

Explosive Response to Fragments: Venting Studies

by
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Research Department

OCTOBER 1986

NAVAL WEAPONS CENTER
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FOREWORD

This report is a summary of work supporting the modeling of fragment initiation of cased explosives and propellants. It describes research into the effects of venting and fuel temperature on rapid pressurization of partially vented devices.

Theoretical equations are developed and compared with actual vented-burning experiments.

This work was performed by the Naval Weapons Center, China Lake, Calif., over a 6-year period beginning in 1980 and continuing to 1986. The work was primarily sponsored by the Naval Air Systems Command under Work Order N0001486WR4B153 (appropriation 1761319W1AJ).

This report has been reviewed for technical accuracy by Mr. Mark Alexander. The NAVAIR Project Manager was Mr. Harry Benefiel.

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INTRODUCTION

Cased explosive munitions can respond to ballistic impact in a variety of ways: deformation, ignition, burning, transition from burning to a violent reaction (after a variable time delay), detonation, or possibly, no reaction at all. Because of the variety of impact conditions and system responses, it has been difficult to quantify the important parameters leading to reaction and the prediction of the ultimate system response.

Thermal and venting situations play key roles in determining the fate of an impacted munition. Sewell and Kinney (Reference 1) have studied in detail the phenomenon of venting. They later developed an equation (Reference 2) to predict the critical vent size necessary to keep a burning system from pressurizing. This equation was applied to a generic explosive, with representative constants in the equation. The results of this calculation provided the foundation for a set of confirming experiments for a real explosive (Composition B). The latest series of tests (Series III) is reported in the following sections.

The purpose of this work is to address the following questions.

1. What is the relationship between the critical vent area and the burning surface area of the explosive?
2. What role does the temperature of the explosive play in the calculation of the critical vent area?
3. What properties of the vented, burning explosive system lead to delayed violent reactions?
4. What constants in the generic venting equation (Reference 2) need to be modified for the explosive, Composition B?

VENTED EXPLOSION CHAMBER (VEC) TEST APPARATUS AND MATERIALS

Explosive samples were contained in 1014 seamless steel cylinders that were 5-1/2 inches tall with a 1/2-inch-thick wall and a 4-inch inside diameter. The bottom plate was electron-beam welded to the

cylinder to provide a continuous, integral "cup-shaped" container; while the top plate, containing the vent hole, was bolted at eight places to the cylinder with 1-inch long, 1/4 x 20 cap screws. Static pressure to separate the lid from the container was about 1400 psi. (See Figure 1.)

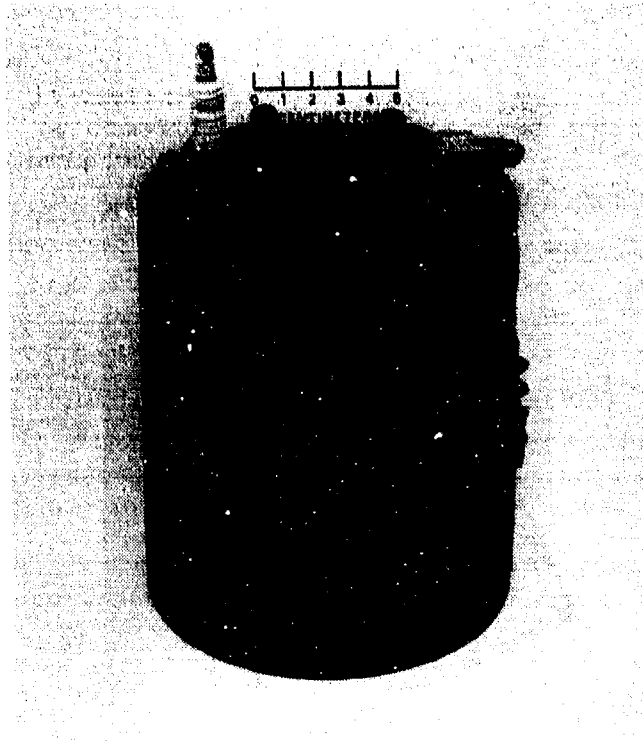


FIGURE 1. VEC Test Apparatus.

In the most recent Series III tests (reported here), the top of the apparatus was modified to include an ignition feed-through and a Bell and Howell Model 4-313A, 0-100 psi, water-cooled pressure transducer. (See Figure 2.)

The empty cylinders were sent to the Naval Weapons Station, Yorktown, VA, for lining and explosive loading. The 1/8-inch-thick liner was a polyethylene/polypropylene material used in the NAVSEA Explosives Advanced Development Program. The explosive load was nominally 2 pounds of cast Composition B (density = 1.70 g/cm³). The explosive filled the cylinder to a height of 3 inches above the 1/8-inch-thick liner, leaving a 1-7/8-inch air space between it and the lid containing the vent hole.

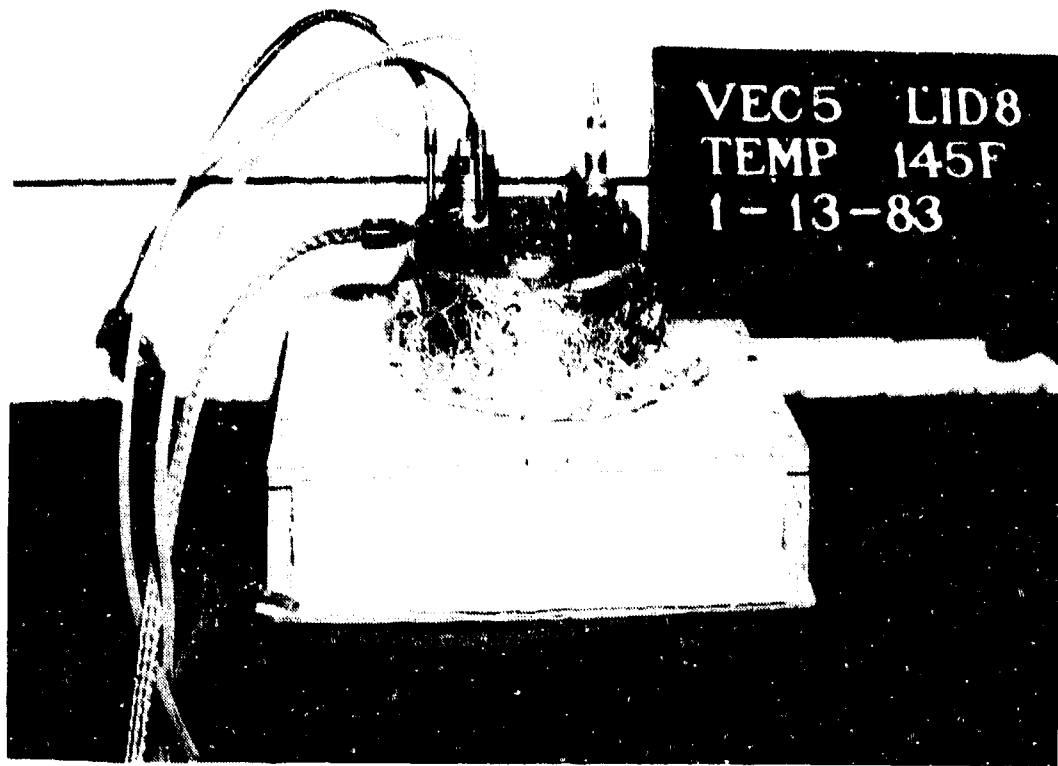


FIGURE 2. Series III Test Apparatus.

The various vent holes were precisely drilled through the center of the 1/2-inch-thick x 5-inch-diameter circular lids. The vent holes functioned as square-edged orifices subject to compressible flow.

Reproducible ignition of Composition B explosive at atmospheric pressure proved to be a very difficult task. Ignition had to be accomplished without initially overpressurizing the vented container, which would lead to destruction of the test. Several "gasless" methods were tried. An electrically heated Constantan ignition wire ribbon, 3/16-inch wide by $\approx 4\frac{1}{2}$ inches long, was tried without success. Next, a combination of thermite powder and thermite ignition mixture was tried. This gave a short-duration, high-heat pulse that sometimes ignited the Composition B, but more often behaved like a dust explosion, which rapidly pressurized the system. A reproducible ignition system was finally developed which consisted of 0.020-inch-thick x 3/4-inch-wide Pyrofuse (a sandwich of palladium and aluminum, which, when heated to 650°C, alloys to PdAl_2 at 2800°C). This was connected (from the feedthrough on one side of the lid to the metal case on the other) to a variable arc welding power supply. Since Pyrofuse has low

resistance, a high current of 200 A was necessary to heat it to reaction temperature. Ignition of the Pyrofuse and Composition B typically occurred between 5 and 8 seconds after application of the power to the Pyrofuse. This ignited a rectangular area on the surface of the explosive that rapidly spread over the exposed surface of the Composition B.

The initial temperature of the explosive was recorded. For low- and high-temperature runs, rounds were conditioned for 24 hours at the desired temperature, then placed in a well-insulated container for test setup and actual run.

Pressure measurements versus time were recorded on magnetic tape for later oscillographic reproduction. Time zero was set at the ignition of the Pyrofuse. Real-time video tape was also employed to aid in determining onset of reaction, ultimate reaction, and completion of the experiment. Pre- and post-still photography were also used. (Test parameters are listed in Table 1.)

TABLE 1. Test Parameters.

Test no.	Serial no.	Vent diameter, in.	Vent area, in ²	Explosive temperature, °C
VEC 1	8	0.234	0.0430	15
VEC 2	9	0.191	0.0287	15
VEC 3	6	0.221	0.0384	0
VEC 4	5	0.266	0.0556	61
VEC 5	7	0.219	0.0376	63

RESULTS

The experimental data are presented in Appendix A. A short summary of results is presented in Table 2.

TABLE 2. Results of Series III VEC Tests.

Test no.	Burn time, ^a s	Reaction
VEC 1	269.0	Slow burn, with several small pressure oscillations ($P_{\max} > 300$ psi at 269 seconds). ($\bar{v} = 0.24$ mm/s.) ^b
VEC 2	7.6	Slow burn until first pressure oscillation at 5.6 seconds. ($P_{\max} > 330$ psi at 7.6 seconds.)
VEC 3	4.08	Slow burn for 2 seconds, then slow runup until 3.9 seconds. Four oscillations in pressure, then pressure rupture (debris scattered 43 feet). (Anomalous--later examination of high-speed film indicated bottom rupture--explosive separated from liner.)
VEC 4	384.0	Quiescent burn for 252 seconds. Large pressure buildup at 267 seconds followed by "hissing" and 13-inch flame out the vent hole from 276 to 291 seconds. Black smoke at 303 seconds. Reaction completed at 384 seconds. ($\bar{v} = 0.17$ mm/s.) ^b
VEC 5	4.4	Steady pressure-rise with no oscillations apparent. At 4.4 seconds, top blew off scattering much unreacted, fractured explosive over a wide area.

^aAfter ignition.^b $\bar{v}$ is the average linear burning velocity of the explosive.

DISCUSSION

THEORY OF VENTED BURNING

Pressure Rise Rate

Kinney and Sewell (Reference 1) determined, from interior ballistics, the rate of pressure rise from combustion of an energetic material. The basic form is given in Equation (1) below:

$$\frac{dp}{dt} = \frac{RT_B}{V} \frac{dn}{dt} \quad (1)$$

where dn/dt is the time rate of change of the number of moles of product gases. This equation may be replaced with one in which the variables are more easily measurable. Thus,

$$\frac{dp}{dt} = \frac{RT_B}{V} \frac{\rho}{M} \frac{\alpha}{(A - BT_0)} S_B P \quad (2)$$

where

R = molar gas constant = 8.314×10^{-5} bar - m^3/mol - K

V = volume, m^3

T_B = flame temperature, K

M = formula mass product gas, kg/mol

ρ = density of explosive, kg/m^3

T_0 = bulk temperature of explosive, K

α, A, B = energetic material constants (see below)

S_B = burn surface area, m^2

P = absolute pressure, bars

The term $[\alpha/(A - BT_0)]$ represents the variation in burning rate with bulk explosive temperature. The values of the generic constants were chosen after examining the work of Johansson and Persson (Reference 3), in which they found that the reciprocal burning rate as a function of temperature for porous RDX ($\rho_0 = 0.9 \text{ g/m}^3$) at ambient temperature was about 0.5 mm/s. However, extrapolated strand burner linear burning rates (Reference 4) showed a lower rate of burning for cast Composition B of 0.13-0.15 mm/s at ambient temperature and pressure. The infinite burn rate intercept was estimated as 510 K (237°C) (Reference 3). From differential thermal gravimetry, differential thermal analysis, and thermal gravimetric analysis experiments at the Naval Weapons Center (NWC) (Reference 5) with granulated Composition B, violent decomposition occurs at about 478 K (205°C). These

observations led Sewell (Reference 6) to assign the following values to α , A, and B.

$$\alpha = 10^{-3} \text{ m/s-bar}$$

$$A = 17.2$$

$$B = 0.0335/\text{K}$$

These generic constants give the infinite burning rate temperature as $\approx 513 \text{ K}$, and give a burn rate of about 0.14 mm/s for cast explosives at $\approx 300 \text{ K}$. Figure 3 illustrates this.

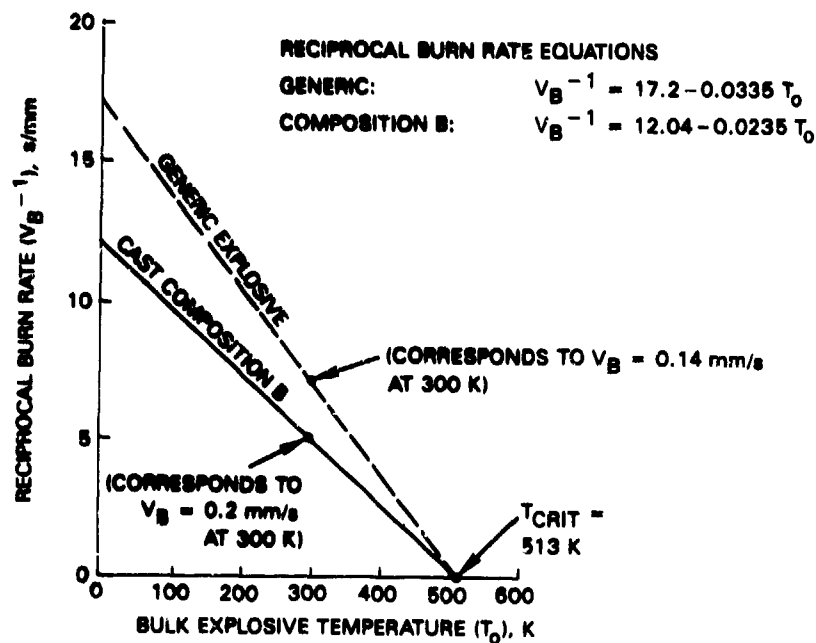


FIGURE 3. Reciprocal Burning Rate as a Function of Explosive Temperature.

Pressure Decay Rate

If the volume under consideration is vented, the flow through the vent tends to decrease the pressure. When the interior pressure exceeds the outside pressure by more than 0.8 bar, the flow velocity becomes sonic (Reference 7) and a very simple expression for the pressure-decrease results.

$$-\frac{dP}{dt} = \frac{A_v C_D}{V} a^* P \quad (3)$$

where

A_v = vent area, m^2

C_D = discharge coefficient, 0.6 to 1.0

V = volume, m^3

a^* = flow velocity, m/s

P = absolute pressure, bars

In the generic equation, C_D , the discharge coefficient was allowed to equal one, i.e., ideal flow. In actuality, flow through a square-edged orifice results in a drag coefficient of $\cong 0.82$ because of the vena contracta formed by the gases exiting the vent hole (Reference 7). The sonic flow velocity of the gases through the vent hole, a^* , is computed from the temperature of the products, and is also affected by compressible fluid flow. Thus (Reference 1)

$$a^* = \sqrt{\frac{RT}{M}} \left[k \left(\frac{2k}{k+1} \right)^{1/2} \left(\frac{2}{k+1} \right)^{1/k-1} \right]$$

where, for a "nominal" combustion gas mixture, with

$T = 2500 \text{ K}$

$R = 8.31434 \text{ J/mol-K}$

$M = 0.028 \text{ kg/mol}$

$k = 1.27,$

a^* is approximately 725 m/s. Note, that to do much better than the generic value requires knowing the actual composition of the product's gas, its specific heat as a function of temperature, and the actual flame temperature. These are different for each explosive material and difficult to measure.

Critical Vent Area

If the magnitudes of the pressure-decay and pressure-rise terms are equal, a critical condition results in which the pressure remains constant. This condition is met when the ratio of vent area to burning surface area is equal to a constant determined by the explosive constants and the initial temperature.

Assuming superposition holds, the pressure-rise and pressure-decay equations can be combined.

$$\frac{dp}{dt} = \left[(RT_B \frac{\rho}{M} \frac{\alpha}{(A - BT_0)} S_B) - (A_V C_D a^*) \right] \left(\frac{P}{V} \right)$$

If the vent-area to burn-surface-area ratio is less than the critical value, the pressure increases exponentially; if greater, the pressure decreases. Thus, the ratio is computed as:

$$\frac{A_V}{S_B} = \frac{RT_B \rho \alpha}{MC_D a^* (A - BT_0)}$$

For the generic constants, and with an explosive of density 1700 kg/m³, the predicted critical vent-area to burn-surface-area ratio as a function of bulk temperature is shown for the Series III test condition in Table 3 below.

TABLE 3. Critical Vent Area as a Function of Initial Explosive Temperature ($S_B = 11.04 \text{ in}^2$).

T_0 , °C	T_0 , K	Critical ratio, A_V/S_B	Calculated critical vent area for VEC test, A_V , in ²
0	273	0.002161	0.02386
15	288	0.002305	0.02545
61	334	0.002896	0.03197

MODIFICATIONS TO GENERIC EQUATIONS FOR CAST COMPOSITION B

The average burning rate of Composition B in over-vented chambers at ambient temperature appears to be about 0.2 mm/s. In Test VEC 1 the average burning rate was 0.24 mm/s. In work done for the Defense Atomic Support Agency (Reference 8), the observed burning rate was 2.5 ft/hr, which translates to 0.21 mm/s. Thus, it might be useful to modify the $[\alpha/A - BT_0]$ term in equation (2). Proposed constants for cast Composition B are

$$\alpha = 10^{-3} \text{ m/s-bar}$$

$$A = 12.04$$

$$B = 0.0235/T$$

These constants give a burning rate of 0.2 mm/s at 300 K while maintaining the 513 K transition to infinite burning. The effect of this change is also shown in Figure 3.

A second change would be to use a more accurate discharge coefficient, C_D . As mentioned earlier, square-edged orifices at sonic velocity demonstrate a C_D of ≈ 0.82 . This would be a good value to use for these experiments, but for fragment-perforated warhead cases, C_D could be even lower (≈ 0.6).

Another variable used in calculating the critical vent area is the burning surface area, S_B . For a system burning linearly (cigarette fashion), S_B is constant if ignited over the whole surface instantaneously. However, for the ignition system used in these experiments, only a strip of the cylindrical explosive surface was initially ignited. Here, S_B should be calculated as a function of time. In the worst case, the explosive could burn at its linear burning rate in the X, Y, and Z directions simultaneously. For this particular geometry, S_B as a function of time was calculated for the over-vented situation. Initially, the burning surface is smaller than the total exposed explosive surface of 11.04 in². At 96 seconds, the burning surface is equivalent to 11.04 in² (7126 mm², the total exposed surface). At 155 seconds, the trough-shaped burning surface reaches a maximum value of 8705 mm² and by 280 seconds has returned to 7126 mm². Figures 4 and 5 illustrate this. Note that if central point ignition had been used, there would have been a 170-second delay to $S_B = 7126$ mm² and an overshoot of almost 87% at 230 seconds. (The burning surface would be spherically shaped.)

The effects of changing the discharge coefficient in the generic equation from 1.0 to 0.82 is shown in Figure 6. Note that VEC data points for Test No. 2 and 5, which rapidly pressurized, fall just beneath this line. Test No. 3 is considered anomalous, as stated in Table 2. Applying the proposed modifications to the burning rate equation for Composition B shifts the boundary between violent pressure rupture and quiescent burning upward to larger values of A_v/S_B . This appears to be a slightly conservative representation of the boundary from a safety point of view since all rapid burns lie below it and the quiescent burns lie upon it. This is in qualitative agreement with the Air Force work (Reference 8) shown in Figure 7. They found quiescent burns in the range of 0.121 to 0.003 A_v/S_B , while violent pressurization occurred in many tests in the range of 0.0058 to 0.0028 A_v/S_B .

THERMAL MODELING OF HEAT FLOW

As was seen in the previous sections, the required critical vent area to burning surface area increases as the bulk explosive temperature increases. One can visualize an impacted explosive round

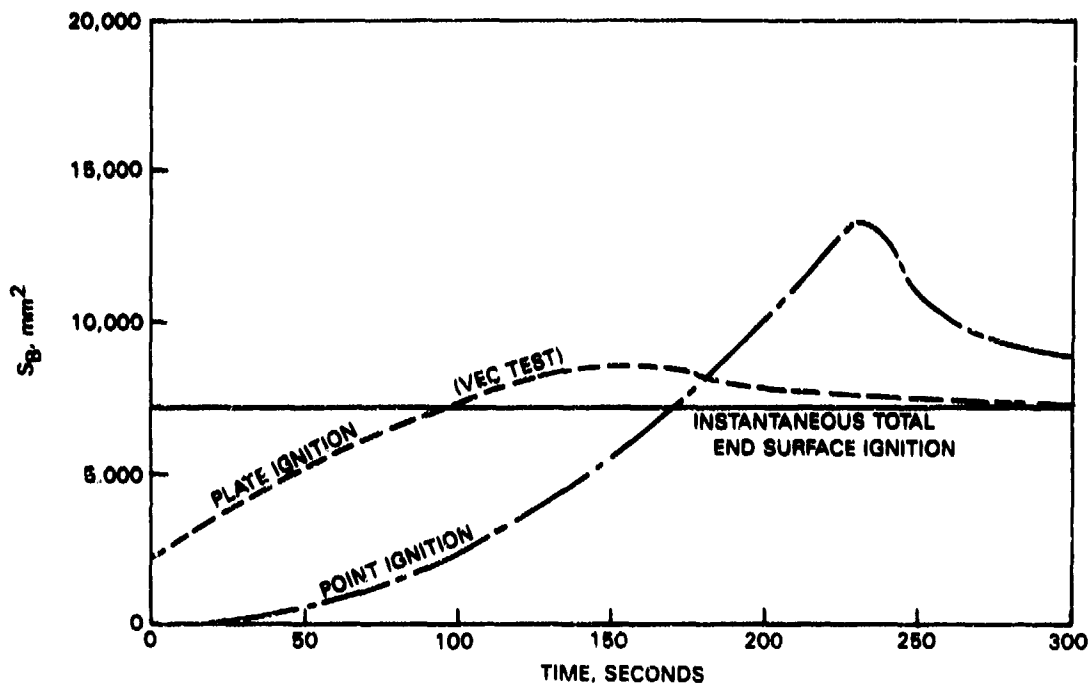


FIGURE 4. Burning Surface Area of Composition B Versus Time for Various Ignition Source Geometries.

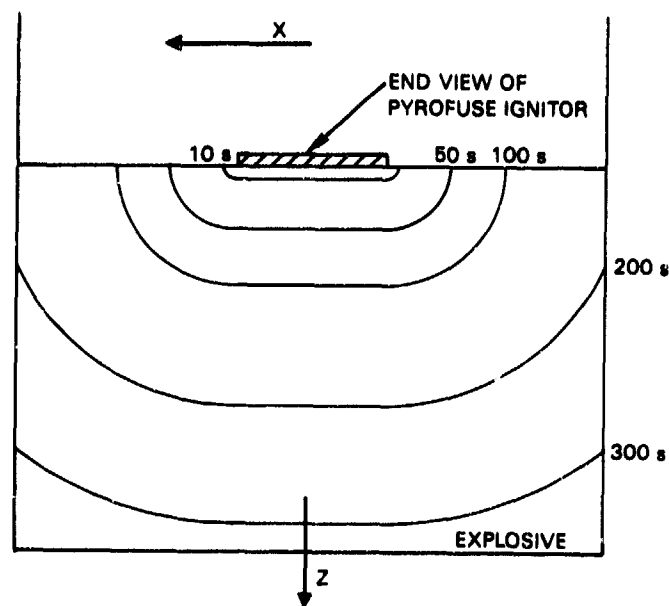


FIGURE 5. Shape of Burning Surface as a Function of Time (X-Z Plane).

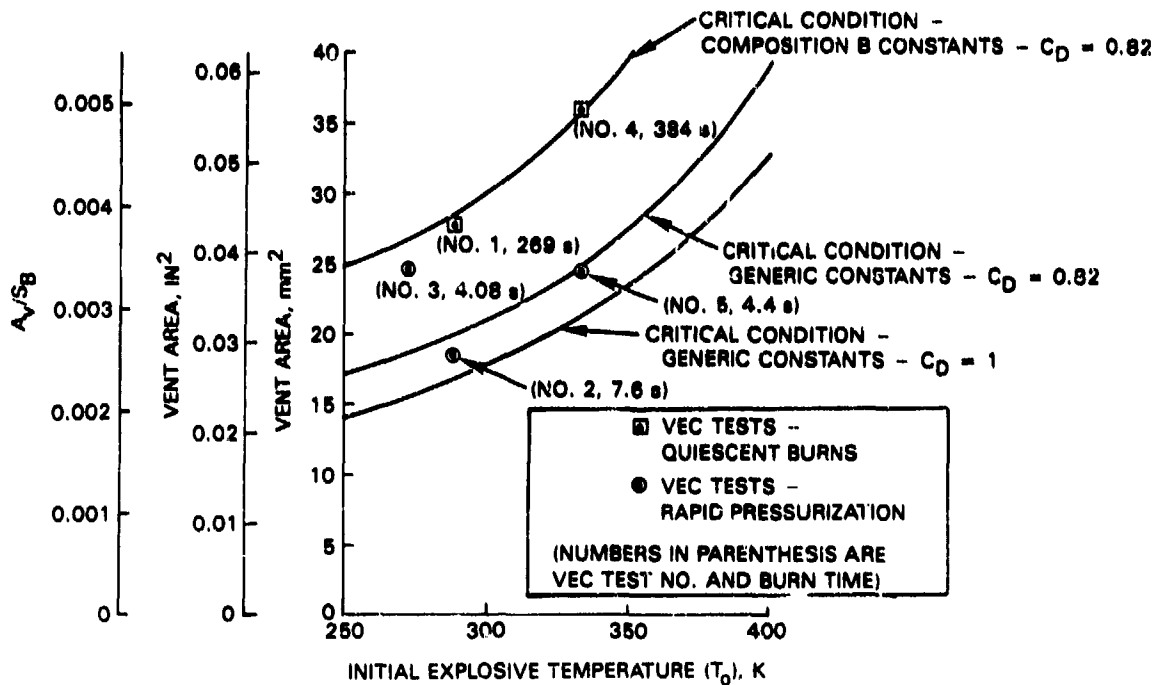


FIGURE 6. VEC Test Results Compared to Predicted Critical Vent Area for $S_B = 11.04 \text{ in}^2$.

that ignites and burns in the over-vented condition for some time; but because of heat transfer down the wall of the device and radiation heating of the bulk explosive, the explosive temperature rises, the reaction rate increases, and the available vent is suddenly too small to prevent pressure rise.

To determine the magnitude of this effect, Stroebel and Graham (Reference 9) (see Appendix B) performed a simplified thermal analysis of the VEC tests. In this initial work, the linear burning rate of Composition B was assumed to be 0.1 mm/s . Thermal contours were generated using the SINDA computer program. These contours show definite preheating of the bulk explosive ahead of the flame front. While the burning rate was too slow, and a kinetic equation for rate of change of burning velocity with temperature was not incorporated into the routine, it is significant that the steel wall was heated ahead of the flame front and that the explosive near this wall was also significantly preheated. Figures 8, 9, and 10 show the results of these calculations at three different response times.

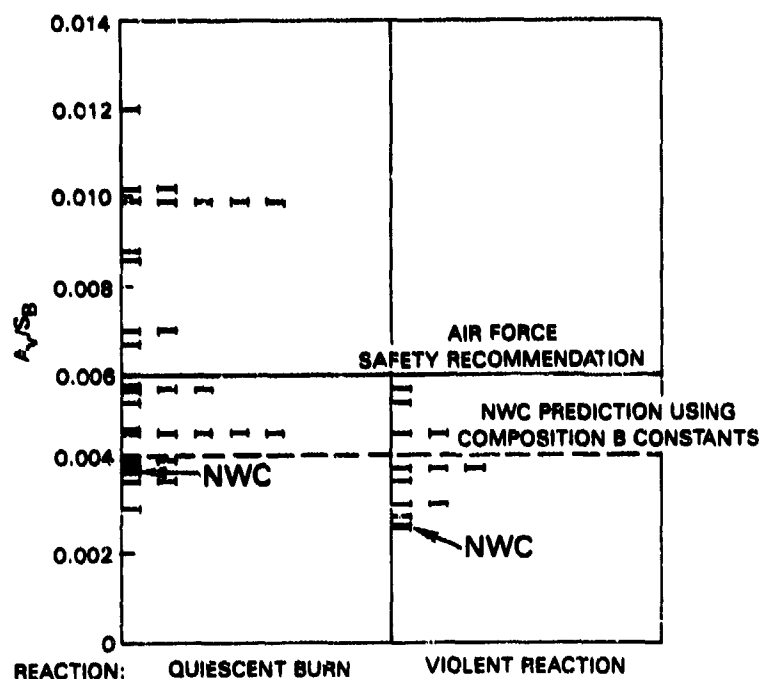


FIGURE 7. Summary of Air Force Vented Burning Studies with Composition B. ($S_B = 12.57 \text{ in}^2$; $T \approx 300 \text{ K}$). Superimposed are Two VEC Test Points (#1 and #2) at $S_B = 11.04 \text{ in}^2$ and $T_o = 288 \text{ K}$.

CONCLUSIONS

In response to the questions posed in the introduction of this report:

1. Two relationships between critical vent area and burning surface area have been developed--one for generic, cast explosives and one specifically for Composition B.

2. The critical vent-area to burning-surface-area ratio (A_v/S_B) is affected by the bulk temperature of the explosive. The higher the bulk temperature, the faster the burning rate and the larger the vent required to prevent rapid pressurization, as indicated in Equation (2).

3. Delayed violent reactions have been observed in burning, vented munitions and in small-scale tests. It appears that the change in critical vent size as the burning surface increases in area and in temperature plays a key role in these delayed reactions.

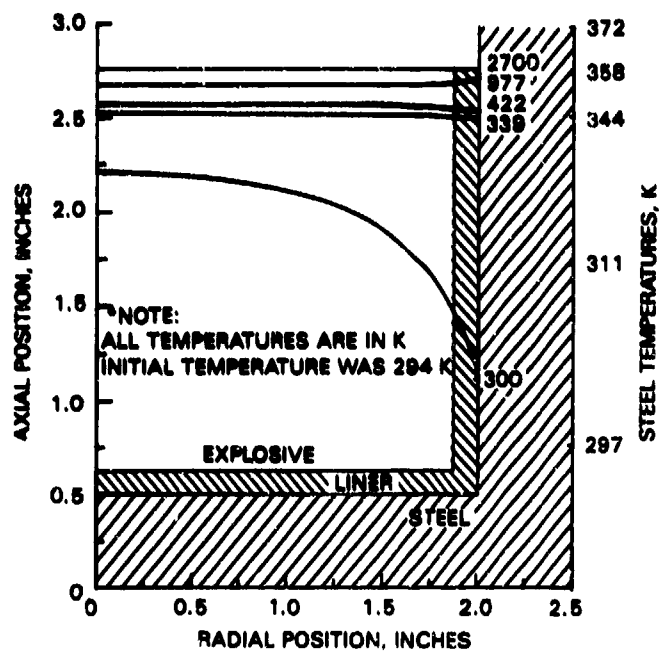


FIGURE 8. Cross Section of Steel Cylinder Showing Isotherms in Burning Explosive at 60 Seconds.

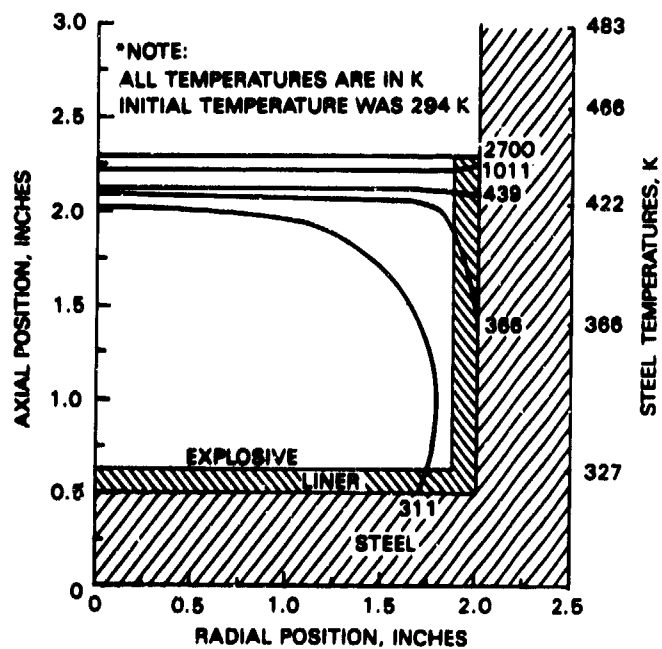


FIGURE 9. Cross Section of Steel Cylinder Showing Isotherms in Burning Explosive at 180 Seconds.

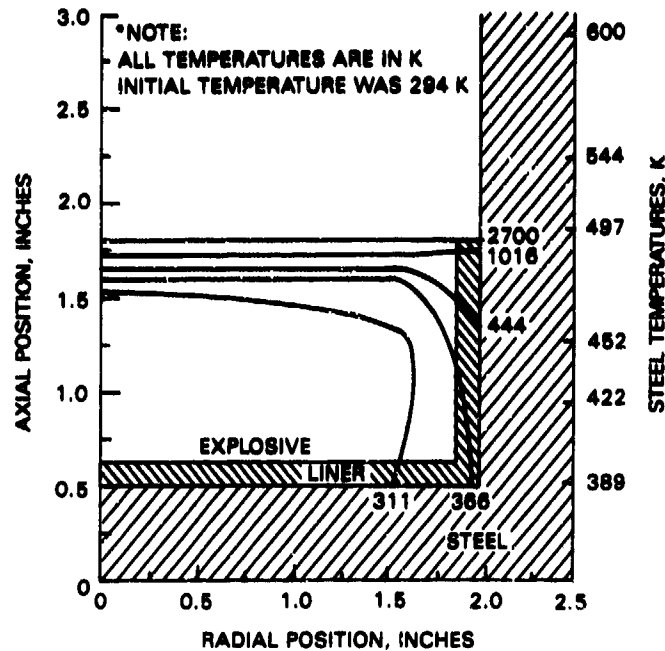


FIGURE 10. Cross Section of Steel Cylinder Showing Isotherms in Burning Explosive at 300 Seconds.

4. It is apparent that either the generic venting equation with $C_D = 0.82$ or the modified equation (also with $C_D = 0.82$) would adequately represent the boundary between quiescent, vented burning; and violent, undervented pressure rupture. In light of the Air Force work cited, and due consideration for a margin of safety, an A_v/S_p ratio of ≥ 0.006 at an explosive temperature of 300 K should prevent violent pressurization in Composition B-loaded rounds.

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Appendix A

SAMPLE TEST DATA FOR VEC
SERIES III TESTS

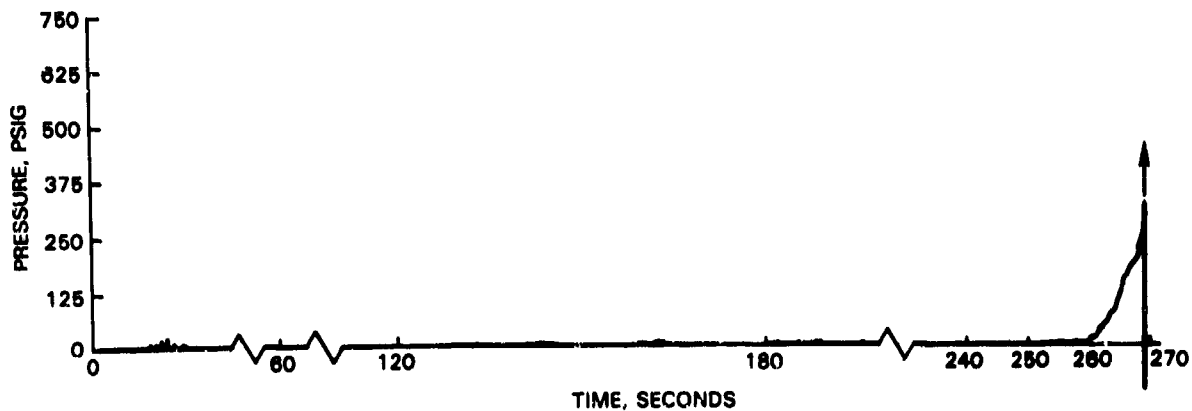


FIGURE A-1. VEC Test 1, Pressure-Time History.
 $A_v = 0.0430 \text{ in}^2$, $T = 15^\circ\text{C}$.

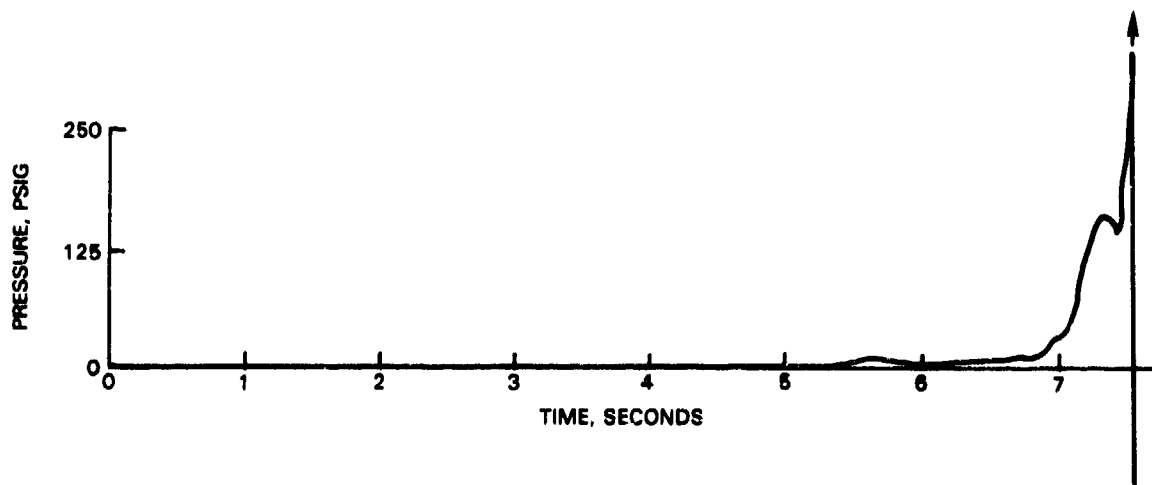


FIGURE A-2. VEC Test 2, Pressure-Time History.
 $A_v = 0.0287 \text{ in}^2$, $T = 15^\circ\text{C}$.

NWC TP 6456

Appendix B

THERMAL MODELING OF VEC TESTS USING THE SINDA PROGRAM



DEPARTMENT OF THE NAVY
NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

IN REPLY REFER TO:
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Reg 3242-27-83
3 Mar 1983

MEMORANDUM

From: F. A. Strobel, Thermal/Structures Branch (Code 3242)
To: K. J. Graham, Warhead Dynamics Branch (Code 3835)
Via: Head, Thermal/Structures Branch (Code 3242) *ACU*

Subj: Composition B thermal analysis

Ref: (a) TRW report 11027-6003-R0-00, dtd Sept 1980.
(b) Chapman, "Heat Transfer," MacMillan Publishing Co., 1974.
(c) Aerotherm report UM-75-68, dtd Dec 1975.

Encl: (1) Sketch of test setup
(2) Sketch of conduction nodal network
(3) Material properties
(4) Explosive thermal response, time = 300 seconds

1. The purpose of this memorandum is to describe the methodology used in conducting the thermal analysis for the Composition B explosive tests conducted by Code 3835. The analysis was used to calculate temperature response of the Composition B explosive due to heat conduction from the hot surface and through the steel walls of the holder. This analysis was completed in November 1982 and the results were forwarded to Code 3835.

2. The temperature calculations were made with the use of the Systems Improved Numerical Differencing Analyzer (SINDA, reference (a)). Enclosure (1) shows a sketch of the test setup and the phenomena considered in the analysis. Besides heat conduction throughout the explosive, liner, and steel, the thermal model included convective heating of the inner surface of the steel cylinder exposed to the hot combustion gases. In addition, the model included cooling of the steel cylinder due to radiation and natural convection to the surroundings.

3. Since the part being modeled is axi-symmetric, a two dimensional conduction model was sufficient. Because the explosive was burning at its upper surface and receding at the rate of 0.1 mm/sec, it was necessary to continuously regrid the conduction model. A sketch of the nodal network for the conduction model is shown in enclosure (2). The Comp B, liner, and steel were comprised of 72, 28, and 38 nodes, respectively. An extra fine grid was applied to the top surface and outer edges of the explosive because these were the areas where largest temperature gradients would occur. In order to keep the nodes aligned all three parts had to be continuously regridded. Since the node centers changed after each time step, an interpolation scheme had to be used to find the temperatures at the new node center locations.

4. Convective heating rates to the inner wall of the steel cylinder were calculated from a method for pipe flow described in reference (b). The accuracy of this method is questionable and this could be an area of improvement if

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Subj: Composition B thermal analysis

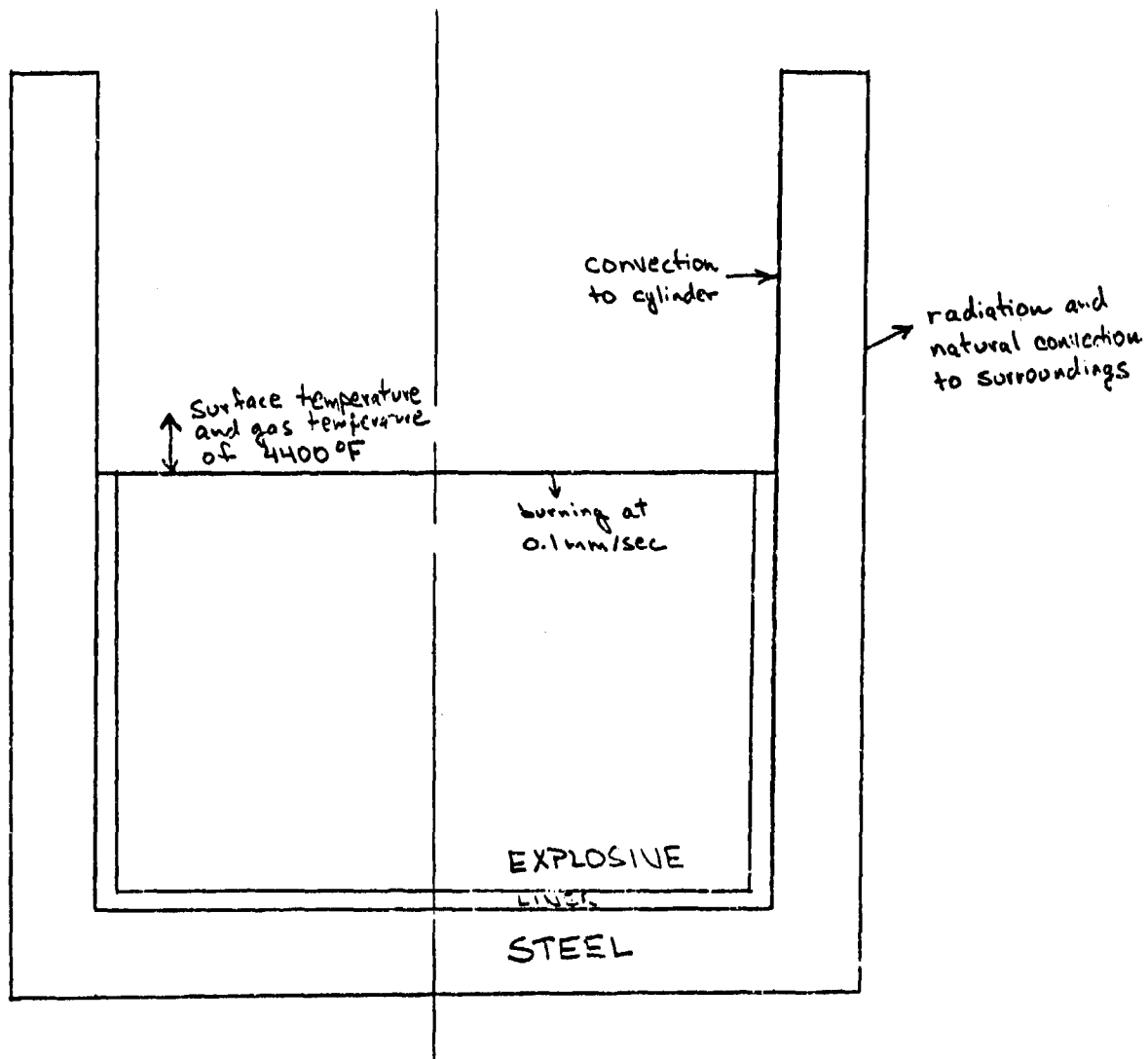
additional analyses were needed. To calculate the convective heating rates it was necessary to know the properties of the hot combustion gases. These properties were obtained through use of the Aerotherm Chemical Equilibrium computer code (ACE, reference (c)).

5. The thermal property data used for the analysis is contained in enclosure (3). More detailed property data for the Comp B and liner materials would add to the accuracy of the calculations. In addition, modelling the decomposition and burning of the liner material would also add to the accuracy of the calculations.

6. In conclusion, a reasonably good thermal model for the Comp B explosive tests has been developed. This model takes into account the most important phenomena occurring. A typical plot of results is shown in enclosure (4). This plot shows steel temperatures and isotherms in the explosive after a burn time of 300 seconds. Possible areas for improvement in the model have been outlined in the preceding paragraphs.

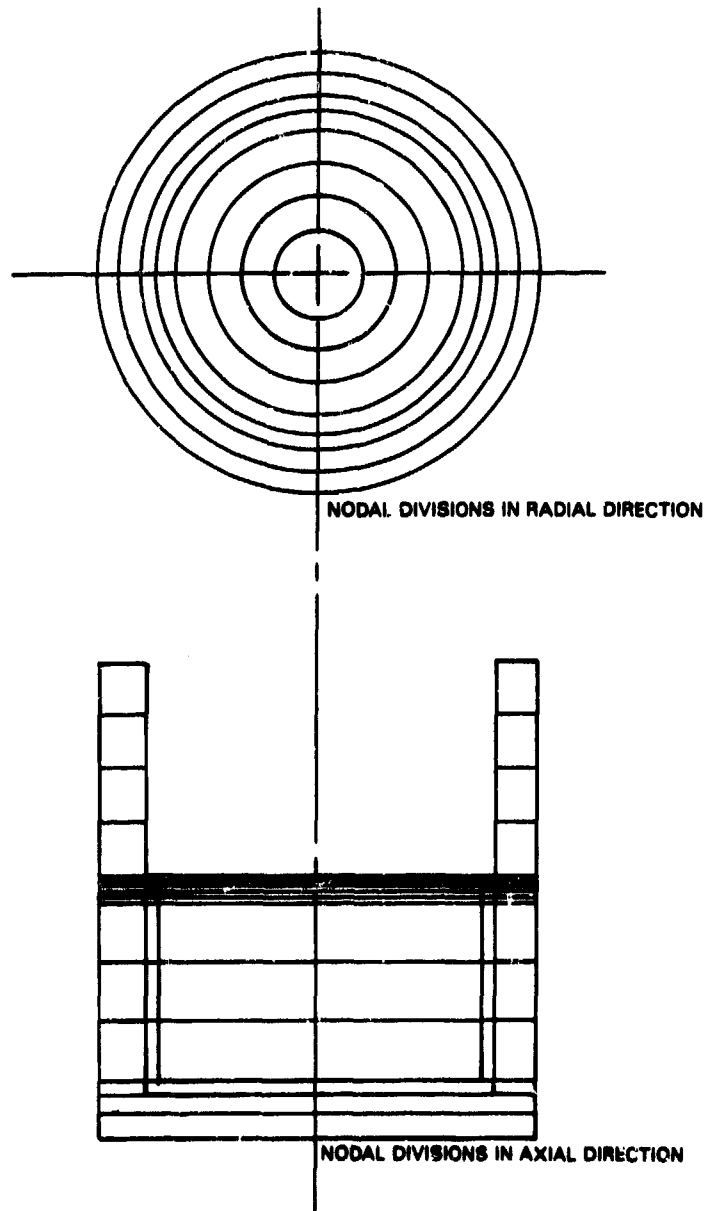
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SKETCH OF TEST SETUP

Enclosure (1)



Enclosure (2)

MATERIAL PROPERTIES

<u>Steel</u>	Temperature (°F)	Density X Specific heat (Btu/in ³ -°F)
	31.4	0.2982
	166.4	0.03408
	391.4	0.03834
	751.4	0.0426
	1111.0	0.0482
	1291.0	0.05679
	Temperature (°F)	Conductivity (Btu/in-sec-°F x 10 ⁴)
	32.0	4.861
	392.0	4.861
	572.0	4.630
	752.0	4.398
	1112.0	4.167
	1472.0	3.704
	1832.0	3.704
	2192.0	3.935
<u>Composition B</u>	Temperature (°F)	Density X Specific heat (Btu/in ³ -°F)
	30.0	0.0186
	86.0	0.0186
	122.0	0.0191
	158.0	0.0203
	212.0	0.0207
	5000.0	0.0207

Conductivity for all temperatures = 3.484×10^{-6} Btu/in-sec-°F)

Liner

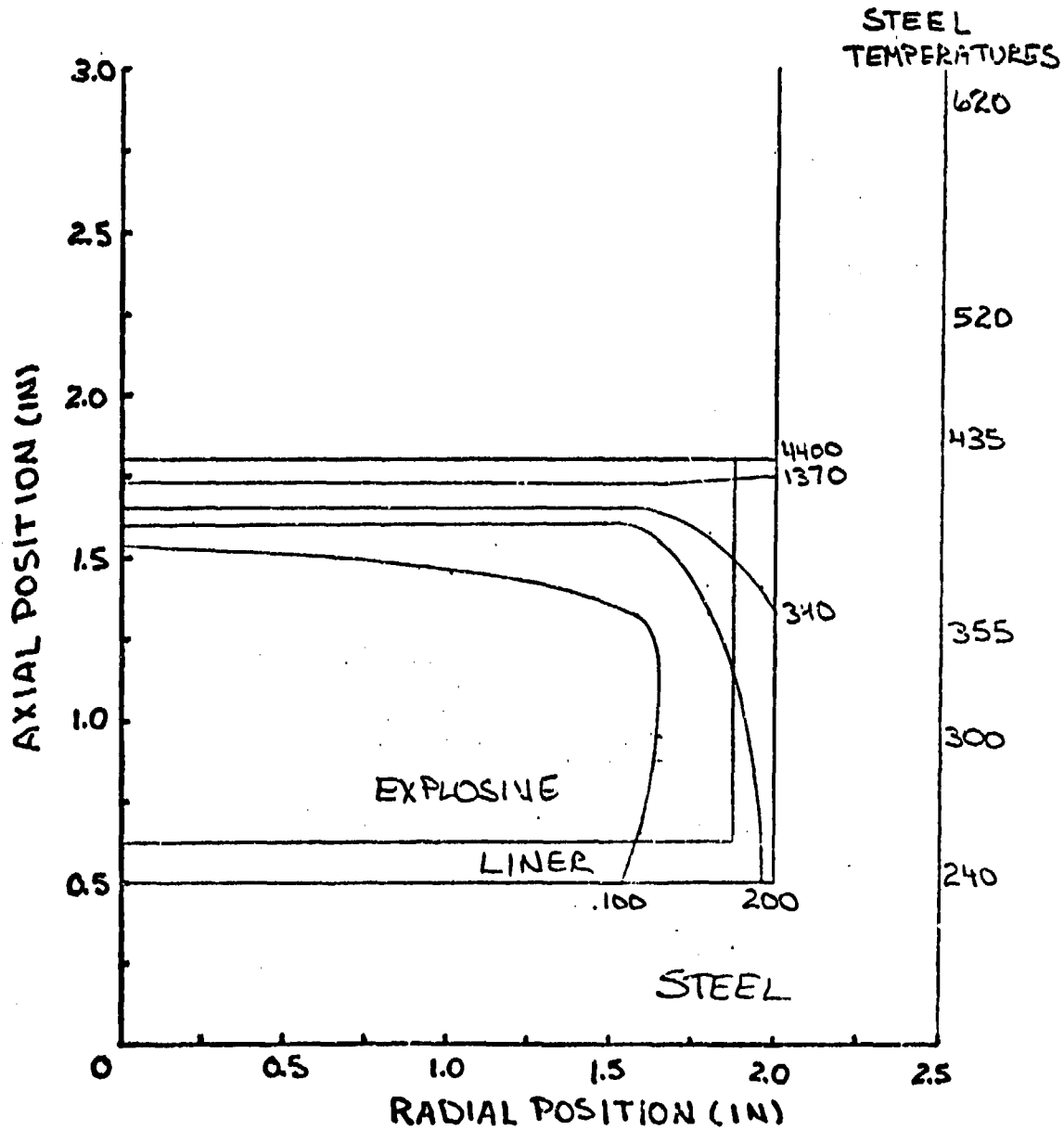
Density X Specific heat = $0.0158 \text{ Btu/in}^3\text{-°F}$

Conductivity = $9.9 \times 10^{-6} \text{ Btu/in-sec-°F}$

} All temperatures

Enclosure (3)

EXPLOSIVE THERMAL RESPONSE TIME = 300 SECONDS



* NOTE: ALL TEMPERATURES ARE IN °F
INITIAL TEMPERATURE WAS 70°F

Enclosure (4)

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