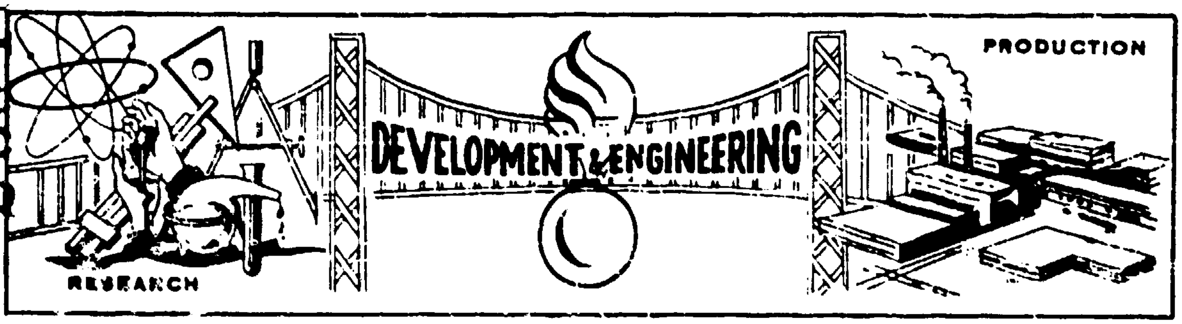

TECHNICAL REPORT

DB-TR: 3-61

ESTABLISHMENT OF IMPROVED STANDARDS FOR CLASSIFICATION OF EXPLOSIVES AND PROPELLANTS

REPORT NO. 1

A METHOD FOR DETERMINATION OF SUSCEPTIBILITY OF PROPELLANTS AND EXPLOSIVES TO UNDERGO TRANSITION FROM DEFLAGRATION TO DETONATION

BY

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PICATINNY ARSENAL - DOVER, NEW JERSEY

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SECTION I

INTRODUCTION

In assessing the hazard of an explosive under operational conditions, consideration of types of initiation which are foreign to the operation could lead to classification and costs far exceeding actual need. The intent of this project is to establish realistic methods of classification which will define precautions required under realistic operating conditions.

One condition of grave concern in this area is the possibility of transition from burning to detonation occurring in large high energy solid propellant motors. Many propellants are known to be detonable under extreme conditions of shock. If all propellants exhibiting this shock sensitivity were handled as high explosives the costs of large missile manufacturing and storage sites could be greatly increased.

In an earlier report (Reference la) recommendations of a series of screening tests were made for establishment of the hazard classification of the propellants in end items. The tests of this series could necessitate testing the end item itself. The method discussed here is an effort to develop a laboratory test which will supply the same type of information that is obtained from large-scale tests but at a much lower cost.

With this in mind, the work in this report is the first step in an attempt to determine under what conditions of thermal ignition the hazard of high order detonation actually exists.

SECTION II

SUMMARY

A new approach to the classification of high energy propellants and explosives according to their susceptibility to undergo transition to detonation shows promising results. Thus far, most of the materials tested show a critical pressure above which this transition can occur. The method involves the burning of large solid cylinders of the material under consideration in a closed bomb at high pressure. At a pressure which is characteristic for each composition and condition, the burning rate vs. pressure curve obtained shows a marked deviation from the results predicted from strand burning tests. This deviation is indicative of a pre-detonation reaction which takes place in the explosive and which could proceed into detonation if sufficient material were available.

At the present time, this method can determine the gross detonation characteristics of propellant materials -- those which will undergo DDT and those which will not -- under most severe conditions. Future developments will be aimed toward determining how such factors as size, physical condition and geometry will affect the detonability of these propellant materials so that a quantitative hazard evaluation can be made. This will eliminate the need for expensive testing programs on full-scale motors.

This interim report covers data obtained by this proposed method for two secondary explosives and a number of rocket propellants.

SECTION III

CONCLUSIONS

It appears from results of these tests that for each of the materials studied, there is a critical pressure above which the transition from deflagration to detonation (DDT) can occur. This is believed to be the result of a surface cracking or crazing which increases the burning surface and the rate of pressure rise to a point where a shock front can form. The existence of this condition is considered necessary for DDT to occur. If enough explosive material were available, the shock front could reach sufficient intensity to establish a detonation in the explosive.

The application of this test to explosives and propellants should eventually give a basis for a quantitative evaluation of these materials in terms of critical transition pressure, slope of the transition curve and minimum charge diameter. This would make possible classification of these materials as to severity of the conditions to which they can be subjected before the danger of DDT will exist. It would also make possible a study of the effects of temperature, porosity, particle size, crystal size and other physical variables on the detonability of existing propellants and new materials as they are developed. This test will be a valuable tool in the development of new formulations to study the effect of composition and processing modifications on the detonability of high energy materials.

SECTION IV

RECOMMENDATIONS

This method of testing should be used to classify propellants and explosives as to the possibility of transition to detonation taking place after ignition. In its present state of development, this testing method can be used to establish the gross detonation hazard characteristics of a propellant when subjected to the most severe conditions of temperature and geometry. For large missile motors, it can replace costly tests, such as fire hazard tests on full-scale motors, which are generally run to determine their transition to detonation (or explosive) characteristics.

SECTION V

STUDY

Background:

Generally, the classification of an explosive material has been based on its ability either to burn or its ability to burn and detonate. This is the basis for ICC Classifications A and B -- tested for by building a fire under the item to be classified and observing the result. The Armed Forces use a similar basis for classification. Class 2 represents fire hazards (violent burning without detonation or explosion or projection of missiles of appreciable size or range). Class 2A represents fire hazards which, under certain conditions, are capable of low order detonations. (These may mass detonate under very heavy confinement.) Class 9 materials are capable of mass detonation and include many of the higher energy compositions. The ability of a material to undergo transition from deflagration to detonation is not considered in this classification, since only the final condition of detonation is of concern.

As long as propellant compositions remained essentially nitrocellulose and nitroglycerin mixtures and were made in fairly small sized units, this method of classification was adequate. With the development of composite propellants and new high energy formulations, the 20% nitroglycerin concept (which had been established as the dividing line between Class 2 and Class 9 for N.C. types) no longer covers the field. For very large propellant motors, booster sensitivity tests do not tell the entire story either ... since there are numerous factors which will affect the ability of such a unit to detonate. Conditions of temperature, mass, particle size, geometry, porosity, aging, etc. will markedly affect the ability of a propellant to detonate. It may also markedly affect its ability to undergo transition from deflagration to detonation.

From an economic standpoint, the detonability or non-detonability of a propellant will have a tremendous effect not only on the cost of propellant manufacturing facilities, but also on the cost of handling large solid propellant motors and in the storage of large motors. Therefore it becomes important to find a method of evaluating the possibility of transition taking place under normal conditions of firing or under abnormal conditions, such as accidental or defective ignition or the development of defects in a propellant grain.

Existing test methods for evaluation of sensitivity fall into two basic categories: 1) those involving thermal ignition (ignition temperatures, friction pendulum, thermal decomposition tests) and 2) those involving shock initiation (booster sensitivity, gap tests). Some methods (drop test, bullet impact test) are a combination of both. None of these gives direct information about the basic property of the material which defines its susceptibility to undergo transition from deflagration to detonation. In this report, a method is presented by which a general evaluation of this property can be made.

Theoretical Basis

Kistiakowsky (Reference 1) described this mechanism for the development of detonation in a large mass of granular or crystalline explosive ignited thermally at a localized region within the bulk: As the explosive burns, the gases formed cannot readily escape between the explosive crystals and a pressure gradient develops. This crease in gas pressure causes an increase in burning rate which, in turn, causes an increase in pressure with constantly increasing velocity. This condition results in the formation of shock waves which are reinforced by the energy released by the burning explosive, these eventually reach an intensity where the entire energy of the reaction is used for propagation of the shock wave, and a stable detonation wave is produced. A critical size exists for each material above which this deflagration can pass over into detonation under proper conditions. Below this size, the burning will first increase, then fall off as the material is consumed. The transition to detonation is considered largely a physical process in which the linear burning rate of the bed of material increases to the rate of several thousand meters per second, although the individual particles are consumed at the rate of only several hundred inches per second.

The validity of this mechanism for propellants in granular form has been demonstrated by a number of investigators (Reference 2 and 4). While this mechanism is applied to granular material, why should it not apply as well to composite or homogeneous propellants, if the growth of a shock front can be shown (Reference 4) which is accompanied by an increasing break-up of the surface of the propellant? Analysis of the data from the following experiments indicates that this is a possible explanation of this phenomenon in solid propellants and explosives.

The apparent non-detonability (through transition) of nitrocellulose propellants may be attributed to the dense surface preventing deflagration from taking place in the interstices of the materials. In spite of this, under conditions (such as low temperature) where the propellant becomes very brittle or possibly crystalline, these propellants have blown up gun tubes. For composite propellants, the continuous and highly elastic nature of the binder probably prevents this type of reaction. However, it has been shown that many highly elastic materials will undergo brittle failure when stress at very high strain rates is applied (Reference 5 and 6).

Experimental Approach

If it is assumed that the surface burning theory holds for the release of energy to support detonation behind a shock front, and that the tremendous increase in burning rate in detonation is due to a large increase in burning surface due to a breaking up or surface cracking of the explosive material at the shock front, then by developing a technique for studying the burning rate of a propellant composition as it progresses into the very high pressure ranges, a basis for evaluating its relative susceptibility to detonation might be found.

Based on experience with some cannon propellants in closed bomb tests -- in which unexpectedly high rates of change of pressure were observed -- it was considered possible that the closed bomb technique might be used to demonstrate the property of detonability for rocket propellants. It had been found that when the tested lot of cannon propellant deviated from normal behavior, the occurrence of high rate of change of pressure started at a reproducible specific pressure. Since the burning rate law holds for these propellants up to high pressures, a reasonable explanation is that surface cracking or crazing occurred under the pressure and thermal stress of the reaction. This increase in burning surface is believed the initial step in the transition from deflagration to detonation and the critical pressure and the rate at which the increase in surface area occurs can be calculated from measurements made in the closed bomb.

The calculation of linear burning rate from closed bomb measurements has been standard procedure for many years (Reference 7 and 8). From a consideration of the original geometry of a grain of material and a knowledge of the rate of change of pressure in the bomb when the grain is burned, the linear burning rate at any particular pressure can be calculated. This calculation assumes that the grain is ignited uniformly over its entire surface and always burns normal to that surface. However, if surface cracking or crazing should occur, the calculated linear burning rate will be far in excess of the value expected, and the increase in surface area can be calculated from this apparent increase in linear burning rate. Details of these calculations is in Appendix A.

RESULTS

1. TNT

To determine whether the closed bomb method would throw any light on the burning of high explosives, cylinders of TNT were prepared with diameters of 1" to 1-1/4" and lengths of 1" to 3". These cylinders were machined from solid blocks of TNT which had been carefully cast to make certain that they contained no voids or porosity. All the cylinders were machined from the same block and were considered to have approximately the same crystalline structure. These cylinders were placed in a standard 200cc closed bomb with a reinforced cylinder wall and fired with a small amount of Grade A5 black powder and an M1A1 Squibb. Tracings of typical oscillograms resulting from the firings are in Figure 1. These represent a series of firings made with cylinders of TNT at various loading densities. In the first of these, a line is inserted representing the trace which should have been obtained if the cylinder of TNT had burned normally. However in each case a marked deviation from normal occurred at 6,000-8,000 psi. In examining these tracings it must be remembered that the standard closed bomb instrumentation produces an oscillogram of dp/dt vs. P and that the horizontal axis represents P and the vertical axis represents rate of change of P. The scale is varied to have the trace fill the oscillogram. The calculated series of P and dp/dt are added to the tracings.

When linear burning rates were calculated from these traces, the results in Table 1 and Figure 2 were obtained. An average line is drawn for burning rates calculated from the closed bomb test.

To establish the true burning rate for TNT strands 1/8" X 1/8" X 7" long were prepared by cutting them from a block of TNT similar to that used previously. These strands were burned in a strand burner using the standard technique at pressures from 1,000 psi to 20,000 psi. The test results are included in Figure 2.

The results in Figure 2 show that the calculated closed bomb burning rates approximately coincide with strand burner result up to about 6,000-8,000 psi and then sharply curve upward. This "apparent" increase in burning rate is consistent with the assumption of an increase in burning surface which occurs on the cylinder due to surface crazing or cracking. Figure 3 shows a graph of the expected surface area vs. pressure (lower curve) assuming normal geometry during burning of the grain and the supposed actual surface area [illegible] TNT calculated by combining the dp/dt of the bomb test with the actual linear burning rate from the strand burner (upper curve). This shows an increase in surface area of close to 20 times for TNT.

It was desired to determine whether the change of slope in Figure 2 was strictly a pressure and thermal effect and independent of the amount of TNT burned. Therefore, a technique was devised whereby a quantity of thin sheets of a very fast burning propellant was loaded into the bomb with the TNT. On ignition, this material burned quickly, giving an initial high pressure and temperature to the bomb before any appreciable burning of the TNT took place. This technique permits a larger mass of TNT to be present at higher pressure. Measurement made in this way showed virtually no change in the pressures at which the change in slope took place in the lower part of the curve or in the slope of the middle part of the curve. However, an increase in the slope of the upper part of the burning rate curve did result. This tends to confirm the idea that there is possibly some minimum mass of explosive necessary to maintain the formation of increasing burning surface. This area will be further investigated.

2. Composition B

Cylinders of Composition B prepared in a manner similar to the TNT samples were then burned in the bomb at varying loading densities. To obtain adequate ignition of Composition B it was necessary to use a small amount of sheet propellant as igniter. This masked that part of the curve below about 5,000 psi. However, strands cut from the same block of Composition B as the cylinders were burned in the strand burner to obtain the normal burning rate vs. pressure curve (Table II and Figure 4 and 5). The conclusion is that the break in the Composition B curve occurs about 4,000-5,000 psi. The slope of the closed bomb curve past the transition may be even greater than that obtained for TNT. The surface area vs. pressure curves for calculated normal burning vs. actual closed bomb burning of a sample of Composition B is in Figure 6.

3. ARP Propellant

A sample of ARP propellant was subjected to the closed bomb test. To establish the applicability of the closed bomb technique to determine detonability of high energy propellants. Figure 7 shows a series of tests resulting from increasing loading densities up to about 0.40. When increased to 0.43 by preloading with sheet propellant, a change in slope occurred at about 35,000-40,000 psi similar to those obtained for TNT and Composition B. This was accompanied by a disintegration of one of the seals in the bomb. Unfortunately, each time conditions were used in which the transition was expected to appear, the rate of energy release was so great that some part of the bomb seal was destroyed and a part of the trace was lost. A bomb is being designed to hold the pressures produced and measure transition pressures similar to those obtained for TNT and Composition B.

Table III and Figure 8 show a plot of linear burning rate vs. pressure calculated from the available data for the ARP propellant burned with and without preloading. The linear burning rates obtained with the strand burner are almost coincident with those calculated from the closed bomb at pressures of 10,000 psi and above.

4. Experimental Propellant

A sample of highly sensitive experimental propellant was then subjected to this detonability test. This material had been found to be detonable with No. 6 blasting cap. Cylinders of different diameters were tested and pressures up to 85,000 psi were obtained. A sharp transition was obtained at about 15,000 psi (Figure 9). Also, the fall-off from the maximum dp/dt begins at a much lower percentage of the maximum pressure than for the high explosive samples. Figure 10 and Table IV show the data and a plot of the linear burning rates calculated from the closed bomb traces. The strand burner curve was extrapolated from low pressure data since strands of this material were not available for high pressure testing. Figure 11 shows the surface area relationship between expected area and supposed actual area obtained.

5. Rohm & Haas QZ Propellant

A sample of QZ propellant composition was obtained from Rohm and Haas at Redstone Arsenal, Huntsville, Alabama. This material is the same propellant composition that detonated in a 7,000-pound motor in the

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summer of 1959. While the failure of this motor was attributed to some porosity of the propellant or poor case bonding in some areas (Reference 9), there is little doubt that the explosion was high order.

The samples were machined to cylinders of 1.25" and 1.50" diameter and tested, first at 70°F and then at -60°F. Figure 12 shows traces of typical oscillograms from these tests. The 70°F tests showed normal burning rates when calculated up to 90,000 psi. The low temperature test showed an abrupt change from normal burning at about 55,000 psi. The increase in burning surface calculated from this apparent increase in burning rate is of the order of four times and is in Table V . . . as are the apparent burning rates. While this increase in burning rate is small compared to some of the other materials tested, the abrupt change at only low temperature indicates the development of an undesirable property which might lead to a hazard.

Discussion of Results

A preliminary study of the data obtained for the ratio of cylinder area to supposed actual area -- the area that would exist if normal burning took place with no break-up -- indicates the existance of a diameter below which the continued cracking or increase in surface area stops and the explosive tends to return to normal burning. This occurs because there is not sufficient material available to develop a shock wave of sufficient intensity to go to detonation.

Figure 13 shows the ratio of surface area from closed bomb to expected surface area for the same cylinder of TNT presented in Figure 3 (assuming no break-up takes place). This shows that the ratio increased until about 50% of the mass of the grain was left (determined from percent of P max).

An equivalent study for a Composition B cylinder in Figure 14 shows that the increase in surface did not start to level off until about 70% of the grain was consumed.

The "Experimental Propellant" was tested in cylinders of different diameters and the changes in burning rate as a function of geometry were calculated. It was found that for cylinders of two different diameters, increases in surface area were obtained as long as burning proceeded to a diameter of about .78 inch -- the same for both sizes tested. This indicates the possibility that there is a minimum diameter characteristic of each material. It may explain why in earlier work on burning of explosives in a closed bomb by Buck, Epstein and Jacobs under the NDRC (Reference 11), the high burning rates described in this report were not observed, since the explosives were burned in small grains.

An analysis of the relationship of unburned fraction and remaining diameter to the changing burning surface for Rohm and Haas QZ Propellant shows that the burning surface stops increasing when the diameter of the grain reaches 0.8 inches at -60°F and then decreases back to normal burning. If sufficient mass were available, it is believed this increasing burning area would be maintained and might be sufficient to set up the conditions necessary for transition to detonation.

In addition to the data reported above, a number of other less sensitive materials were tested in the bomb, with and without preloading. OIO propellant taken from "Honest John" grains were tested in 1" diameter cylinders and Polysulfide Perchlorate propellant samples from XM30 motors were tested and found to give normal traces up to pressures of 80,000 psi. This indicates that, at the temperature of testing and in the physical condition of the tested samples, transition to detonation from normal burning could not occur unless conditions were more severe than those used in the tests.

The correlation of severity of conditions in the bomb, with the severity of conditions which might be encountered in actual burning still needs to be investigated. Since the Rohm & Haas QZ propellant is considered to have detonated in a 7,000-lb. motor on a test stand after high pressure conditions were obtained because of porosity and poor bonding (Reference 9), the possibility exists that the shock conditions resulting from the high pressure development in this test motor might have induced this material to undergo transition.

The question has been raised: Is it possible for cracking or crazing of the surface of this material to occur due to hydrostatic pressure applied in the bomb? Considering the rapidity of the rate of pressure rise under the conditions of the bomb test, it is conceivable that hydrostatic conditions are not attained within the time that the event occurs; rather an unbalanced stress develops in the grain giving rise to a tensile stress in the material. For crystalline materials like TNT the cracks could develop in the crystal boundaries. Confirmation of this might be obtained if castings of TNT of different crystal size were subjected to the Closed Bomb Test. Different rates of change of surface area should be obtained for the different crystal sizes. For Composition B, the brittle matrix of TNT plus the interfaces of the RDX particles probably lowers the pressure and dp/dt at which this phenomenon occurs. For propellants which are more elastic in nature, this mechanism does not occur until very high pressures and rates of change of pressure are reached. The fact that brittle fracture occurs for highly elastic materials at very high rates of strain has been demonstrated by J. W. Jones (Reference 5 and 6).

In any case, the pre-detontation reaction is probably a function of the three conditions of pressure, rate of change of pressure and temperature.

It is believed that any explosive or propellant material which can be detonated should exhibit the phenomenon of the pre-transition reaction and critical pressure described in this work. In the case of very sensitive primary explosives, the level of the controlling parameters required to start high order detonation is so low that they cannot be measured by present techniques. For "non-detonable" composites or single base propellants, it is possible that the pressures and rates of change of pressure required are extremely high. Efforts are being made to develop the technique into a practical test of propellants at much higher pressures so that any materials which can be detonated with high explosive boosters can give a positive test in the closed bomb. After this technique has been worked out, entire series of propellants in use in existing missiles, and those compositions under development, will be subjected to this test for the purpose of classification.

Future Work

A program has been undertaken to design a high pressure vessel capable of making the required measurements up to 400, 000 psi. The principle being explored is that of a disposable unit which will hold the pressure long enough to make the necessary measurements of pressure and rate of change of pressure. The design of a transducer with a frequency response sufficiently high (200-500 KC) to obtain accurate measurements is also being investigated.

To relate the results of this test to actual conditions in a large motor, an effort is being made to establish the relationship between the rate of pressure rise which might occur in a large mass of propellant and the time to tensile failure of this mass of propellant, if a small defective area should exist (one containing a porous section in which the surface area available for burning is much larger than normal). If it can be shown that the local pressures obtainable under reasonable conditions of defects are in the range of the critical pressure required for the pre-transition reaction to occur, then it is considered reasonable to assume that transition from burning to detonation is possible in the given full scale grain.

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APPENDICES

APPENDIX A

METHODS OF DATA REDUCTION AND CALCULATIONS

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METHODS OF DATA REDUCTION AND CALCULATIONS

I. Linear Burning Rate

A. Theory

The linear burning rate is the rate at which the burning surface of a propellant recedes in a direction normal to the flame front.

If dx is the distance burning proceeds during any time interval dt, then dx/dt is the linear burning rate.

By assuming that all surfaces of the burning propellant burn at the same rate, and by using a known geometry, the linear burning rate can be deduced from the mass rate of burning. By the assumption of a suitable equation of state the mass rate of burning can be deduced from the rate of change in pressure surrounding the burning propellant in a closed vessel.

For particles of known shape, such as perforated or solid cylinders, the closed bomb fitted with a rapid response pressure gage is a suitable experimental apparatus for determining the linear rate of burning of propellants or explosives at any pressure.

The apparatus produces an oscillographic trace of piezo-originated voltages as measures of the rate of change of pressure, dp/dt, and pressure, P. Sample traces are shown in Figure 1. The rate of change of pressure is calculated from the ordinate voltage V_x, and the pressure from the abscissa voltage, V_y, after appropriate calibration and determination of gage constants.

$$P = K_g C_x V_x + K_1 \qquad (1)$$

$$dp/dt = \frac{K_g V_y}{R} \qquad (2)$$

The maximum pressure (at the end of burning) can be used to measure the combined temperature and gas molecular weight function, thus completing an expression for the equation of state in terms of Z, the weight fraction burned, and P_i, the pressure due to prepressurizing and igniter, if any, where K_g, C_x and K_1 are equipment constants:

$$P_{max} = K_g C_x V_{xmax} + K_1 \qquad (3)$$

$$P = P_i + \frac{Z \left[\left(1 - \frac{m_i a_i}{m_o} + a\right) D_o \right]}{1 - \left[b + \frac{m_i a_i}{m_o} + (a-b) Z \right] D_o} (P_{max} - P_i) \qquad (4)$$

To simplify calculations the term $(m_i/m_o)\, a_i$ is considered negligible because of the relatively small quantity involved in m_i, the mass of igniter and prepressurizing materials.

The geometry for solid cylinders of propellant or explosives burning on all surfaces is stated in terms of fraction burned, Z, and dimension remaining, (d-2x) and (h-2x), at any time:

$$Z = 1 - \frac{(d-2x)^2 (h-2x)}{d^2 l} \qquad (5)$$

The derivative, dp/dZ, may be found from equation 4 and the derivative dZ/dx from Equation 5:

$$dp/dZ = f_1 \; (Z) \qquad (6)$$

$$dZ/dx = f_2 \; (x) \qquad (7)$$

The linear burning rate can be calculated from Equations 2, 6, and 7:

$$dx/dt = \frac{dp/dt}{(dp/dZ) \; (dZ/dx)} \qquad (8)$$

B. Calculation Method.

The Equations 4-8 have, in principle, been re-arranged by W.F. Wallace (Reference 8) to a form suitable for direct solution. The solution was made in terms of the surface area (S_x) at any value of x. With slight modifications, Wallace's equations were used to convert the closed bomb data to linear burning rates.

The equations used for this solution for a solid cylinder are listed below. These equations were programmed for solution in an IBM 650 computer.

$$K_6 = (d-h)^2 / 1.5 \, hd^2 \qquad (9)$$

$$K_5 = 27 \, hd^2 / 2 \, (d-h)^3 \qquad (10)$$

$$B = (P_{max} - P_i)(1 - aD) / (a-b) \, D \qquad (11)$$

$$C = (1-bD) / (a-b) \, D \qquad (12)$$

$$Z = \frac{(P - P_i)(1-bD)}{(P_{max} - P_i)(1-aD) + (P-P_i)(a-b) \, D} \qquad (13)$$

$$E = 1 + K_5 (1-Z) \quad (14)$$

If $E < 1$

$$\phi = \cos^{-1} E \quad (15)$$

$$S_x/V_o = \left[1-2 \cos (60° + 2/3 \phi)\right] K6 \quad (16)$$

If $E \geq 1$

$$S_x/V_o = \left[\left(\left[E+(E^2-1)^{\frac{1}{2}}\right]^{1/3} + \left[E-(E^2-1)^{\frac{1}{2}}\right]^{1/3}\right)^2 -1\right] K_6 \quad (17)$$

$$dx/dt = \frac{dp/dt}{\frac{B}{C}\left(1+\frac{P}{B}\right)^2 \frac{S_x}{V_o}} \quad (18)$$

In these equations certain special cases had to be recognized to allow for discontinuities introduced by algebraic and trigonometric solutions. When diameter exactly equals length, a discontinuity arises in (Equation 9) for K_6. An increment of 0.01 inch is therefore added to one dimension for this special case. If the quantity E is less than unity a cosine procedure is used (Equation 15); if equal to or greater than unity a cube-root procedure is used (Equation 17). Either procedure leads to S_x/V_o which is then used in the final equation (Equation 18) with the experimentally observed dp/dt to calculate the linear burning rate dx/dt.

II. Equivalent Surface Areas

A. Theory

When linear burning rates of single cylinders of propellant or explosive are found from closed bomb data using the solid cylinder geometry as described above, the results compare well with strand burner results below a certain characteristic pressure. At other pressures the burning rate so calculated must be regarded as an "apparent" burning rate because it deviates a great deal from strand burner results.

This suggests that the general configuration may be cylindrical, but the surface may be full of cracks or may be breaking into small pieces, with the strand burning rate governing the reaction for each burning particle. Combining experimentally determined rate of pressure rise, dp/dt, and pressure, p, with strand burning rates, dx/dt, permits solving for a surface area, Sx, which will reflect the abnormally high mass rate of burning.

Thus P, dp/dt, and P_{max} are found as before Equations 1, 2, 3. The equation of state showing total pressure as function of fraction burned is also applicable (Equation 4). Likewise the fraction burned is related to the burning cylinder dimensions by Equation 5 for a smooth cylinder. In Equations 8 and 18, however, the predicted linear burning rate from strand burner data,

$$dx/dt = ap^n$$

would be used. Then from Equation 18 the equivalent area S_x is found representing surface area of cracks and convolutions on the surface of a rough cylinder. The equivalent areas are found to proceed through a maximum (Figure 3) before reaching zero during burning.

APPENDIX B

TABLES

Test #7

Loading Density, g cc-.11
Max Pressure, psi-14,310
Diameter, in-1.00
Length, in-1.01

$PX10^{-3}$	dp dt $X10^{-5}$	Burning Rate in sec	Fraction Burned (Z)
2.11	[illegible]	.237	.160
3.52	.315	.473	.264
4.94	.460	.749	.366
6.35	.751	1.35	.467
7.76	1.36	2.72	.565
9.17	2.08	4.88	.662
10.5	2.86	8.23	.757
11.9	3.68	14.3	.850

Test #10

Loading Density, g cc-.165
Max Pressure, psi -23,600
Diameter, in-1.00
Length, in-1.65

$PX10^{-3}$	dp dt $X10^{-5}$	Burning Rate in sec	Fraction Burned (Z)
3.39	.448	.439	.162
6.08	1.07	1.13	.286
8.77	2.69	3.08	.407
11.46	6.90	8.81	.522
14.15	12.6	18.6	.634
16.84	18.3	32.6	.742
19.53	21.1	51.0	.847
22.22	16.6	77.6	.949

Test #24

Loading Density, g/cc-.350
Max Pressure, psi-63,650
Diameter, in-1.25
Length, in-2.00

PX10	dp dt $X10^{-5}$	Burning Rate in/sec
12.[illegible]	25.7	13.6
16.5	64.6	37.5
20.9	103.3	61.3
24.9	131.3	80.1
28.9	155.0	97.9
33.0	170.0	112.3
37.0	165.1	129.4
41.0	168.3	141.5
45.1	177.5	146.4

Test #12

Loading Density, g/cc-.221
Max Pressure, psi-35,885
Diameter, in-1.00
Length, in-1.95

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
4.74	.978	.71	.159
6.75	1.71	1.27	.223
8.77	3.18	2.41	.286
10.8	6.60	5.18	.347
12.8	13.0	10.6	.407
16.8	32.0	28.5	.522
20.9	47.0	47.0	.632
24.9	56.7	66.8	.738
26.9	56.7	74.6	.788

Test #14

Loading Density, g cc-.273
Max Pressure, psi-41,286
Diameter, in-1.25
Length, in-1.55

$PX10^{-3}$	dp dt $X10^{-5}$	Burning Rate in sec	Fraction Burned (Z)
13.1	25.8	20.9	.381
19.3	54.8	49.3	.537
25.4	78.5	82.9	.681
31.6	83.9	116.4	.813
37.8	50.6	130.2	.936

Test #51

Loading Density, g/cc-.197
Pre-Loading, psi-5,000
Max Pressure, psi-36,170
Diameter, in-1.08
Length, in-1.45

$PX10^{-3}$	dp dt $X10^{-5}$	Burning Rate in/sec
[illegible]	[illegible]	[illegible]
9.86	27.0	22.0
[illegible]	[illegible]	36.8
16.01	55.0	49.0
19.12	62.4	62.7
22.21	72.8	81.4
25.30	74.9	96.3
28.39	62.4	97.5

1

TABLE I

CLOSED BOMB AND STRAND BURNING DATA FOR TNT

Test #24

Loading Density, g/cc-.350
Max Pressure, psi-63,650
Diameter, in-1.25
Length, in-2.00

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
12.8	23.7	[illegible]	.275
16.8	64.6	[illegible]	.351
20.9	103.3	[illegible]	.424
24.9	131.3	[illegible]	.492
28.9	155.0	[illegible]	.557
33.0	170.0	[illegible]	.618
37.0	185.1	[illegible]	.677
41.0	188.3	[illegible]	.732
45.1	177.5	[illegible]	.785

Test #25

Loading Density, g/cc-.387
Max Pressure, psi-72,040
Diameter, in-1.25
Length, in-2.20

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
12.8	21.5	11.6	.260
16.8	64.9	29.7	.331
20.9	104.4	57.0	.400
24.9	146.3	81.0	.462
28.9	175.4	98.9	.521
33.0	195.8	113.0	.578
37.0	213.0	127.3	.632
41.0	222.7	138.9	.682
45.0	222.7	146.4	.731
49.1	213.0	149.9	.776

Test #20

Loading Density, g/cc-.273
Max Pressure, psi-45,150
Diameter, in-1.25
Length, in-1.55

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
12.8	15.6	10.5	.325
15.8	55.1	40.6	.394
18.9	76.9	[illegible]	.461
21.9	89.5	65.5	.526
24.9	101.6	82.1	.588
27.9	108.1	[illegible]	.648
31.0	110.3	[illegible]	.705

Test #51

Loading Density, g/cc-[illegible]
Pre-Loading, psi-5,000
Max Pressure, psi-36,170
Diameter, in-1.08
Length, in-1.45

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
6.78	2.08	1.62	.065
9.86	27.0	22.0	.182
12.95	42.6	36.8	.292
16.04	53.0	49.0	.398
19.12	62.4	62.7	.499
22.21	72.8	81.4	.597
25.30	74.9	96.3	.692
28.39	62.4	97.5	.783

Test #52

Loading Density, g/cc-.197
Pre-Loading, psi-10,000
Max Pressure, psi-45,060
Diameter, in-1.08
Length, in-1.45

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
12.95	26.0	18.2	.099
16.04	49.9	36.5	.200
19.13	68.6	52.8	.297
22.21	85.3	69.7	.391
25.30	98.8	86.9	.482
28.39	107.1	103.0	.570
31.48	110.2	118.0	.655
34.56	107.1	133.8	.737
37.56	88.4	135.7	.818

Str

Pressure, psi
2,000
3,000
6,000
10,000
20,000

NG DATA FOR TNT

#25

ding Density, g/cc-.387
Pressure, psi-72,040
meter, in-1.25
gth, in-2.20

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
	21.5	[illegible]	.260
	54.9	29.7	.331
	104.4	57.0	.400
	146.3	81.0	.462
	175.4	98.9	.521
	195.5	113.0	.578
	213.0	127.3	.632
	222.7	138.9	.682
	222.7	146.4	.731
	213.0	149.9	.776

Test #20

Loading Density, g/cc-.273
Max Pressure, psi-48,150
Diameter, in-1.25
Length, in-1.55

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
[illegible]	[illegible]	10.5	.325
15.8	[illegible]	40.6	.394
18.9	[illegible]	55.9	.461
[illegible]	[illegible]	65.5	.526
24.9	[illegible]	82.1	.588
27.9	[illegible]	93.5	.648
31.0	[illegible]	103.7	.705

Test #23

Loading Density, g/cc-.330
Max Pressure, psi-55,900
Diameter, in-1.25
Length, in-1.85

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
12.8	26.9	16.9	.302
16.8	56.0	36.2	.386
20.9	89.3	59.7	.465
24.9	108.7	75.8	.539
28.9	128.0	94.3	.610
33.0	132.3	104.6	.677
37.0	135.6	117.3	.740
41.1	121.6	118.8	.800

Test #52

ng Density, g/cc-.197
Loading, psi-10,000
Pressure, psi-45,060
eter, in-1.05
h, in-1.45

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
	26.0	18.2	.099
	49.9	36.5	.200
	65.6	52.8	.297
	85.3	69.7	.391
	98.8	86.9	.482
	107.1	103.0	.570
	110.2	118.0	.655
	107.1	133.8	.737
	88.4	135.7	.818

Strand Burning Rate of TNT

Pressure, psi	Burning Rate, in/sec
2,000	0.296
3,000	0.457
6,000	[illegible]
10,000	1.6[illegible]
20,000	3.46

Test #61

Loading Density, g/cc-.110
Pre-Loading, psi-none
Max Pressure, psi-20,620
Length, in-1.06
Diameter, in-0.800

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
2.23	.52	.46	.115
3.85	1.04	.97	.197
5.48	2.34	2.32	.279
7.10	2.60	2.75	.360
8.72	4.16	4.76	.440
10.35	5.46	6.83	.519
11.98	8.32	11.55	.597
13.60	9.86	15.61	.675

Test #62

Loading Density, g/cc-.110
Pre-Loading, psi-5,000
Max Pressure, psi-27,900
Length, in-1.06
Diameter, in-0.900

[illegible]	dp/dt [illegible]	Burning Rate [illegible]	Fraction [illegible]
7.10	6.84	5.41	.098
8.75	11.33	9.36	.172
10.35	15.60	13.57	.246
11.98	21.84	20.11	.319

Test #68

Loading Density, g/cc-.165
Pre-Loading, psi-10,000
Max Pressure, psi-50,675
Diameter, in-1.06
Length, in-[illegible].20

[illegible]	dp/dt [illegible]	Burning Rate [illegible]
12.30	6.2[illegible]	3.24
15.23	24.96	13.66
21.08	67.60	40.61
26.93	119.6	81.08
32.78	164.3	131.53
38.63	182.0	185.6
41.55	176.8	214.6
47.40	104.0	243.9

Test #64

Loading Density, g/cc-.110
Pre-Loading, psi-2,500
Max Pressure, psi-24,260
Diameter, in-1.06
Length, in-0.800

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
3.85	2.08	1.69	.066
5.48	4.16	3.55	.145
7.10	8.32	7.49	.223
8.73	13.52	12.90	.300
10.35	18.72	19.0[illegible]	.377
11.98	24.96	27.40	.452
13.60	28.08	33.60	.527
15.23	33.28	44.07	.602
16.85	36.40	54.49	.675
18.47	38.48	67.21	.747

Test #65

Loading Density, g/cc-.110
Pre-Loading, psi-5,000
Max Pressure, psi-27,640
Diameter, in-1.06
Length, in-0.800

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
7.10	7.28	5.80	.099
8.73	13.52	11.30	.174
10.35	21.84	19.24	.249
11.98	28.08	26.23	.323
13.60	34.32	34.22	.396
15.23	39.52	42.43	.468
16.85	45.76	53.52	.541
18.48	49.92	64.53	[illegible]
20.10	53.04	77.38	.682
21.73	54.08	91.78	.752

Test #70

Loading Density, g/cc-.220
Pre-Loading, psi-10,000
Max Pressure, psi-66,432
Diameter, in-1.06
Length, in-1.60

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec
16.[illegible]	50.27	21.83
[illegible]	[illegible]	40.64
[illegible]	[illegible]	64.41
[illegible]		133.7
35.70	305.5	171.3
39.60	346.7	207.2
47.40	[illegible]	283.[illegible]
51.30	377.9	313.[illegible]

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TABLE II

CLOSED BOMB AND STRAND BURNING DATA FOR COMPOSITION B

Test #68

Loading Density, g/cc-.[illegible]
Pre-Loading, psi-10,000
Max Pressure, psi-50,[illegible]
Diameter, in-1.06
Length, in-1.20

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
12.30	6.24	[illegible]	.063
15.23	24.96	[illegible]	[illegible]
21.08	67.60	[illegible]	.295
26.93	119.6	[illegible]	.443
32.78	164.3	[illegible]	.557
38.63	182.0	[illegible]	.726
41.55	176.8	[illegible]	.794
47.40	104.0	[illegible]	[illegible]

Test #69

Loading Density, g/cc-.220
Pre-Loading, psi-5,000
Max Pressure, psi 58,090
Diameter, in-1.06
Length, in-1.60

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate	Fraction Burned (Z)
7.75	6.24	2.72	.060
[illegible]	[illegible]	[illegible]	[illegible]
14.60	[illegible]	[illegible]	.211
22.05	123.8	65.11	.356
25.63	153.9	85.45	.426
32.78	216.3	137.2	.562
36.35	237.1	163.7	.627
47.08	234.0	240.3	.817

Test #66

Loading Density, g/cc-.110
Pre-Loading, psi-10,000
Max Pressure, psi-34,140
Diameter, in-1.06
Length, in-0.[illegible]

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
12.30	14.56	10.90	.101
14.25	27.04	21.37	.186
16.20	35.36	29.69	.270
18.15	42.64	38.33	.353
20.10	49.92	48.51	.435
22.05	56.16	59.76	.516
24.00	59.28	70.26	.596
25.95	59.28	80.18	.676

Test #70

Loading Density, g/cc-[illegible]
Pre-Loading, psi-1[illegible]
Max Pressure, psi-[illegible]
Diameter, in-1.06
Length, in-1.60

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
16.20	50.27	[illegible]	.126
20.10	90.13	[illegible]	[illegible]
24.00	136.9	[illegible]	.275
31.80	256.5	[illegible]	.421
35.70	305.5	[illegible]	[illegible]
39.60	346.7	[illegible]	.563
47.40	390.0	[illegible]	.697
51.30	377.9	[illegible]	.761

Test #71

Loading Density, g/cc-.164
Pre-Loading, psi-15,000
Max Pressure, psi-58,090
Diameter, in-1.06
Length, in-1.20

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
[illegible]	[illegible]	4.34	.089
22.05	[illegible]	7.55	.179
25.63	178.5	98.8	.268
29.20	208.0	122.9	.351
32.78	228.8	145.9	.439
39.93	253.1	196.2	.605
41.50	253.1	224.4	.686
47.08	234.0	247.1	.765

Test #72

Loading Density, g/cc-.220
Pre-Loading, psi-15,000
Max Pressure, psi-76,310
Diameter, in-1.06
Length, in-1.60

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (Z)
21.72	[illegible]	[illegible]	.125
25.95	[illegible]	[illegible]	[illegible]
30.18	[illegible]	[illegible]	[illegible]
34.40	[illegible]	[illegible]	[illegible]
38.65	[illegible]	[illegible]	.423
42.9	563.4	290.6	.493
55.5	585.0	[illegible]	.695
[illegible]	[illegible]	405.2	.760

…R COMPOSITION B

…ction …ned (Z)
.101
.186
.270
.353
.435
.516
.596
.676

Test #[illegible]

…nsity, g/cc-.220
…n, psi-5,000
…re, psi-58,090
…in-1.06
…1.60

dp/dt X10^-5	Burning Rate in/sec	Fraction Burned (Z)
6.21	2.72	.080
[illegible]	[illegible]	[illegible]
46.[illegible]	22.53	.211
[illegible]	62.11	.356
[illegible]	[illegible]	.426
[illegible]	137.2	.562
[illegible]	163.[illegible]	.627
[illegible]4.0	240.3	[illegible]

Test #66

Loading Density, g/cc-.110
Pre-Loading, psi-10,000
Max Pressure, psi-34,140
Diameter, in-1.06
Length, in-[illegible]

PX10^-3	dp/dt X10^-5	Burning Rate	Fraction
12.30	14.[illegible]	10.[illegible]	.101
14.[illegible]	[illegible]	[illegible]	.186
16.20	[illegible]	[illegible]	.270
18.[illegible]	42.64	[illegible]	.353
20.10	[illegible]	45.51	.435
22.05	56.[illegible]	59.[illegible]	.516
24.00	[illegible]	70.26	.596
[illegible]	[illegible]	80.[illegible]	.676

Test #67

Loading Density, g/cc-.164
Pre-Loading, psi-5,000
Max Pressure, psi-42,620
Diameter, in-1.06
Length, in-1.20

PX10^-3	dp/dt X10^-5	Burning Rate	Fraction [illegible]
5.80	3.42	1.73	.024
8.40	6.24	3.61	.100
11.00	14.56	8.77	.175
13.60	27.04	16.92	.248
18.80	63.44	44.37	.393
24.00	95.68	77.28	.532
29.20	115.4	113.[illegible]	.668
31.80	119.6	134.4	.734
37.00	100.9	171.7	.864

…ction …ned (Z)
.125
.203
.278
.351
.423
.493
.695
.760

Test #71

…sity, g/cc-.[illegible]
…, psi-5,000
…, psi-[illegible]
…in-1.06
…1.20

dp/dt X10	Burning Rate in/sec	Fraction Burned (Z)
[illegible]	4.14	.049
14.[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	.268
[illegible]	122.9	.354
[illegible]	145.9	[illegible]
253.1	196.2	.605
253.1	224.4	.656
[illegible]14.0	247.1	.765

Test #72

Loading Density, g/cc-[illegible]
Pre-Loading, psi-15,000
Max Pressure, psi-76,[illegible]
Diameter, in-1.06
Length, in-[illegible]

PX10^-3	dp/dt X10	Burning Rate in/sec	Fraction Burned (Z)
21.72	[illegible]	[illegible]	.125
[illegible]	[illegible]	152.1	.203
[illegible]	442.0	191.3	.278
34.[illegible]	[illegible]07.0	[illegible]	.351
[illegible]	572.0	274.2	.421
[illegible]	[illegible]	290.6	.493
[illegible]	595.0	[illegible]	.695
[illegible]	[illegible]	403.2	.760

Strand Burning Rate Test

Pressure	Burning Rate in/sec
2,000	0.51
3,000	[illegible]
5,000	[illegible]
10,000	[illegible]
20,000	[illegible]
30,000	10.4[illegible]

TABLE III

CLOSED BOMB AND STRAND BURNING DATA FOR

Test #32

Loading Density, g/cc-.249
Max Pressure, psi-45, 160
Diameter, in-1.25
Length, in-1.40

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction [illegible]
6.34	2.44	1.43	.157
12.08	4.[illegible]	2.[illegible]	.294
17.83	5.05	3.58	.426
23.57	5.92	4.80	.554
29.31	6.35	6.30	.678

Test #33

Loading Density, g/cc-.273
Max Pressure, psi-50, 440
Diameter, in-1.25
Length, in-1.55

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (%)
6.34	2.70	1.47	.143
12.08	[illegible].26	2.49	.265
17.83	5.74	3.65	.388
23.57	6.79	4.79	.504
29.31	7.31	5.11	.617
35.05	7.22	7.05	.725

Loading De[illegible]
Max Pressu[illegible]
Diameter, [illegible]
Length, in[illegible]

$PX10^{-3}$
10.39
20.18
29.96
39.75
49.54
59.32
69.11
78.90

Test #34

Loading Density, g/cc-.299
Max Pressure, psi-56, 410
Diameter, in-1.25
Length, in-1.70

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (%)
6.34	3.05	1.53	.130
12.08	4.79	2.55	.244
17.83	6.35	3.62	.353
23.57	7.83	4.85	.460
29.31	8.70	5.98	.561
35.05	9.14	7.18	.660

Test #37

Loading Density, g/cc-.327
Max Pressure, psi-62, 065
Diameter, in-1.25
Length, in-1.85

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in/sec	Fraction Burned (%)
10.39	4.79	2.34	
20.18	7.83	4.21	[illegible]
29.96	10.01	6.16	.530
39.75	10.88	8.15	.683
49.54	9.57	10.02	.827
59.33	[illegible]	[illegible]	.963

Loading De[illegible]
Pre-Lo[illegible]
Max Press[illegible]
Diameter[illegible]
Length, [illegible]

$PX10^{-3}$
25.07
29.96
34.86
39.75

TABLE III

CLOSED BOMB AND STRAND BURNING DATA FOR ARP PROPELLANT

Test #33

Loading Density, g/cc-.273
Max Pressure, psi-50,440
Diameter, in-1.25
Length, in-1.55

PX10^{-3}	dp/dt X10^{-5}	Burning Rate in/sec	Fraction Burned (Z)
[illegible].34	2.70	1.47	.143
[illegible].08	4.26	2.49	.268
[illegible].83	5.74	3.65	.38[illegible]
[illegible].57	6.79	4.79	.504
[illegible].31	7.31	5.11	.617
[illegible].05	7.22	7.05	.725

Test #39

Loading Density, g/cc-.393
Max Pressure, psi-83,600
Diameter, in-1.25
Length, in-2.20

PX10^{-3}	dp/dt X10^{-5}	Burning Rate in/sec	Fraction Burned (Z)
10.39	5.00	2.33	.154
20.18	10.27	4.18	.283
29.96	14.01	6.10	.417
39.75	16.70	7.95	.537
49.54	18.27	9.83	.650
59.32	17.84	11.45	.758
69.11	15.23	13.01	.859
78.90	10.88	17.78	.956

Test #41

Loading Density, g/cc-.297
Pre-Loading, psi-15,000
Max Pressure-82,425
Diameter, in-1.25
Length, in-1.70

PX10^{-3}	dp/dt X10^{-5}	Burning Rate in/sec	Fraction Burned (Z)
25.07	11.57	4.96	.172
29.96	12.98	5.77	.252
34.86	14.62	6.87	.330
39.75	15.75	7.81	.406
44.64	16.53	8.74	.553
49.54	17.66	10.07	.624
54.43	17.40	11.51	.694
59.33	16.53	12.19	.761
64.21	15.33	13.04	.828

Test #37

Loading Density, g/cc-.327
Max Pressure, psi-62,065
Diameter, in-1.25
Length, in-1.85

PX10^{-3}	dp/dt X10^{-5}	Burning Rate in/sec	Fraction Burned (Z)
[illegible].39	4.79	2.34	.195
[illegible].18	7.83	4.21	.368
[illegible].96	10.01	6.16	.530
[illegible].75	10.88	8.15	.683
[illegible].54	9.57	10.02	.827
[illegible].33	4.35	11.42	.963

Test #42

Loading Density, g/cc.331
Pre-Loading, psi 15,000
Max Pressure, psi-98,500 (approx)
Diameter, in-1.25
Length, in-1.85

PX10^{-3}	dp/dt X10^{-5}	Burning Rate in/sec	Fraction Burned (Z)
25.07	13.05	4.65	.143
29.96	14.79	5.43	.209
34.86	17.52	6.47	.274
39.75	23.92	9.41	.338

Strand Burning Test

Pressure psi	Burning Rate in/sec
10,000	[illegible]
15,000	[illegible]
20,000	[illegible] 00
30,000	5.5[illegible]

2

TABLE IV

CLOSED BOMB DATA FOR EXPERIMENTAL PROPELLANT

Test #83

Loading Density, g/cc-.204
Max. Pressure, psi-42,720
Diameter, in.-1.25
Length, in-1.00

$PX10^{-3}$	dp/dt $X10^{-5}$	Burning Rate in sec	Fraction Burned (Z)
1.9	1.62	.845	.049
3.2	[illegible]	.858	.084
4.5	2.92	[illegible]	.117
5.8	3.58	1.95	.151
7.1	3.9	2.17	.184
8.4	4.94	2.80	.216
9.7	5.85	3.39	.249
11.0	6.5	3.85	.281
12.3	7.15	4.33	.313
13.6	29.2	18.1	.345

Test #84

Loading Density, g/cc-.204
Max Pressure, psi-42,200
Diameter, in-1.25
Length, in-1.00

$P(10^{-3})$	dp/dt (10^{-5})	dx/dt	Fraction Burned (Z)
3.2	1.6	.858	.085
4.5	2.4	1.31	.119
5.8	3.2	1.78	.153
8.4	4.8	2.77	.219
11.0	6.4	3.85	.285
13.6	8.0	5.05	.349
17.5	10.4	7.12	.447
20.1	142.5	103.8	.507
21.4	173.7	131.0	.538
24.0	197.6	161.3	.598

Test #87

Loading Density, g/cc-.308
Max Pressure, psi-70,570
Diameter, in-1.25
Length, in-1.50

$P(10^{-3})$	dp/dt (10^{-5})	dx/dt	Fraction Burned (Z)
2.71	2.08	.811	.047
4.12	4.10	1.64	.083
[illegible]	8.32	3.37	.153
15.4	14.0	5.95	.255
17.5	98.0	42.6	.288
19.6	195.0	85.6	.321
21.7	273.0	122.2	.353
23.8	348.4	159.3	.385
26.0	391.0	183.5	.417
34.4	501.8	240.8	.539
45.0	[illegible]	293.6	.681

Test #88

Loading Density, g/cc-.255
Pre-Loading, psi-5,000
Max Pressure, psi-65,500
Diameter, in-1.25
Length in. -1.25

$P(10^{-3})$	dp/dt (10^{-5})	dx/dt	Fraction Burned (Z)
4.8	2.6	[illegible]	[illegible]
9.1	5.2	[illegible]	
13.4	7.3	[illegible]	.15
17.5	163.8	73.9	.23
21.7	249.6	117.9	.31
26.0	[illegible]	157.9	.38
30.2	[illegible]	206.1	.45
34.4	416.0	[illegible]	.52

TABLE IV

CLOSED BOMB DATA FOR EXPERIMENTAL PROPELLANT

Test #84

Loading Density, g/cc-.204
Max Pressure, psi-42,200
Diameter, in-1.25
Length, in-1.00

Fraction Burned (Z)	P (10^{-3})	dp/dt (10^{-5})	dx/dt	Fraction Burned (Z)
.049	3.[illegible]	1.6	[illegible]	.085
.084	[illegible]	[illegible]	[illegible]	[illegible]
.117	5.8	3.2	1.78	.153
.151	8.4	4.8	2.77	.219
.184	11.0	6.4	3.[illegible]	.285
.216	13.6	8.0	5.05	.349
.2[illegible]	17.5	10.4	7.12	.447
.281	20.1	142.5	103.8	.507
.313	21.4	173.7	131.0	.538
.345	24.0	197.6	161.3	.598

Test #85

Loading Density, g/cc-.255
Max Pressure, psi-57,800
Diameter, in-1.25
Length, in-1.25

P (10^{-3})	dp/dt (10^{-5})	dx/dt	Fraction Burned (Z)
3.8	2.6	1.14	.073
[illegible]	5.2	2.34	.141
10.4	7.8	3.62	.204
16.8	13.0	6.48	.326
[illegible]	169.0	88.0	.385
23.4	253.5	138.4	.443
36.3	292.5	208.0	.666

Test #88

Loading Density, g/cc-.255
Pre-Loading, psi-5,000
Max Pressure, psi-65,500
Diameter, in-1.25
Length in. -1.25

Fraction Burned (Z)	P(10^{-3})	dp/dt (10^{-5})	dx/dt	Fraction Burned (Z)
.047	4.8	2.6	1.05	-.0085
.083	9.1	5.2	2.17	.073
.153	13.2	7.8	3.38	.15
.255	17.5	165.[illegible]	[illegible]	.23
.288	21.7	[illegible]	117.9	.31
.321	26.0	[illegible]7.2	[illegible]57.9	.38
.353	30.2	390.0	[illegible]	.45
.385	34.4	416.0	236.0	.52
.417				
.539				
.683				

Test #94

Loading Density, g/cc-.377
Max Pressure, psi-89,000
Diameter, in. -1.50
Length, in. -1.27

(P 10^{-3})	dp/dt (10^{-5})	dx/dt	Fraction Burned (Z)
6.1	5.2	1.9	.089
11.6	10.4	3.8	.16[illegible]
17.2	15.6	5.8	.239
22.7	113.8	44.0	.311
28.2	364.0	146.0	.379
33.8	585.0	243.3	.446
39.3	780.0	340.0	.510

2

Table V

Linear Burning Rates of Rohm & Haas QZ Propellant Obtained From

Closed Bomb Test

Pressure	Linear Burning Rate		Calculated Surface Area	
	70°F	-60°F		
$PX10^3$	in/sec	in/sec	70°F	-60°F
5.8	2.04	1.55	-	-
11.0	3.91	2.82	-	-
16.2	[illegible]	[illegible]	-	-
21.4	7.34	6.31	-	-
31.8	8.92	7.60	-	-
37.0	10.30	9.54	-	-
42.2	11.25	10.20	4.95	4.95
47.4	12.14	10.77	4.40	4.40
52.6	12.88	11.72	3.79	3.79
57.8	13.20	45.51	3.27	12.40
63.0	11.39	42.17	2.67	9.00

APPENDIX C

FIGURES

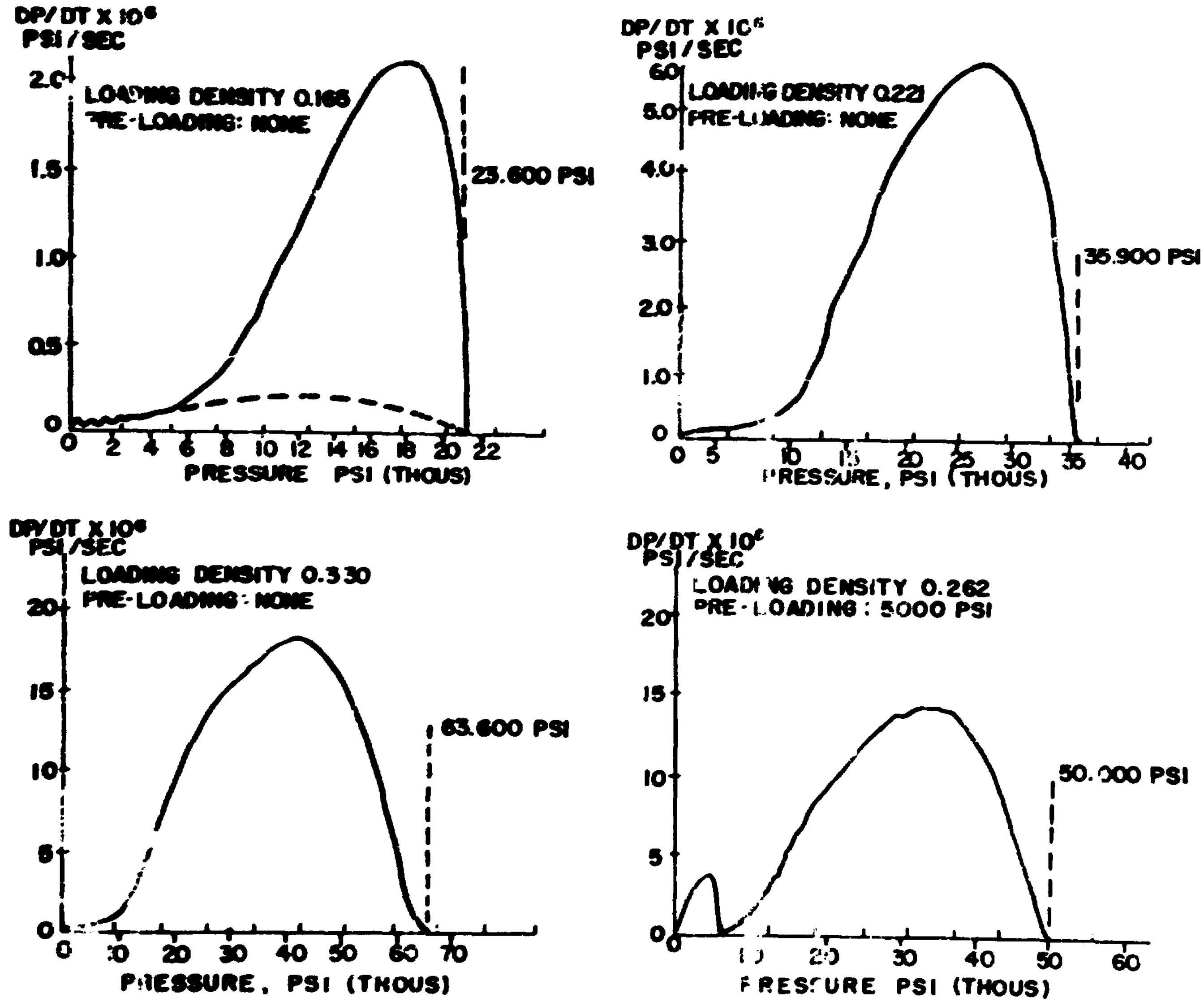

Figure 1. Closed Bomb Test TNT

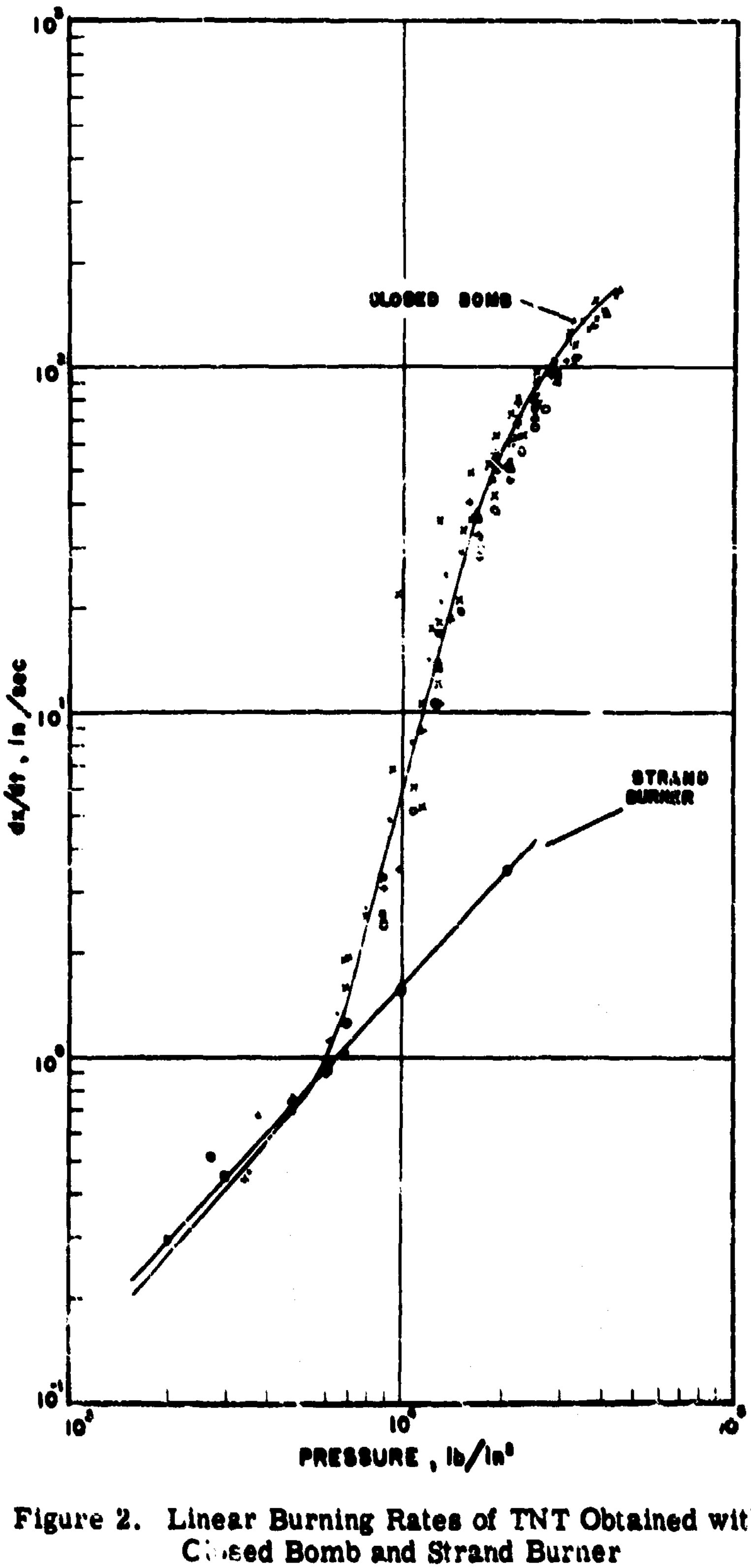

Figure 2. Linear Burning Rates of TNT Obtained with Closed Bomb and Strand Burner

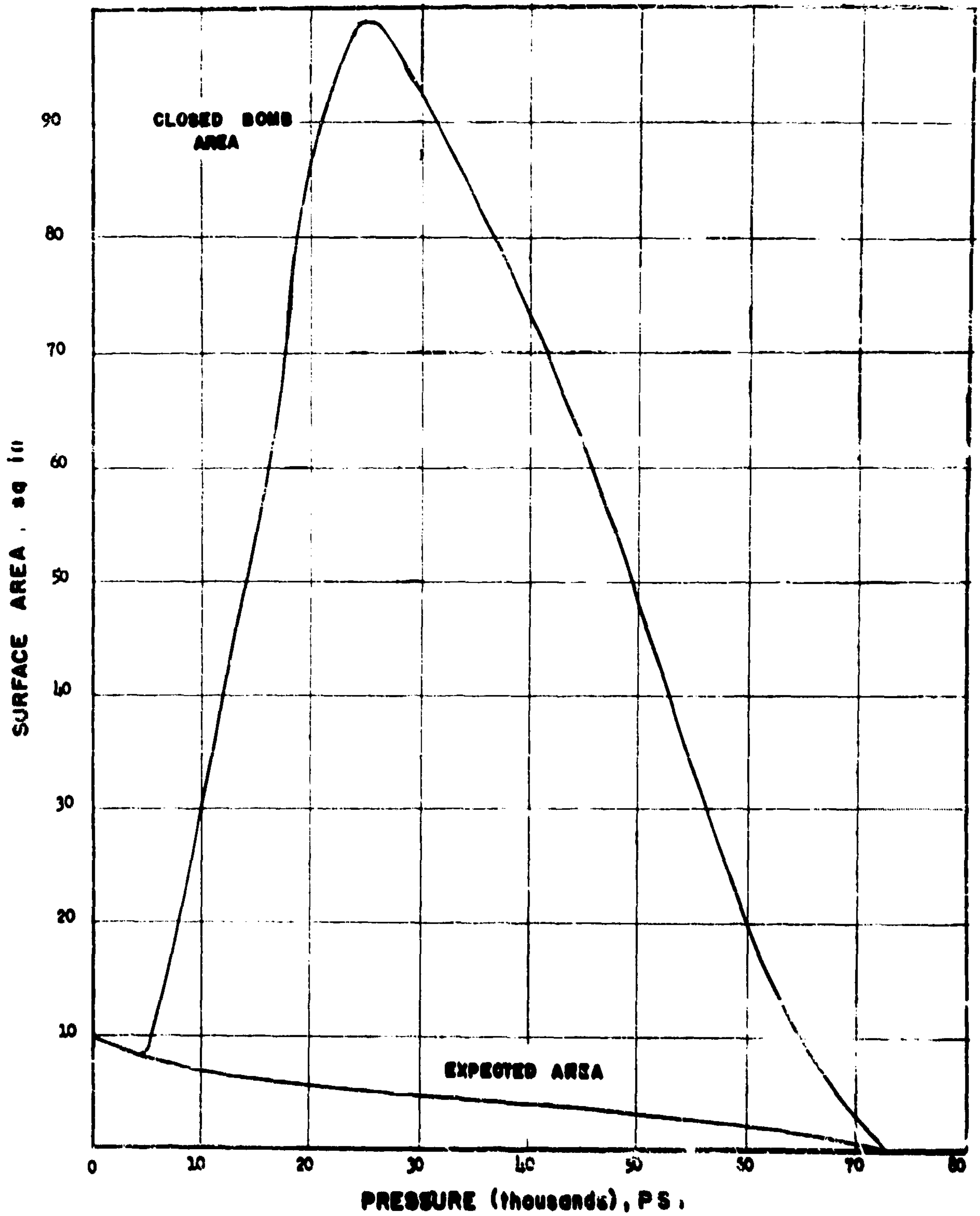

Figure 3. Expected Surface Area vs Actual Area Obtained for TNT Cylinder Burned in Closed Bomb

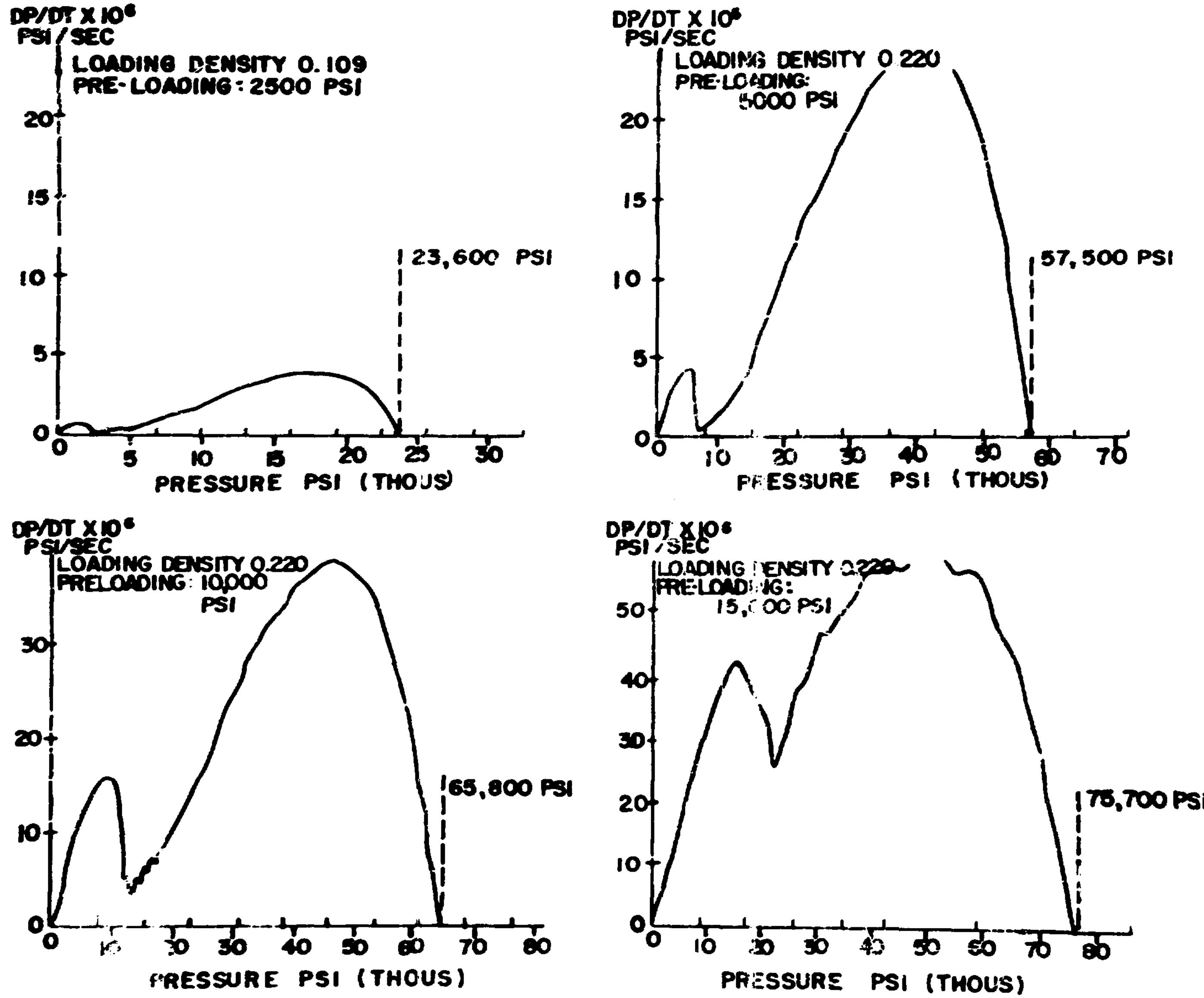

Figure 4. Closed Bomb Test Composition B

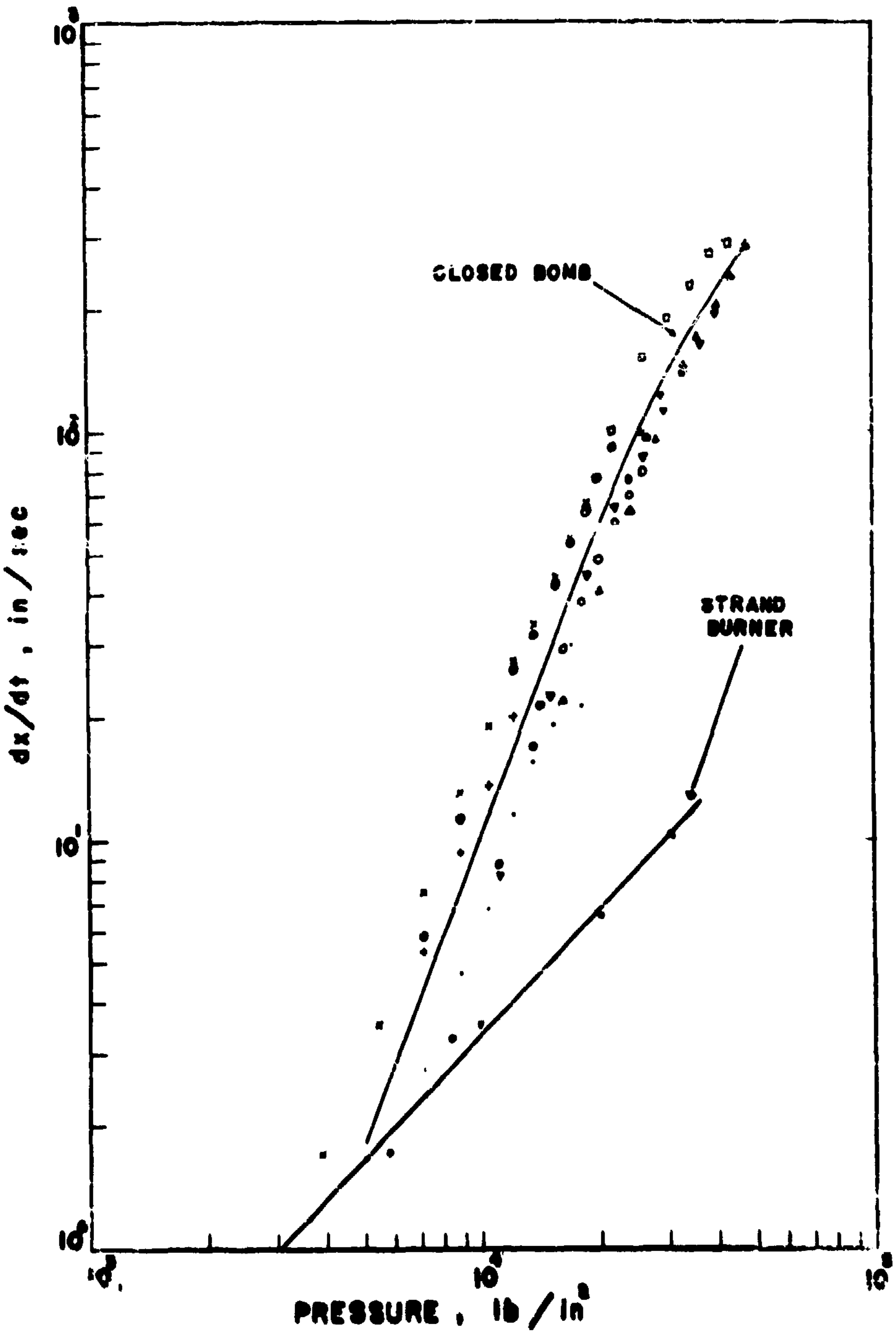

Figure 5. Linear Burning Rates of Composition B Obtained with Closed Bomb and Strand Burner

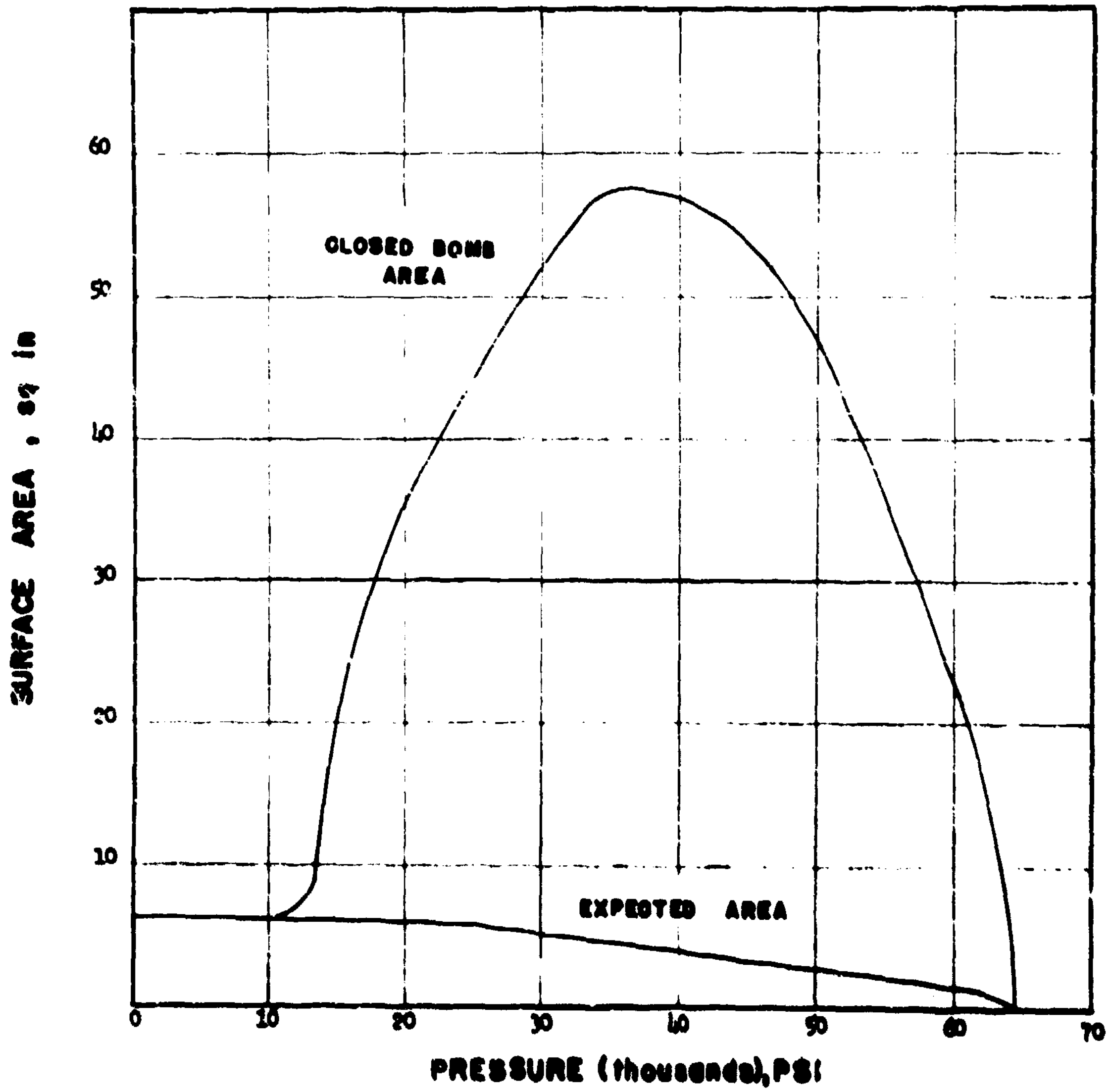

Figure 6. Expected Surface Area vs Actual Area Obtained for Composition B Cylinder Burned in Closed Bomb

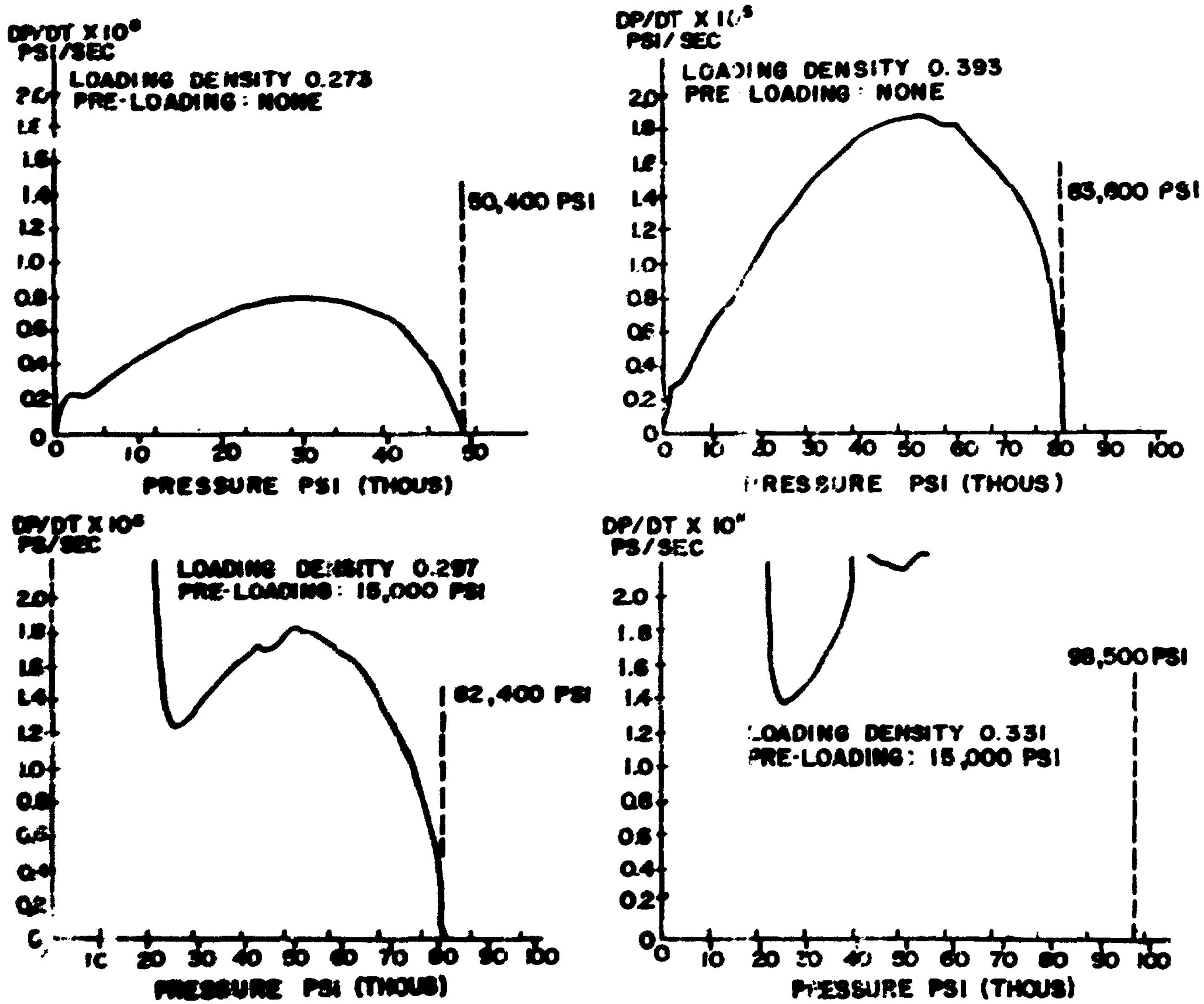

Figure 7. Closed Bomb Test AR.: Propellant

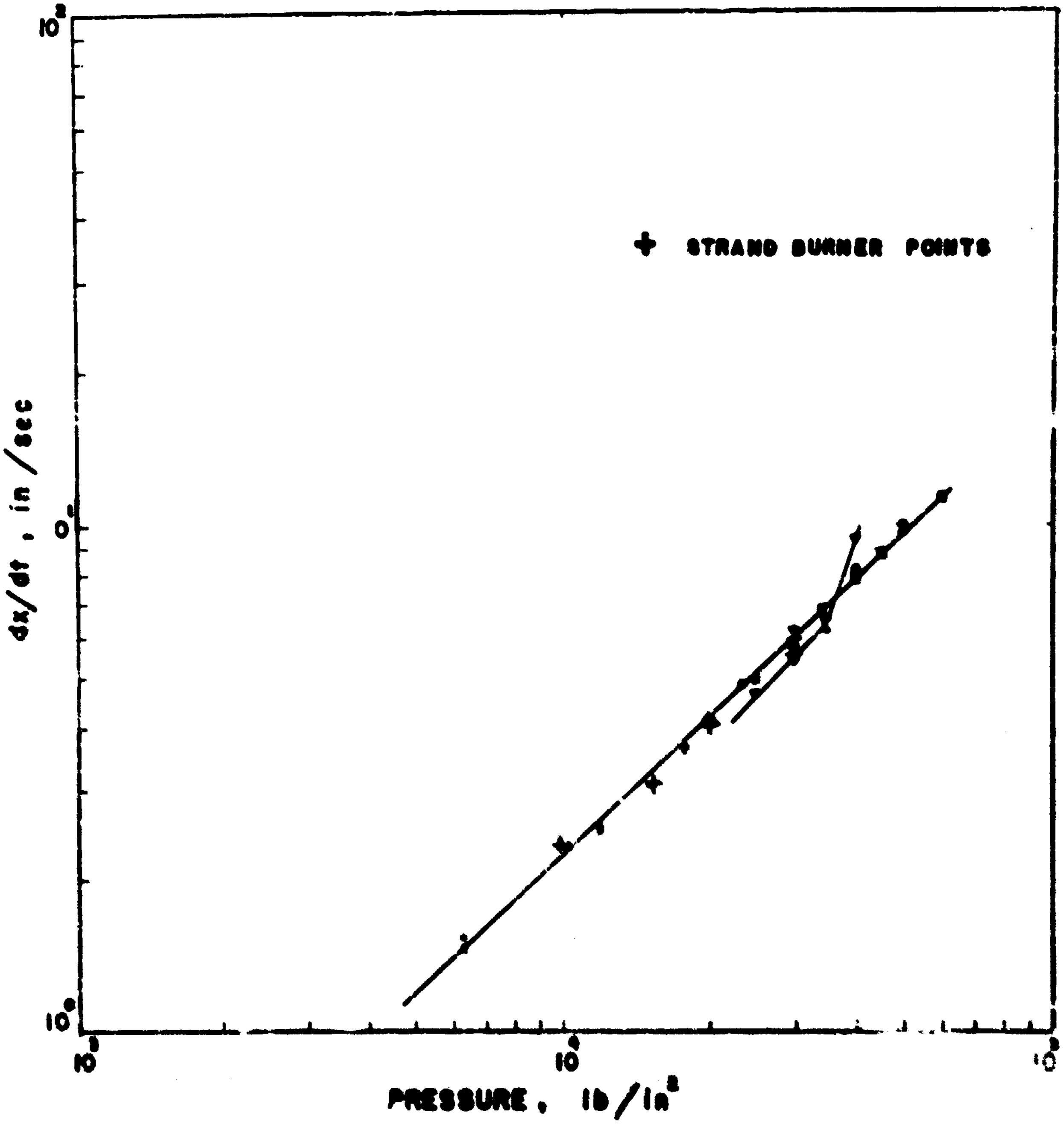

Figure 8. Linear Burning Rates of ARP Propellant Obtained with Closed Bomb and Strand Burner

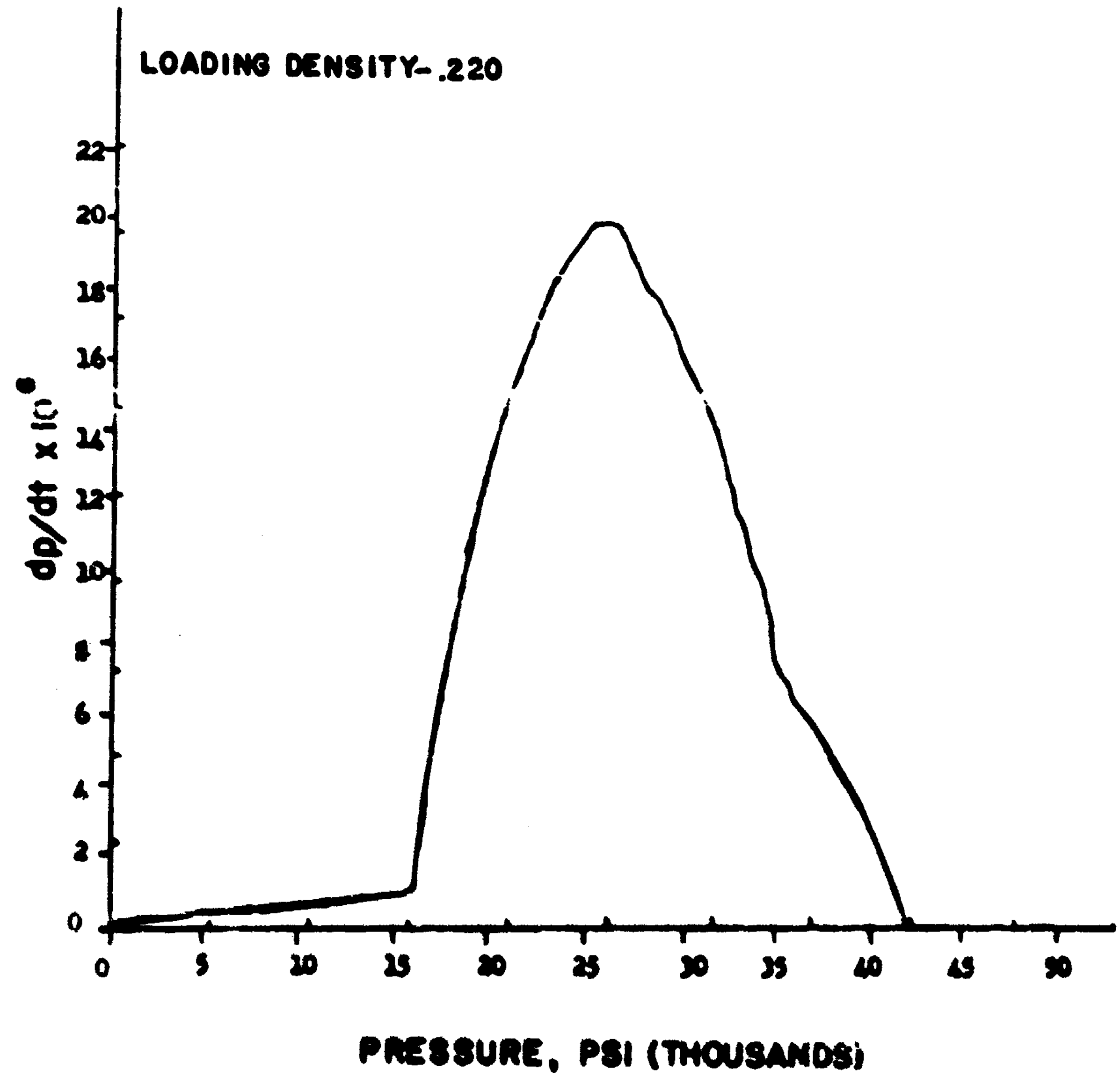

Figure 9. Closed Bomb Test Experimental Propellant

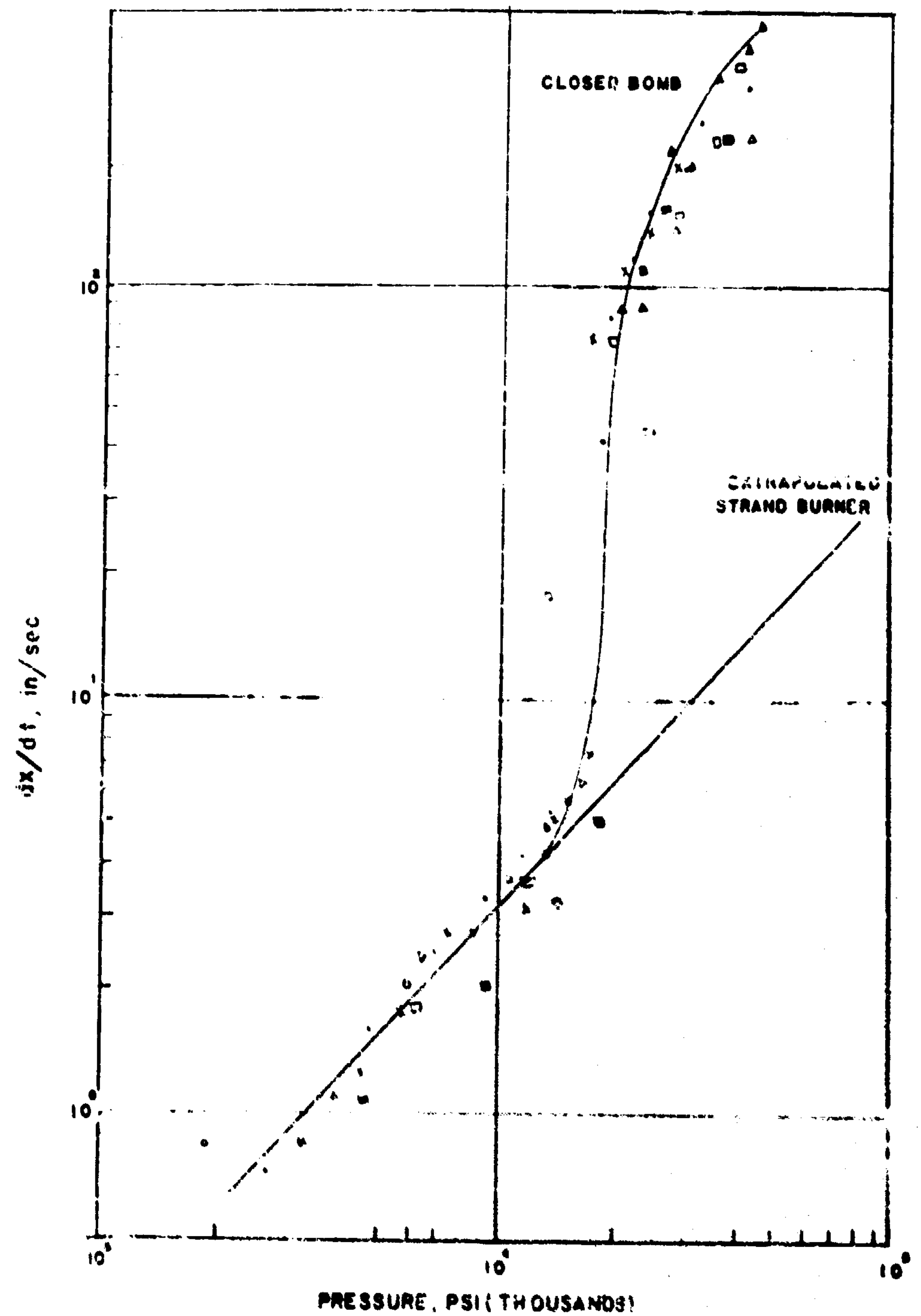

Figure 10. Linear Burning Rate of Experimental Propellant Obtained with Closed Bomb

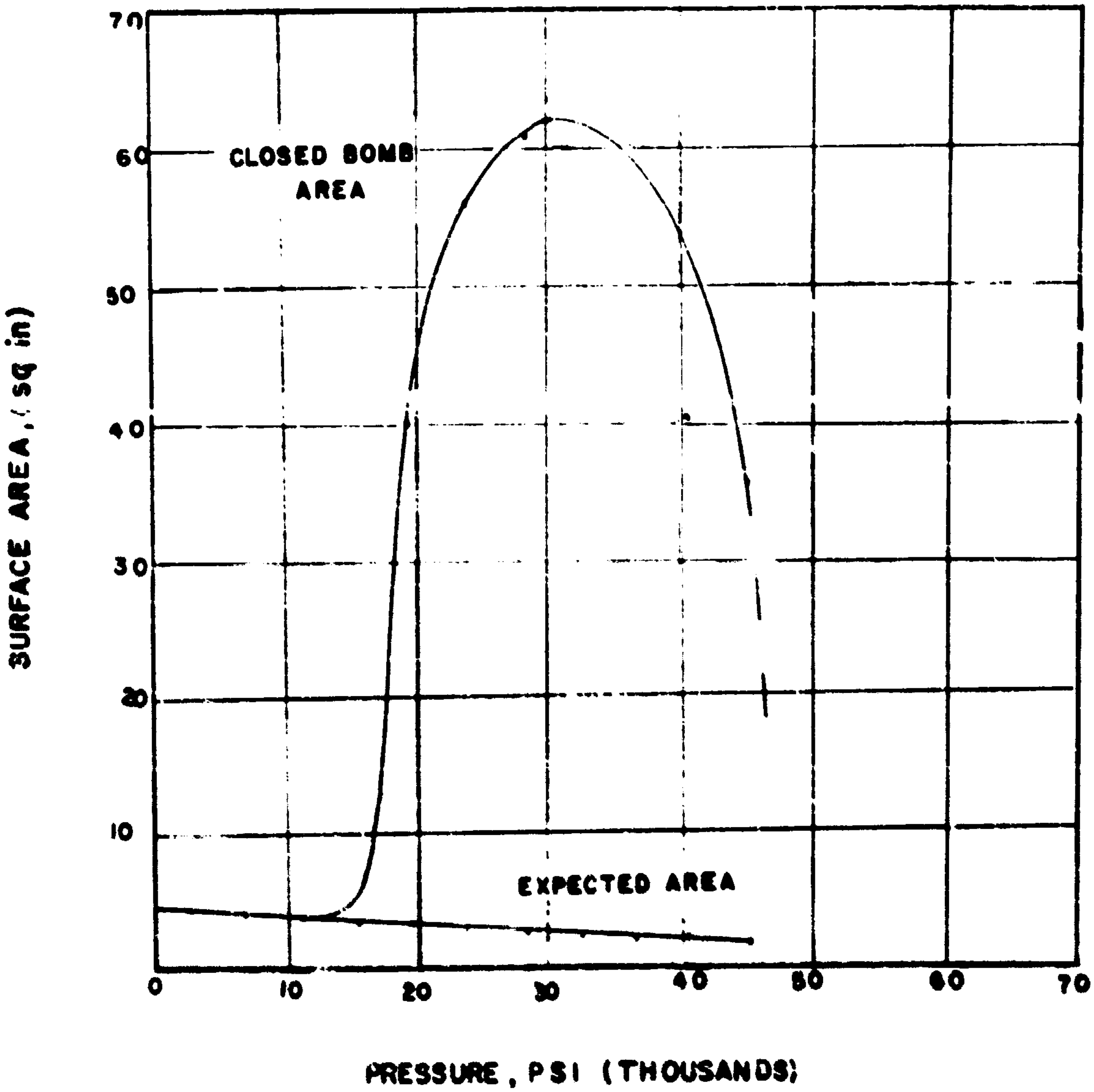

Figure 11. Expected Surface Area vs Actual Area Obtained for Experimental Propellant Burned in Closed Bomb

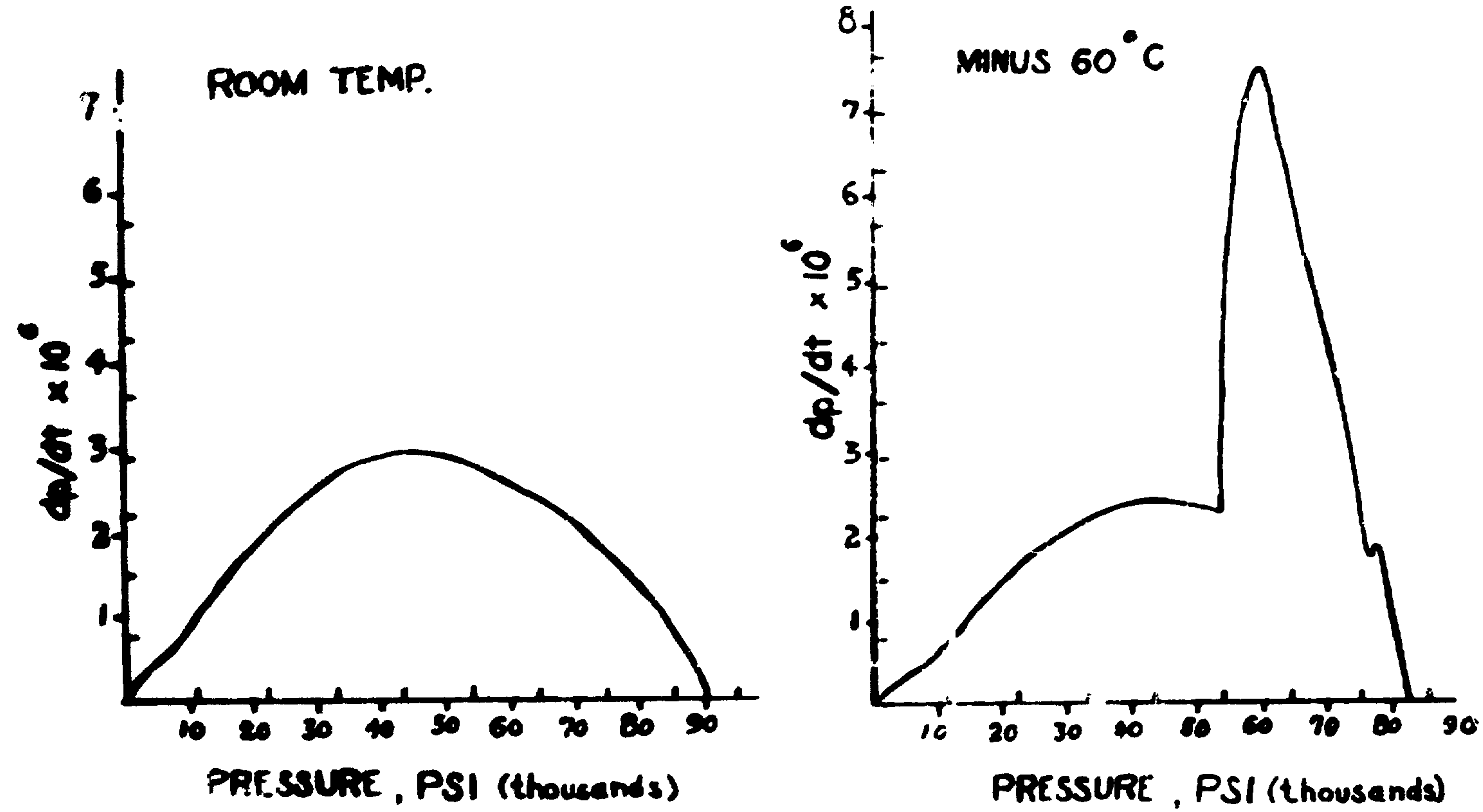

Figure 12. Closed Bomb Test Rohm and Haas Propellant Composition QZ

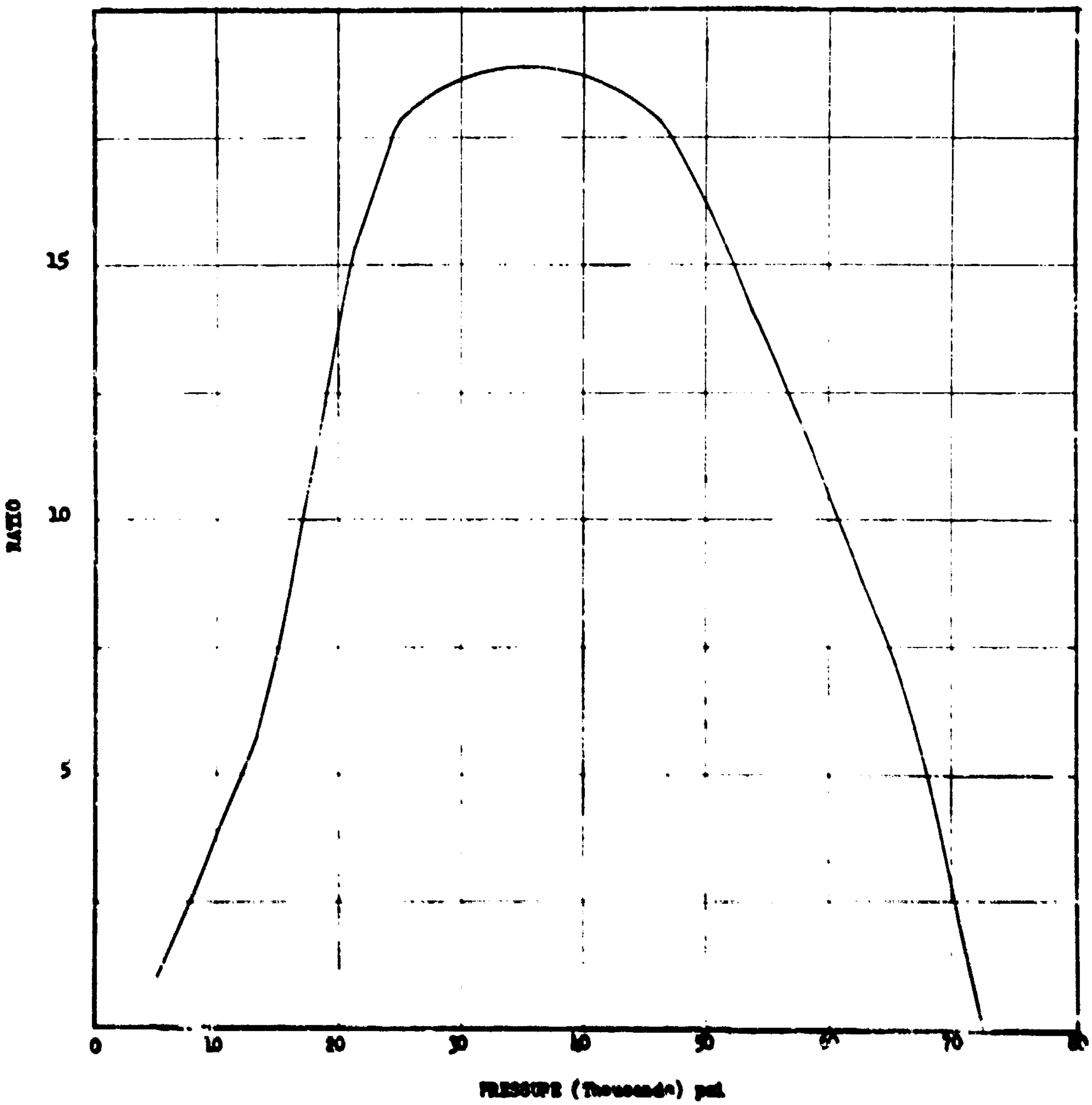

Figure 13. Ratio of Expected Area to Actual Area Found for TNT Cylinder

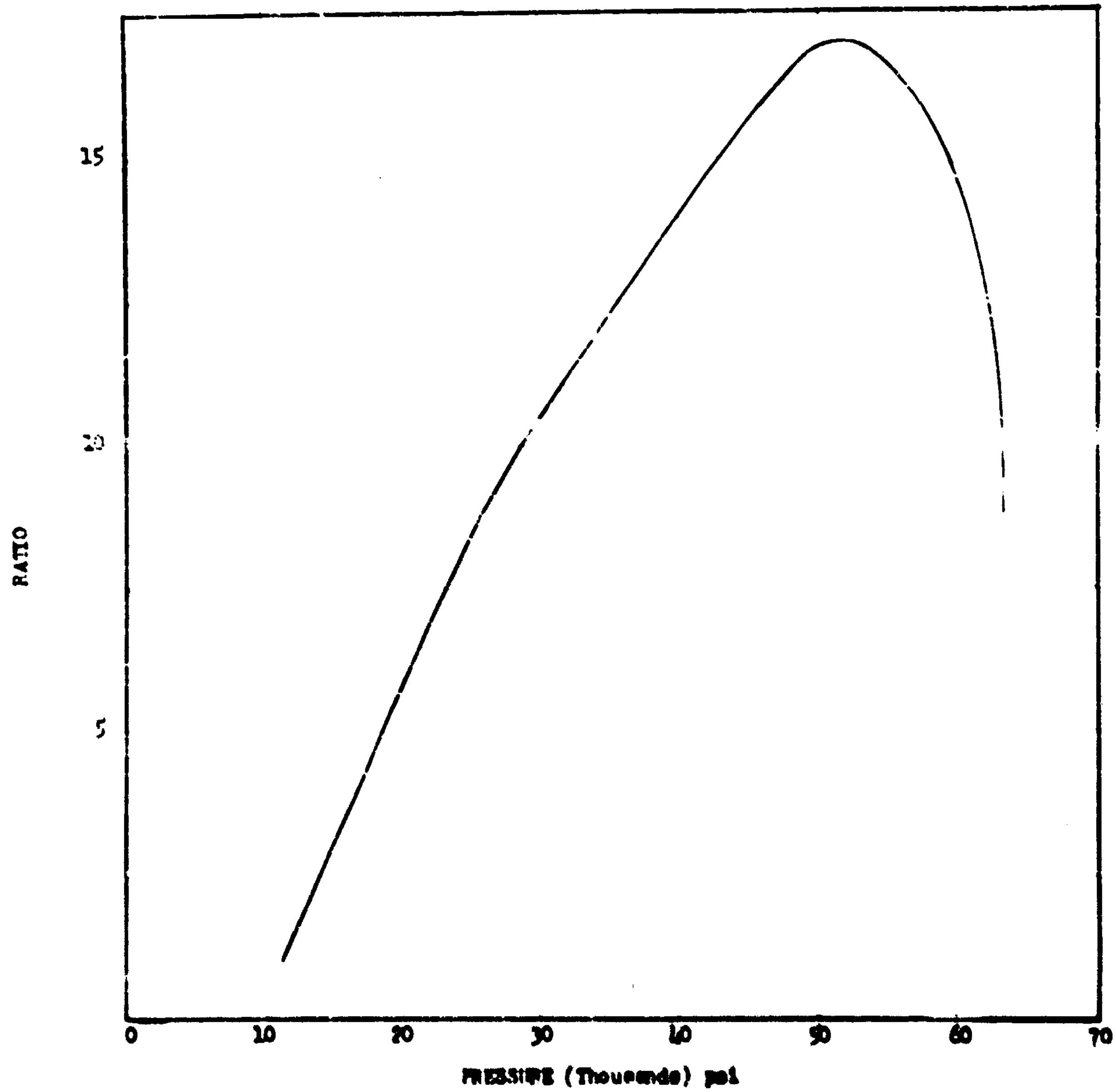

Figure 14. Ratio Expected Area to Actual Area Found for Composition B Cylinder

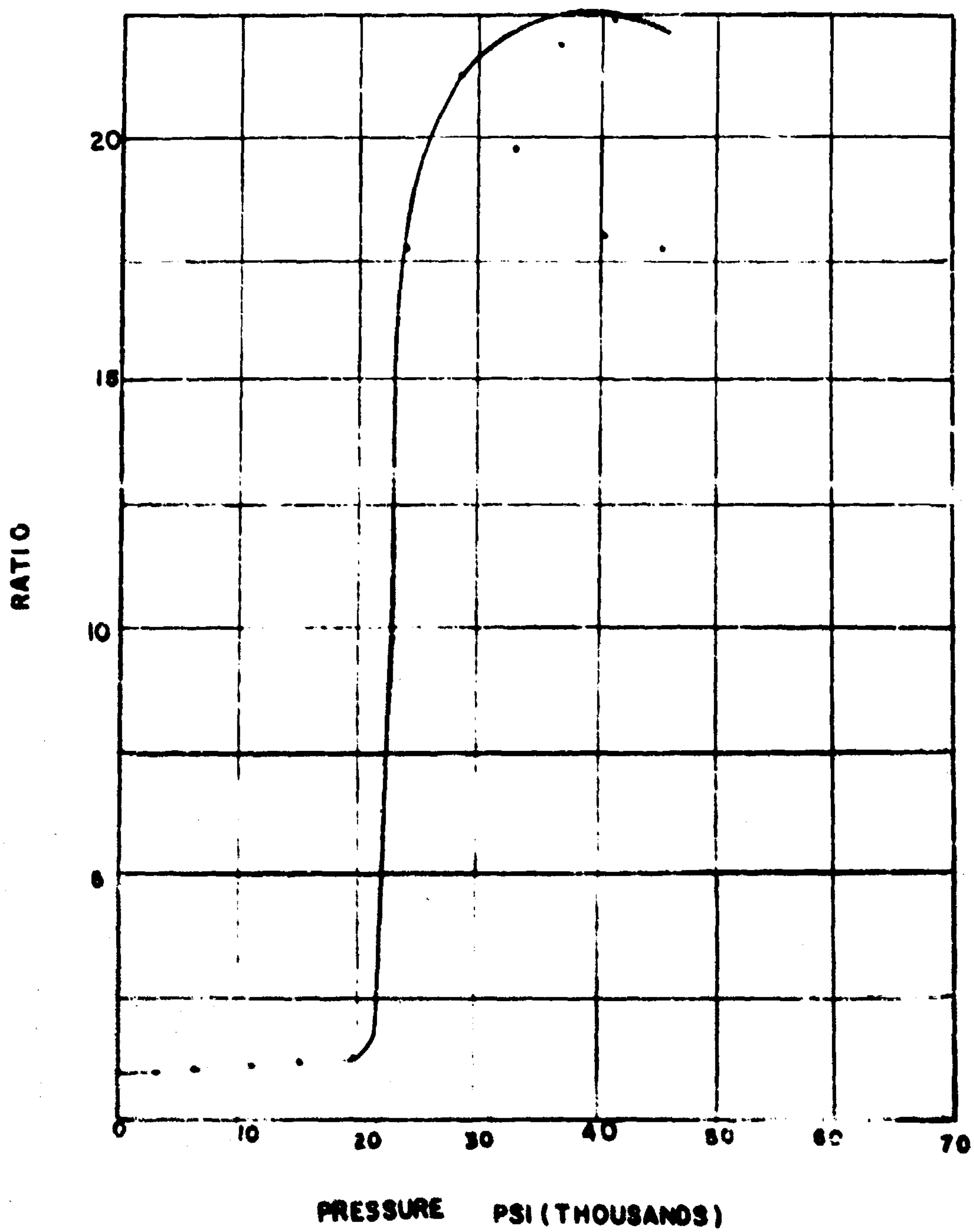

Figure 15. Expected Area to Actual Area Found for Experimental Propellant

ABSTRACT DATA

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Picatinny Arsenal, Ammunition Group
Dover, New Jersey

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2. Explosives—Detonation

I. Wachtell, S.
II. Proj No. 7503.0100

UNITERMS

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Schulman, L.

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Detonation
Hazards
Classification
Closed bomb test
TNT

UNCLASSIFIED

Unclassified report

(OVER)

TN

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UNITERMS

Composition B
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QZ
Wachtell, S.
Proj No. 7503.0100

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Schulman, L.

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Picatinny Arsenal, Ammunition Group
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S. Wachtell, C. E. McKnight, I. Shulman

Technical Report DB-TR: 3-61, June 1961, 24 pp, figures, tables.

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1. Propellants—Detonation
2. Explosives—Detonation

I. Wachtell, S.
II. Proj No. 75[illegible]

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