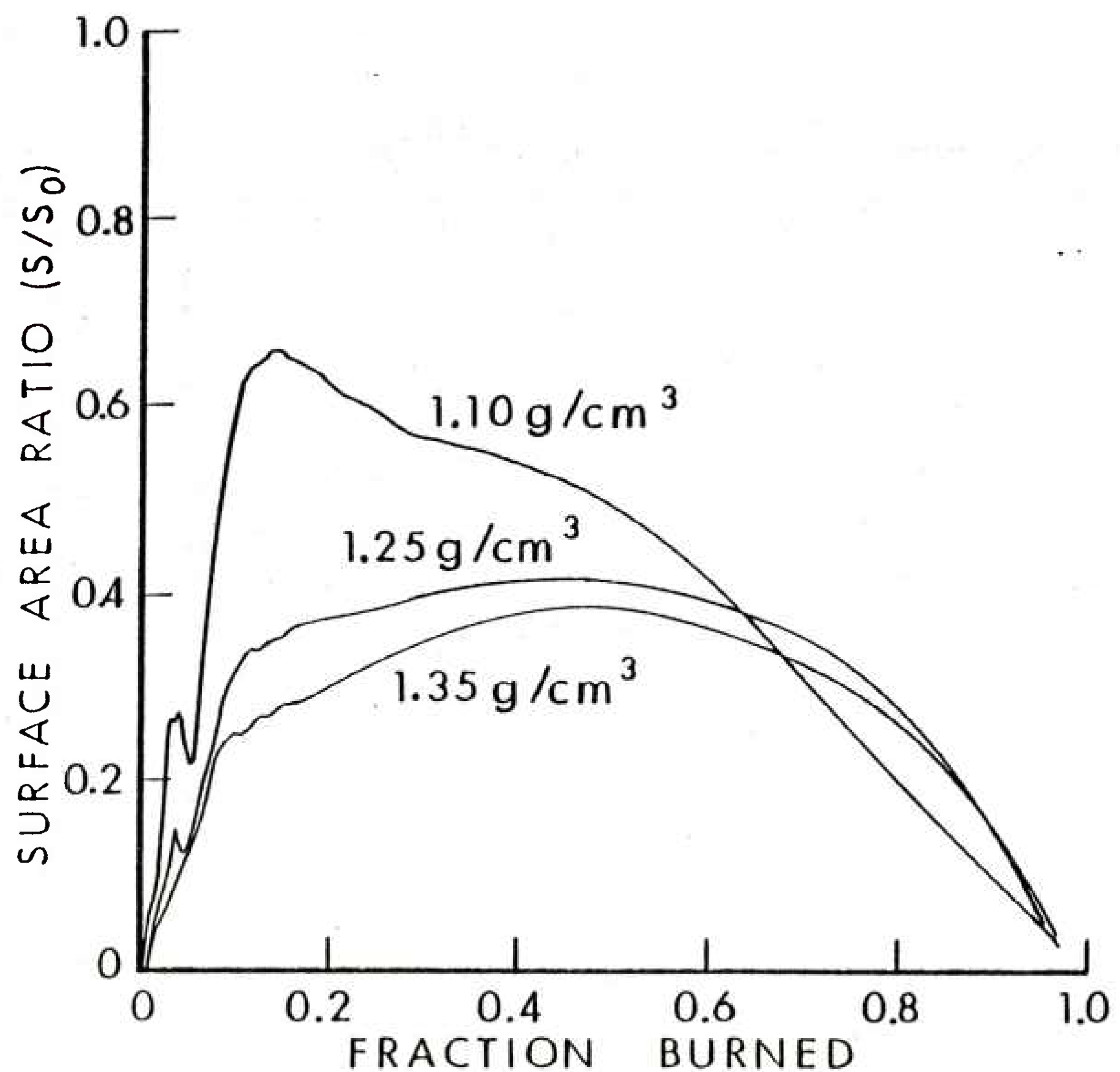

Figure 15. Compaction Effects on M1 Propellant with "Soft" Ignition

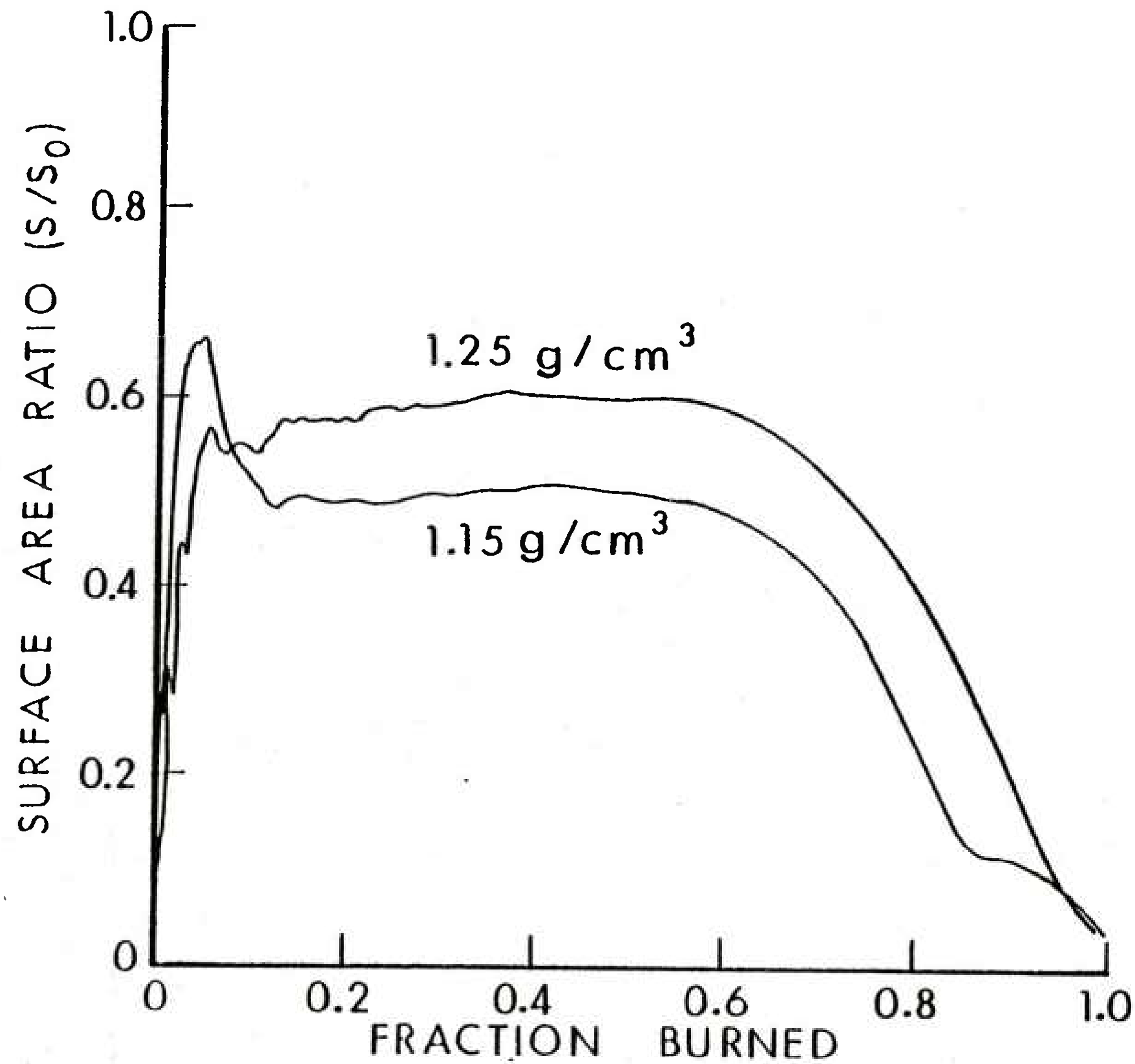

Figure 16. Compaction Effects on HES Propellant with "Soft" Ignition

in Figure 17. The "soft" ignition shows a fairly normal behavior. The initial overshoot in the surface area profile may be due to a small amount of igniter induced wafer break-up which is then burned up and collapses to the bulk wafer combustion mode. A rapidly damped, local pressure disturbance can also explain the overshoot. The "harsh" ignition case, however, shows clear evidence of pressure waves in the dp/dt data. These pressure wave disturbances then result in very erratic surface area profiles. At this time, we speculate that the "harsh" ignition, besides inducing a pressure wave disturbance in its own right, causes enhanced igniter-induced wafer fracture which may amplify the pressure wave problem. For future tests, it seems worthwhile to find the threshold ignition pulse which begins to have substantial effects on the combustion behavior of a consolidated charge of any compaction density.

Charge ignition delays were observed to be nearly 1.5 times longer for the soft igniter configuration. In addition, M1 is substantially less ignitable than the HES propellant as shown by a factor of two increase in ignition delay times.

5. SUMMARY

The postulated fracture-and flamespread-caused macroscopic surface area progressivity attributed to consolidated charges has indeed been experimentally verified, at least for the M1 single base propellant wafers. Figure 18 illustrates that even for the double base propellant an increase in the surface area ratio over loose, single-perforated grains is obtained. The compaction sensitivity of this phenomenon suggests that possibilities exist for improving and controlling the surface area profiles.

Reproducibility has been found to be strongly related to compaction density and, in this study, weakly ignition-dependent. We conjecture that with a much stronger ignition pulse than our "harsh" igniter, a larger igniter dependence might also be observed for the structurally-stronger, high-compaction density wafers. This hypothesis will be tested in the near future.

From the results of this experimental survey it has become apparent that sample burning characteristics can be related back to charge strength and base grain geometry characteristics. Some of the progressivity hoped for from consolidated propellants has already been realized. Further experimental efforts would do much to improve consolidated charge design capabilities. In addition to grain L/D, wafer strength can be controlled by other properties, such as presence/absence of graphite on the base grain or the use of a "binder" such as collodion in forming the base grain. The binder coating on the grains could act as a chemical deterrent as well. The combustion and progressivity characteristics of such samples could be readily examined via the closed bomb technique. Further, flash

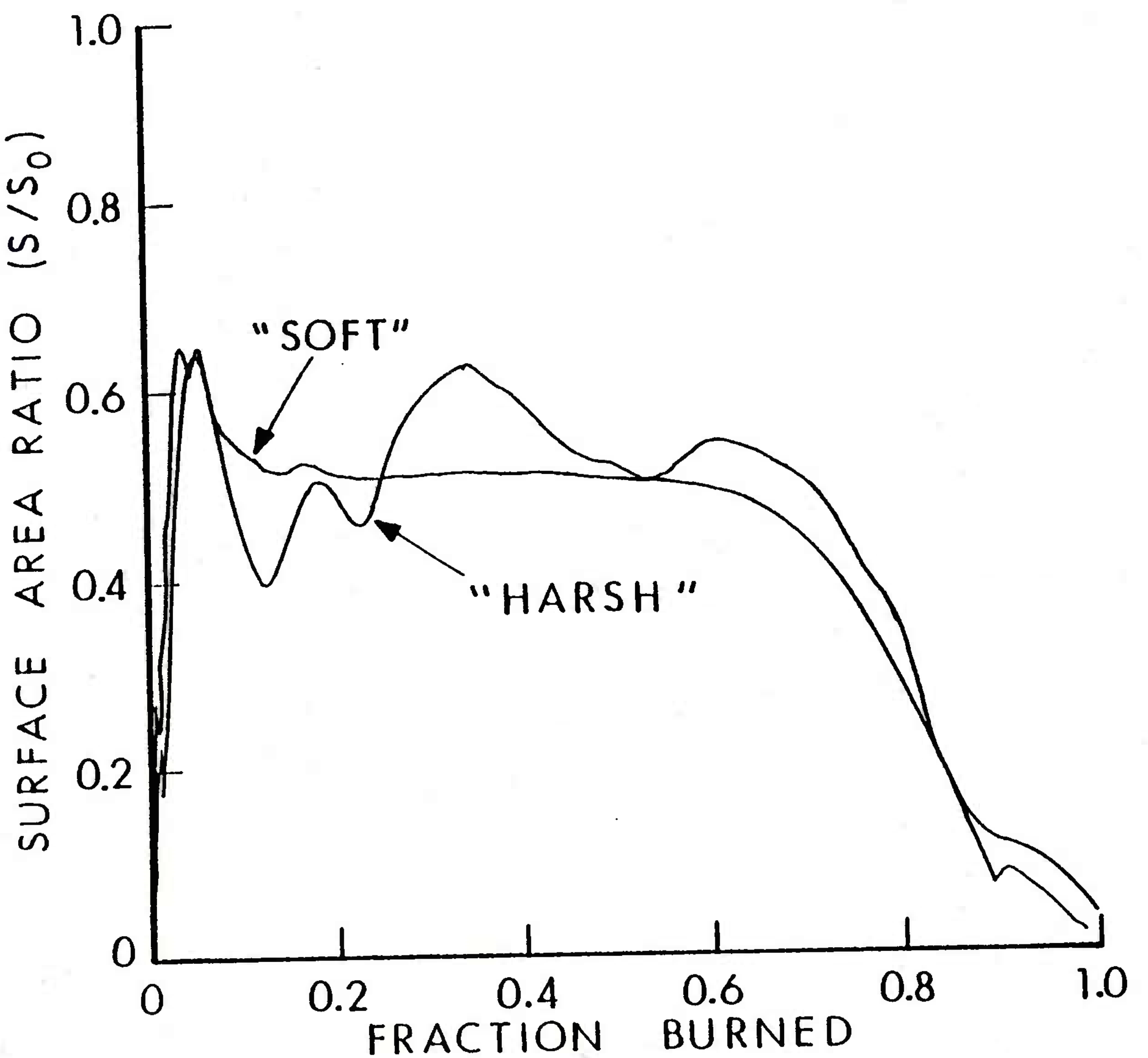

Figure 17. Ignition Effects on Low Compaction Density Double Base Propellant

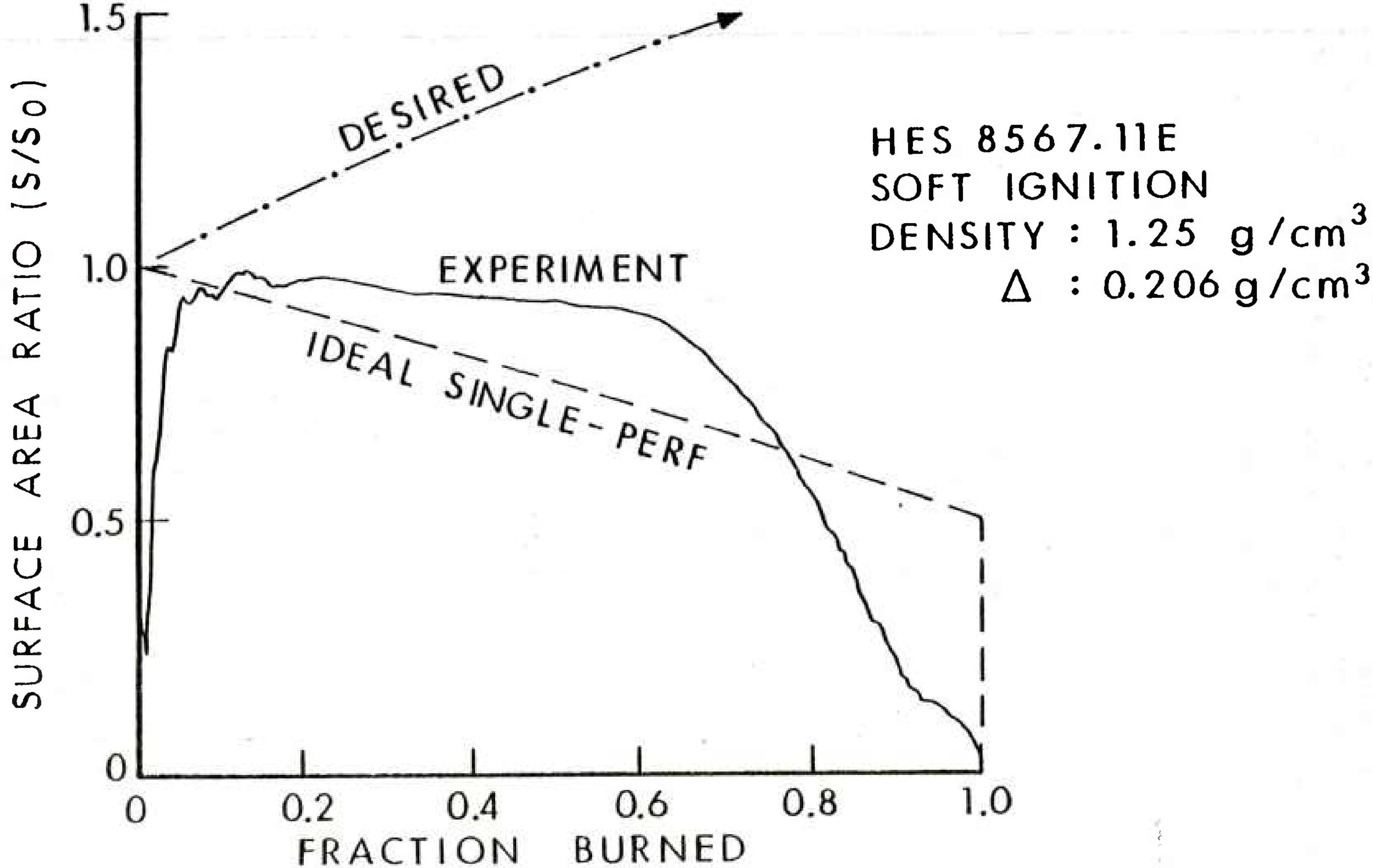

Figure 18. Progressive Burning in Consolidated Charges

x-ray diagnostics would be of great use in visualizing sample deconsolidation processes during burning. Real advances in consolidated charge design methodology can be realized through the interaction of preparation techniques, combustion diagnostics, and theoretical and experimental interior ballistic studies.

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