AD

AD-E403 295

Technical Report ARMET-TR-10003

EXPLOSIVE VENTING TECHNOLOGY FOR COOK-OFF RESPONSE MITIGATION

T. Madsen
S. DeFisher
E.L. Baker
D. Suarez
N. Al-Shehab
A. Wilson
B. Fuchs

July 2010

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Munitions Engineering Technology Center

Picatinny Arsenal, New Jersey

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-01-0188*

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (*From - To*)
July 2010		

4. TITLE AND SUBTITLE	
EXPLOSIVE VENTING TECHNOLOGY FOR COOK-OFF RESPONSE MITIGATION	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHORS	5d. PROJECT NUMBER
T. Madsen, S. DeFisher, E.L. Baker, D. Suarez, N. Al-Shehab, A. Wilson, and B. Fuchs	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, METC Energetics, Warheads & Manufacturing Technology Directorate (RDAR-MEE-W) Picatinny Arsenal, NJ 07806-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC, ESIC Knowledge & Process Management (RDAR-EIK) Picatinny Arsenal, NJ 07806-5000	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S) Technical Report ARMET-TR-10003

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Small and large scale explosive venting experiments were conducted using highly controlled thermal cook-off test fixtures. These experiments allowed us to characterize the explosive violence as a function of a known vent area and controlled heating rate. The required venting area was experimentally determined at different heating rates. Large scale hardware was used to investigate scaling effects. Tests results indicate that some explosives (PAX-28 and PBXN-109) intrinsically require less vent area to achieve a non-violent response than others (Comp B). However, the results also indicate that for solid explosives, a violent reaction commonly occurred when the samples were heated without the use of a melt out liner, which allows gaseous products to reach the vents. This is in contrast to melt cast explosives that may respond in a non-violent manner without the use of a liner. Thermal modeling, including explosive kinetics, was also conducted using ALE-3D and for some solid explosives (PBXN-109) shows close agreement with actual test results. However, very limited modeling is available for melt pour explosives. Slow cook-off experiments were conducted at 27.8°C/hr (50°F/hr) and 3.3°C/hr (6°F/hr) heat rates. At the lower rate, the ignition normally occurred near the center of the billet. In this case, gas products can be confined, resulting in a violent reaction. Recent work has concentrated on concepts for using energetic materials to force the reaction to the billet surface during 6°F/hr heating in order to produce a non-violent reaction.

15. SUBJECT TERMS

Explosive venting technology   Vent   Thermal modeling   Cook-off   PAX-28   PBXN-109

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON E.L. Baker
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
U	U	U	SAR	29	(973) 724-5097

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

CONTENTS

FIGURES

FIGURES
(continued)

INTRODUCTION

Insensitive munitions (IM) requirements place a great demand on the ability of ordnance to withstand unplanned external stimuli. When subject to slow cook-off (SCO) for example, ordnance is required to exhibit a response no more severe than a burning reaction (type V by MIL-STD 2105C). The U.S. Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey and the Program Executive Office for Ammunition (PEO Ammo) are developing and applying IM warhead venting technology in order to survive unplanned stimuli produced by fires (slow and fast cook-off). The technology development is concentrating on warhead venting and explosive billet liners for the release of explosive products, while maintaining required structural body characteristics and high warhead performance. Warhead venting for mitigating the violent response to unplanned thermal stimuli caused by fires or other heating sources is not a new concept (refs. 1 through 6). However, explosive venting requirements characterization and quantification for different explosives, sizes, and heating rates is generally lacking. As a result, warheads venting to date was primarily developed using a purely iterative experimental approach for a given warhead and venting geometry. This methodology is typically very expensive and does not assure a well optimized or cost effective venting solution. In addition, each additional munition venting development essentially starts with virtually no information to aid in the venting design process.

Our current effort concentrates on developing a venting design capability through the use of laboratory characterization and computer modeling. Before designers can mitigate the response of munitions subject to SCO, they must first understand how confined explosives behave when heated. A variety of effects control the response, including venting area, sample size, and heating rate. Small and large scale venting experiments have been conducted using highly controlled thermal cook-off test fixtures. These experiments allow us to characterize the explosive violence as a function of a known vent area and controlled heating rate. The required venting area is experimentally determined at different heating rates. Large scale hardware has been used to investigate scaling effects. Thermal modeling, including explosive kinetics, has also been conducted using ALE-3D. Recent work has concentrated on concepts for using energetic materials to force the reaction to the billet surface during heating in order to produce a non-violent reaction.

WARHEAD VENTING CONCEPTS

Venting techniques using melt venting and pressure rupture are being addressed. The melt venting techniques use vent plugs or thread adaptors that will soften or melt when heated in cook-off scenarios. The pressure rupture techniques use pressure blow-out plugs or thread adaptors that rely on pressure build-up from the explosive during a cook-off event. Pressure rupture applications must provide sufficient venting area and respond at low enough pressures to prevent explosive high burning rates associated with violent response. Another approach is the use of shape memory alloys to provide a mechanical venting response at a desired temperature. Warhead IM liner technology using melting materials is also part of the development. Such a liner is applied around the explosive billet between the explosive billet and the warhead case material. This liner is incorporated in order to provide a path for explosive products release to the vent positions, as well as to provide some initial volume for burning products in order to prevent extreme rapid pressurization. The liner melts in a cook-off event before the explosive billet initiates burning. The melted liner material then flows and allows explosive products a path to the body vent positions regardless of the ignition position. The concepts outlined are primarily passive venting techniques. Active venting techniques include some separate sensing, safe and arm, and activation technique in order to produce venting. One such active venting approach being pursued is the application of shaped charges to create a vent and promote explosive burning in order to produce a controlled munitions response. In order to have design capability for these warhead venting concepts, explosive burning and venting requirement characterization is required. Initial efforts are concentrating on laboratory scale experimentation for venting requirements characterization, as well as thermal modeling for the ignition onset.

SMALL SCALE LABORATORY FIXTURE

Venting design capability development through venting requirement characterization is being conducted using small scale laboratory hardware experimentation. Figure 1 presents a diagram of the small scale testing hardware configuration and photograph of the assembled test fixture. The small scale venting experiments use a highly controlled thermal cook-off test fixture very similar to non-vented experimentation conducted at Lawrence Livermore National Laboratories [LLNL (ref. 7)]. The small scale test fixtures consist of a small diameter explosive billet highly confined in a steel housing. The inner chamber of the test fixture measures just over 25 mm in diameter by 100-mm long. The high explosive (HE) billet is either melt cast directly into the test cylinder or pressed/cure cast and then machined. All explosive billets are x-ray inspected for voids and cracks and only used for testing if determined to be acceptable from the inspection. One end of the housing has a circular vent disc with an adjustable vent diameter. The vent disc, two o-rings, and 16 bolts were inserted and assembled in the fixture. The bolts were torqued in a star pattern and the entire fixture is normally placed vent side up on a ceramic tile inside of the heavy steel cylinder located in the test chamber. Ceramic tiles were used as insulation between the fixture and steel floor to make it easier to control the fixture temperature. A mirror and light are then aligned to allow a camera to remotely record the vented side of the fixture through a viewing port located on the side of the test chamber. Normally, two test fixtures, with different vent diameters, are loaded into the chamber for each test. This is done simply to increase the testing through-put. Figure 2 presents the assembled test fixture in the chamber ready for testing. The steel housing is heated using four heating bands and electric current feed-back control based on measured thermocouple temperatures. Standard digital video cameras (30 fps) output images directly to the hard disk drive of a Panasonic DMR E-500H DVD video recorder via S-video cable. The hard disk drive feature of this recorder provided the opportunity to capture hundreds of hours of video at full resolution and frame rates without any risk of running out of recording space. A pair of cameras and Panasonic recorders is operated so that the reactions of both assemblies can be recorded simultaneously. These experiments characterize the explosive violence for a known venting area and controlled heating rate. Figure 3 presents an example of the inside of the chamber after one of the experiments in which one round exhibited a violent reaction and the other round did not. The standard test procedure is to increase and decrease the vent size in order to bracket a non-violent/violent reaction threshold. Normally, this can be done fairly quickly with a set of eight test fixtures.

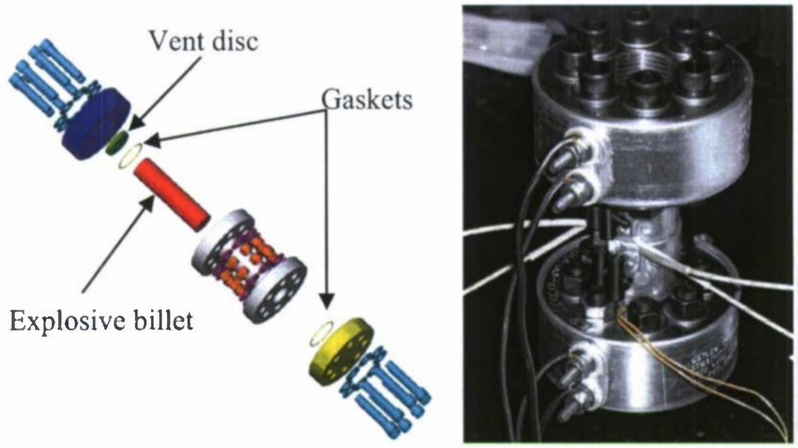


Figure 1
Small scale cook-off venting laboratory hardware configuration

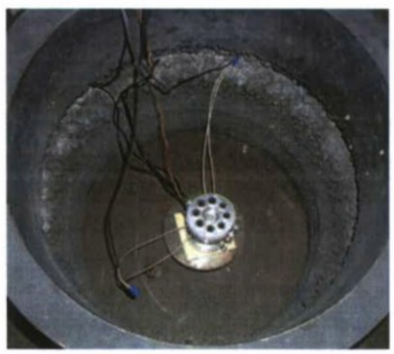


Figure 2
Assembled test fixture in the chamber ready for testing

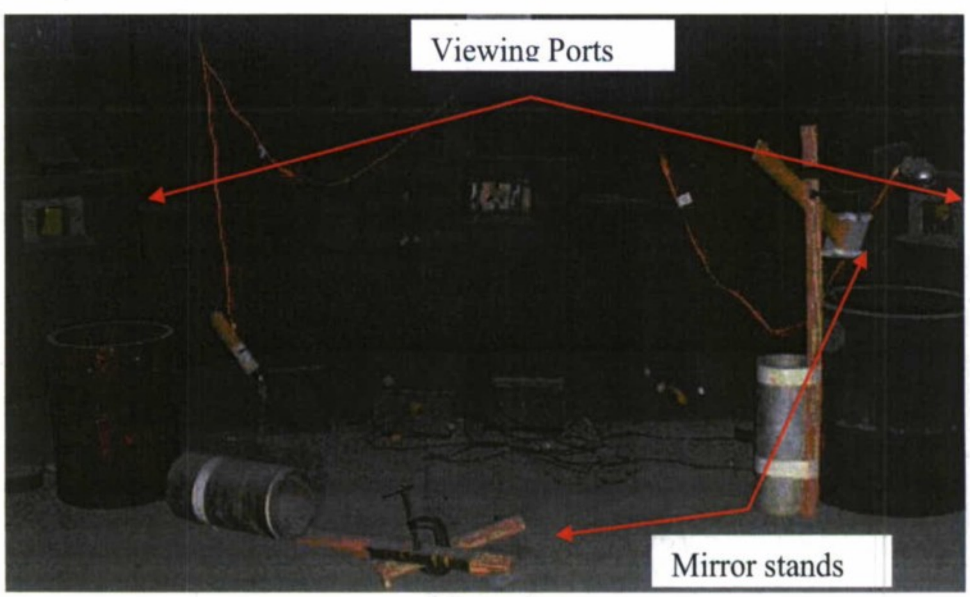


Figure 3
Test chamber post test
(violent reaction on left, benign reaction on right)

SMALL SCALE LABORATORY TESTING

For melt cast formulations, the largest vent diameter reactions proceeded from melting with liquid formation at the top of the vent hole through bubbling to vigorous boiling and smoking and then on to burning. All hardware for large non-violent vent diameters has showed evidence of burning. For the non-violent tests, videos and surrounding evidence did indicate that burning had occurred, but the reactions were relatively benign resulting in no damage to both the test fixtures and the ceramic insulating tiles.

Figure 4 shows the two largest vent diameters for PAX-28 during the vigorous bubbling and smoking phase. For these large vent diameters, the point of ignition appears to be somewhere in the center of the boiling pool of molten (HE). Although the cameras used to record the event only operated at 30 fps, on a few occasions, initiation was captured early enough to indicate an approximate ignition location. Figure 5 presents photographs of the PAX-28 ignition. The burning period for the three largest vent diameter test cases extended for greater than 30 sec, for the 7.6-mm case and over 1 min, for the 10.2 mm and 12.6-mm cases. Figure 6 presents the resulting test fixture from the PAX-28 7.6-mm vent diameter case. Some amount of the melt cast explosive boils up and over the top and down the side of the test fixture, ending up in a molten but otherwise unreacted puddle next to and on the fixture. Hardware response for smaller violent producing vent diameters shows varied results from extensively damaging the test configuration to simply blowing off the end fixture. The result of the PAX-28 5.1-mm diameter vent test was to blow off the top fixture and peel off three out of the four heating bands while leaving the fixture in its original position as seen in figure 7. However, the PAX-28 6.4-mm diameter vent test yields a more typical violent result where the test fixture is blown open. Figure 8 shows the results of this test.

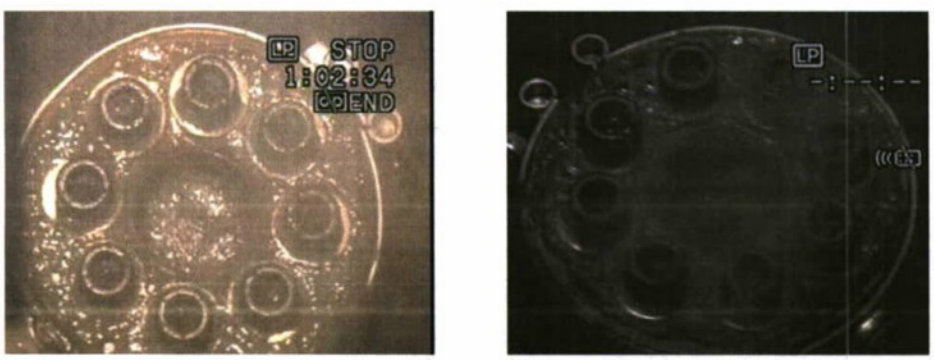


Figure 4
10.2 and 12.6-mm vent diameters before ignition for PAX-28

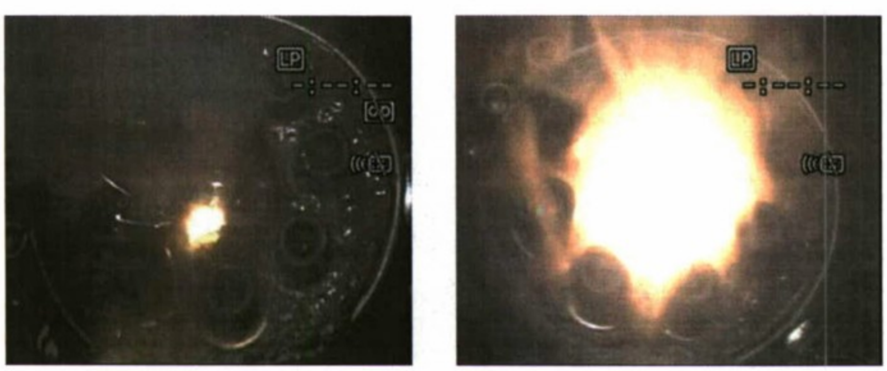


Figure 5
10.2 and 12.6-mm diameter vent disc ignition for PAX-28

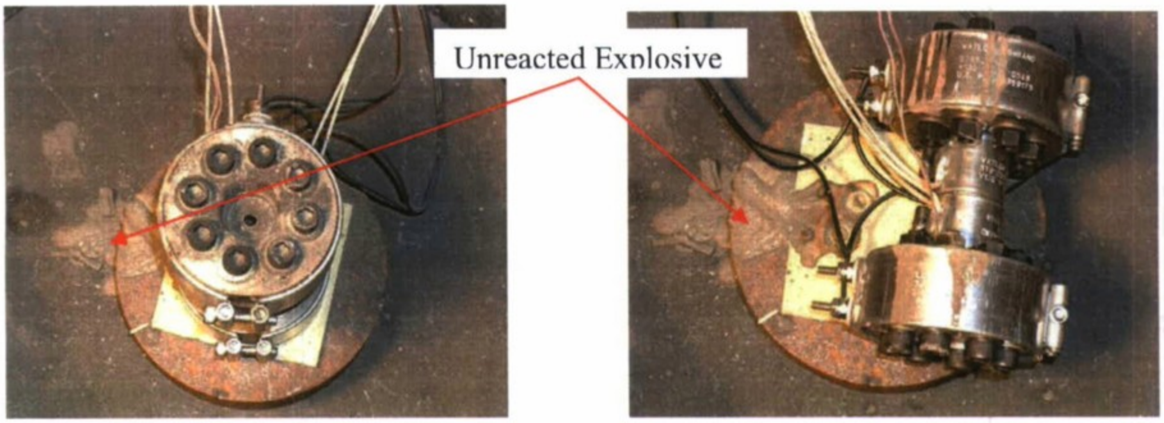


Figure 6
Two views of 7.6-mm diameter vent hole test fixture post test

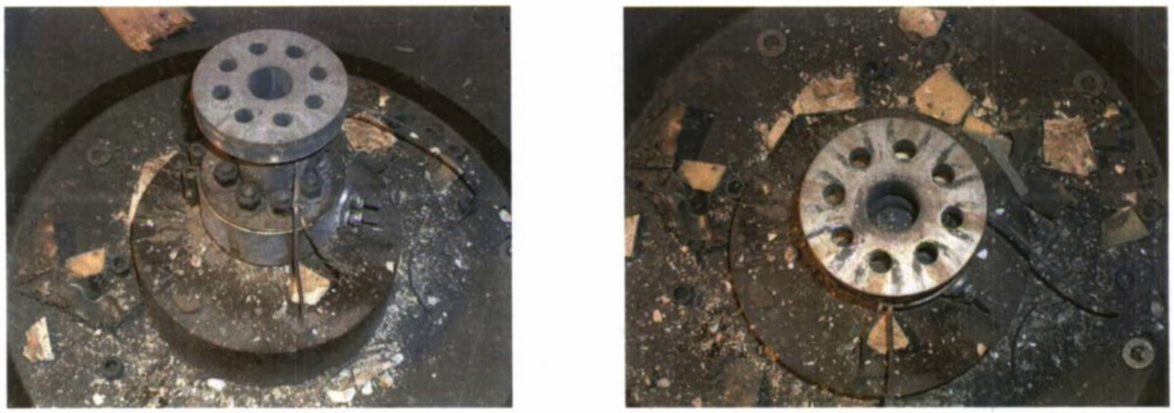


Figure 7
5.1-mm diameter vent test result for PAX-28

Figure 8
6.4-mm diameter vent test result for PAX-28

The only cast cure composition tested to date is PBXN-109. Initial testing was conducted using test samples that were machined to fit directly into the test fixture without a melt liner to surround the billet. Testing of this configuration with a large vent hole (12.7-mm diameter) had a violent reaction. Subsequent testing was performed using a 0.76-mm thick high density polyethylene (HDPE) liner that surrounded the entire explosive billet. The IM venting melt liners were made from HDPE by precision machining of rod material. Figure 9 presents a photograph of the HDPE melt liner and associated explosive billet. Testing using the HDPE liner resulted in more consistent test results: smaller vent diameters resulted in violent response and larger vent diameters resulted in non-violent responses. Testing with other solid pressed explosives has also required the use of a melt liner to achieve consistent results. Table 1 presents a summary of Comp B, PAX-28, and PBXN-109 test results. The results indicate that PAX-28 and PBXN-109 require less venting area than Comp B to achieve a non-violent response.

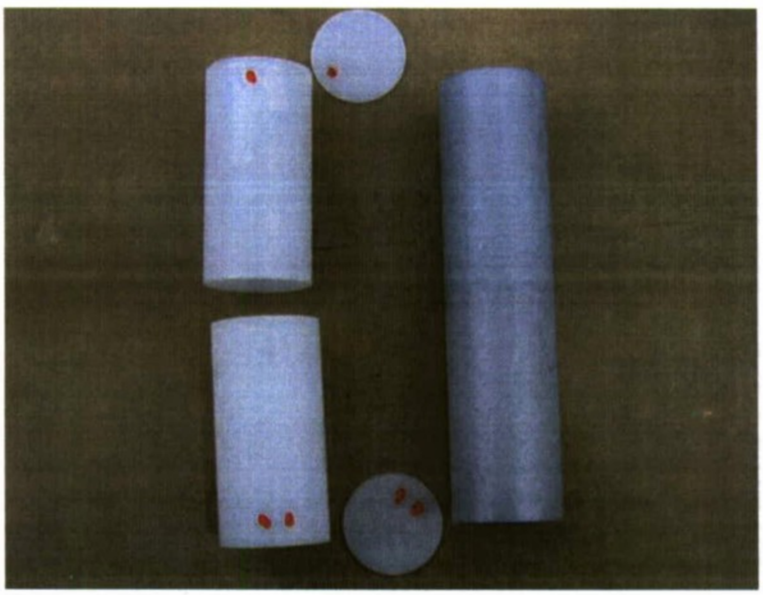


Figure 9
HDPE IM melt liner (left) and explosive billet (right)

Table 1
Small scale venting experiments summary

Explosive	Go/no go	Vent size	Notes	T(°C)
Comp B	Go	2.5	Throttle plate blow out	187.8
Comp B	Go	5.1	Explode	204.4
Comp B	Go	5.1	Fixture on side, violent, bolts sheared, center burst	192.8
Comp B	Go	10.2	Explode, top end plate came off	191.1
Comp B	No go	10.2	Burn off	198.9
Comp B	No go	11.5	Burn off, fixture in one solid piece	183.3
Comp B	No go	12.7	Burn off	212.8
Comp B	No go	12.7	Burn off	190.6
Comp B	No go	12.7	Burn off	204.4
Comp B	No go	20.3	Fixture on side, burn off, fixture in one solid piece	192.2
PAX-28	Go	5.1	Explode, HE boiled out, top endplate blew off	190.6
PAX-28	Go	5.1	Explode, HE boiled out, top endplate blew off	188.3
PAX-28	Go	6.4	Explode, HE boiled out, body banana peeled	177.8
PAX-28	No go	7.6	Burn, HE boiled out of fixture, smoking, then burn	191.1
PAX-28	No go	10.2	Burn, HE boiled out of fixture, smoking, then burn	185.0
PAX-28	No go	12.7	Burn, HE boiled out of fixture, smoking, then burn	173.9
PBXN-109	Go	12.7	No HDPE liner, exploded	198.9
PBXN-109	Go	5.1	HDPE liner, explode, vent bent outwards	180.6
PBXN-109	No go	5.8	HDPE liner, HE extruded, nonviolent reaction	187.8
PBXN-109	Go	6.8	HDPE liner, body cavity blown apart	183.9
PBXN-109	No go	7.6	HDPE liner, burn, HE extruded through vent	191.7
PBXN-109	No go	10.2	HDPE liner, burn, HE extruded through vent	177.8
PBXN-109	No go	12.7	HDPE liner, burn, some HE left in fixture	186.1

SMALL SCALE HEATING RATE STUDY

The effect of heating rate on required venting area was investigated using the small scale hardware. The three explosives that were chosen for this heating rate study were Comp B, PBXN-109, and PAX-3 from the melt pour, cast cure, and pressed families, respectively. The results of these heating rates are tabulated in table 2. For Comp B, at each heating rate, the reactions proceeded from melting with liquid formation at the top near the vent hole, through bubbling to vigorous boiling and smoking and then on to burning. These reactions were similar to those seen by other melt cast explosives such as PAX-28 (ref. 8). Initial melting occurred resulting in a honey colored liquid rising to the surface. As the volume and temperature of this liquid increased, it would darken and then begin to boil, at first only slightly, but then more vigorously, often boiling over the sides of the fixture. Figure 10 shows this progression.

Table 2
Heating rate study venting experiments summary

Explosive	Rate	Go/no go	Vent size (mm)	Notes	T(°C)
Comp B	3.3	Go	10.2	Violent reaction	179.4
Comp B	3.3	No Go	11.4	Ignited in vent disk, fast burn	183.3
Comp B	3.3	No Go	12.7	External ignition propagated inside, mild burn	191.1
Comp B	3.3	No Go	15.2	Ignited in vent disk, expelled material, fast burn	Unkn
Comp B	27.8	Go	2.5	Vent disk blown out	187.8
Comp B	27.8	Go	5.1	Explode	204.4
Comp B	27.8	No Go	10.2	Burn	198.9
Comp B	27.8	Go	10.2	Explode, top end plate came off	191.1
Comp B	27.8	No Go	10.2	Burn Off	191.1
Comp B	27.8	No Go	11.5	Burn off, Fixture in one solid piece	183.3
Comp B	27.8	No Go	12.7	Burn Off	212.8
Comp B	27.8	No Go	12.7	Burn Off	204.4
Comp B	278.0	Go	2.5	Violent, bolts sheared, center burst	225.6
Comp B	278.0	Go	3.8	Violent, bolts sheared, center burst	236.7
Comp B	278.0	No Go	5.1	Burn Off	241.7
Comp B	278.0	No Go	7.6	Burn Off	218.3
Comp B	278.0	No Go	10.2	Burn Off	245.0
PBXN-109	3.3	Go	7.6	w/HDPE Liner, Exploded center section	168.9
PBXN-109	3.3	No Go	10.2	w/HDPE Liner, Burn Off	160.0
PBXN-109	3.3	No Go	12.7	w/HDPE Liner,	165.6
PBXN-109	27.8	Go	5.1	w/HDPE Liner, Exploded	180.6
PBXN-109	27.8	No Go	5.1	No HDPE Liner, Burn Off	190.6
PBXN-109	27.8	No Go	5.8	w/HDPE Liner, extrusion and burn off	187.8
PBXN-109	27.8	Go	6.8	w/HDPE Liner, exploded but not all HE reacted	183.9
PBXN-109	27.8	No Go	7.6	w/HDPE Liner, Burn Off	191.7
PBXN-109	27.8	No Go	10.2	w/HDPE Liner, Burn Off	177.8
PBXN-109	27.8	No Go	12.7	w/HDPE Liner, Burn Off	186.1
PBXN-109	27.8	Go	12.7	No HDPE Liner, Exploded	187.8
PBXN-109	27.8	No Go	12.7	No HDPE Liner, Burn Off	198.9
PBXN-109	27.8	No Go	17.8	No HDPE Liner, Burn Off	190.0
PAX-3	3.3	No Go	17.8	2.5-mm HDPE Liner, Burn off	215.6
PAX-3	27.8	Go	10.2	No HDPE Liner, Explode	200.0
PAX-3	27.8	Go	12.7	No HDPE Liner, Explode	203.3
PAX-3	27.8	Go	12.7	w/1.3-mm HDPE Liner, Explode	190.0
PAX-3	27.8	Go	12.7	w/2.5-mm HDPE Liner, Explode	212.8
PAX-3	27.8	Go	15.2	No HDPE Liner, Explode	202.2
PAX-3	27.8	Go	15.2	w/2.5-mm HDPE Liner, Explode	201.7
PAX-3	27.8	No Go	17.8	w/2.5-mm HDPE Liner, Burn Off	207.2
PAX-3	27.8	Go	20.3	No HDPE Liner, Explode	199.4
PAX-3	27.8	Go	20.3	w/1.3-mm HDPE Liner	213.3
PAX-3	27.8	No Go	20.3	w/2.5-mm HDPE Liner	221.1
PAX-3	278.0	Go	12.7	2.5-mm HDPE Liner, varied heating profile	Unkn
PAX-3	278.0	No Go	14.6	2.5-mm HDPE Liner, varied heating profile	179.4
PAX-3	278.0	Go	16.0	2.5-mm HDPE Liner, Explode	250.6
PAX-3	278.0	No Go	17.8	2.5-mm HDPE Liner, Burn Off	253.3

Figure 10
5.1-mm vent diameter Compos B heated at 278°C/hr

Ordinarily when Comp B was tested, the HE would ignite and then burn for a relatively brief period of time, generally only 10 to 20 sec, before either transitioned to a violent reaction or simply burning out completely. Violent reactions typically blew out the middle section and often sheared several of the 16 bolts used to secure the top and bottom to the center portion. Examples of each type of reaction are seen in figure 11. It is worth noting that at higher heating rates, the samples reacted at higher temperatures. This is in agreement with historical data gathered previously and is reasonable given the increased thermal gradient from the outside skin to the inside of the HE that results when items are not allowed to undergo a slower quasi-static thermal increase. Although the number of samples at each heating rate was not the same and outlying temperatures could have thrown off the averages, the average temperatures for reaction for samples heated at 3.3, 27.8, and 278°C/hr were 184.4, 196.7, and 233.3°C, respectively.

Figure 11
Two post test views of the 5.1 mm (left) and 20.3 mm (right) diameter vent fixtures

The most important result of the variable heating rates is the change required in the vent area. For the intermediate heating rate of 27.8°C/hr, the vent diameter that allowed the fixture to vent in a nonviolent fashion was between 10.2 and 11.5 mm in diameter. Exclusively, violent reactions resulted from testing fixtures with vent diameters below this critical diameter. When samples were heated at 278°C/hr, however, the vent size that caused violent reactions to cease dropped to somewhere between 3.8 and 5.1 mm. Interestingly, the trend did not continue as expected at the slower heating rate of 3.3°C. At this lower rate, the vent area did not increase, but rather stayed the same.

Although it is only speculation, one possible reason that was proposed to explain this behavior is that at both the 3.3 and 27.8°C/hr heating rates, all of the Comp B was a liquid at the time of reaction. Perhaps burning liquids behave in a more erratic fashion than burning solids due to variations in surface area, among other differences. When heated at a much higher 278°C/hr heating rate, however, some of the explosive pellet might not have melted by the time the molten Comp B ignited, thus, a smaller amount of liquid ignited and burned before the reaction proceeded to the remaining solid. This solid could have burned mildly, especially in light of the newly liberated volume that resulted from the surrounding liquid HE, which had burned off. If this is in fact what occurred, a result that should be verified empirically, then a potential solution to the problem of mitigating cook-off violence for Comp B loaded munitions might be to cause a reaction to occur at a lower temperature in a munition while the energetic is still a solid.

PBXN-109 - composed of 64% RDX, 20% aluminum, and 16% hydroxy-terminated polybutadiene [HTPB (nominal)] - is another explosive fill of interest due to its rather insensitive nature and in depth characterization. It is the only cast-cure composition tested under this effort. Initial testing was conducted using test samples that were machined to fit directly into the test fixture. Testing this configuration with a large vent hole (12.7-mm diameter) resulted in a violent reaction, while testing at a smaller diameter resulted in a non-violent reaction on at least one occasion. Due to this unanticipated erratic behavior, as well as prior experience with the benefits of using liners for decreasing sensitivity, HDPE liners were used to improve the cook-off response. Subsequent testing was performed using a 0.76-mm thick HDPE liner machined to encapsulate the entire explosive billet. Figure 9 is a photograph of an HDPE melt liner and explosive billet. Testing using the HDPE liner resulted in more consistent test results: smaller vent diameters resulted in violent response and larger vent diameters resulted in non-violent responses. When liners were used, there was an apparent trend of vent diameter decreasing as vent area increased similar to that witnessed for Comp B. At the time of this writing, however, the higher heating rate of 278°C/hr had not yet been completed, so it is presently unclear whether or not the trend continues at this higher rate. At the 3.3 and 27.8°C/hr rates, however, the vent area did show signs of decreasing from between 7.6 and 10.2-mm to somewhere between 5.1 and 6.8 mm. This is in contrast to Comp B, which showed no evidence of reducing the required vent area in this heating rate range. This is not unanticipated as PBXN-109 remains solid through the reaction. Unlike melt pour explosives, cast cure and pressed explosives do not change phase with heating. As a result, an accurate description of their overall behavior must take into account their thermo-mechanical response. PBXN-109 and PAX-3, a pressed aluminized HMX based explosive, were both highly affected by temperature and grew irreversibly during tests at each heating rate. The results for both of these explosives are included in the table 2. These reactions proceeded from extrusion, during which un-reacted explosive and HDPE liner for the tests in which it was used, exuded from the vent hole until ignition occurred. Other than extruding explosive and some smoking, the violent cases resulted in little to no warning, but rather exploded violently without the typical burning reactions that Comp B demonstrated. This process typically proceeded quite slowly, although sometimes energetic material was extruded quite vigorously, usually preceding ignition. Ignition would occur in the interior of the STEX fixture. This most often resulted in a mild burn as seen in figure 12.

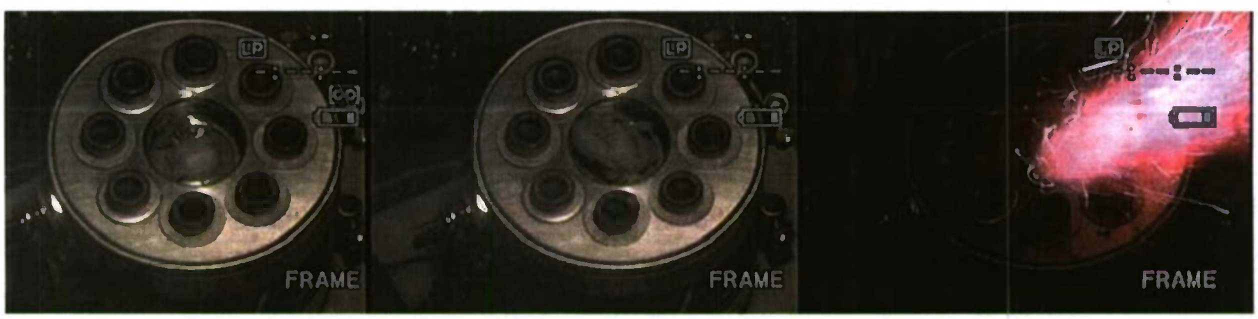


Figure 12
PBXN-109 w/HDPE liner extruding then burning

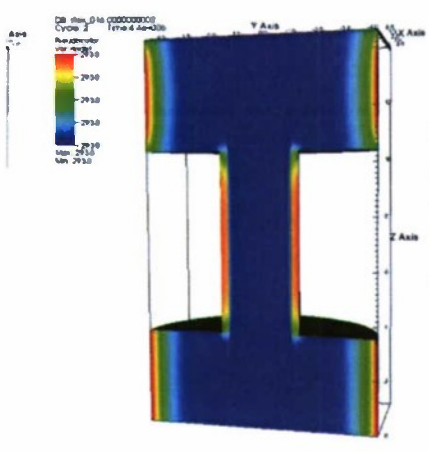
The behavior of PAX-3 was different than the two other HEs tested here. The vent area that PAX-3 required remained relatively constant throughout the range of heating rates. At 3.3°C/hr, for example, a vent area less than 17.8 mm in diameter was required to preclude a violent reaction. This was similar for both the 27.8 and 278°C/hr cases. Although there are numerous differences between PBXN-109 and PAX-3 in composition, processing, and physical parameters, the exact cause of these differences in behavior has not been pinpointed.

COMPOSITION B GEOMETRIC SCALING

A basic study was conducted in order to investigate the effect of geometric scaling on the venting area required for a melt pour explosive at a heating rate of 27.8°C/hr. Comp B was selected as the explosive for investigation, due to the availability of small scale experimental results. A scaled-up version of the small scale test was designed using a 78-mm diameter billet. Figure 13 presents diagrams of the small and large scale test set-ups.

Figure 13
Large scale cook-off venting laboratory hardware configuration

Modeling of the small and large configurations was conducted using ALE-3D. A preliminary heat flow analysis was completed using an inert Teflon insert in order to check how closely the model predicted the thermal profile in an inert slug before moving onto the more complicated scenario of predicting the thermal situation of a live explosive billet. Thermocouples were placed in the Teflon to provide quantitative validation data and the fixture was heated at a rate of 27.8°C/hr. The three-dimensional model was created with tracer particles capturing temperature data in the locations that the thermocouples were positioned on the actual hardware. As can be seen in figure 14, the modeled temperature histories match the experiments nearly identically at all the thermocouple positions. Figure 15 presents modeling results using a Comp B model. These are some of the first modeling attempts using this model, which includes explosive melting and subsequent convection behavior. Little model verification has been done to date for these evolving models (refs. 9 through 11).



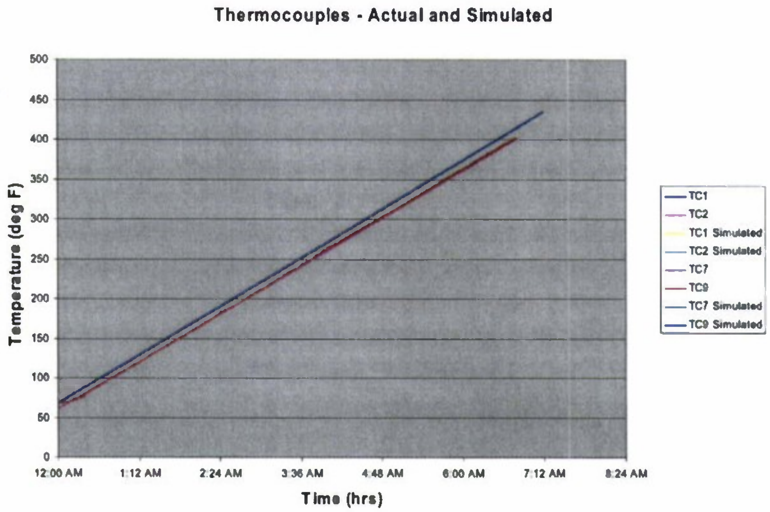


Figure 14
Inert generic hardware baseline modeling

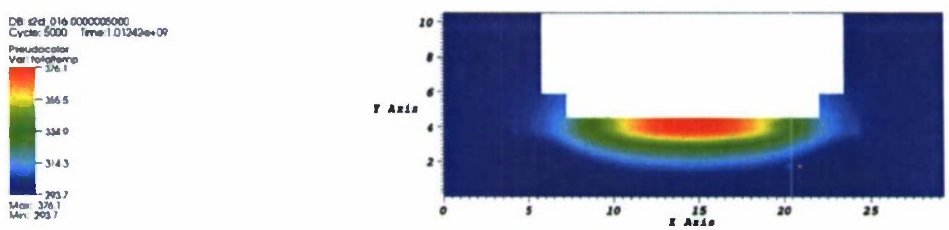


Figure 15
Comp B generic hardware modeling

Experimentation was undertaken to determine the venting requirements for Comp B loaded small scale and large scale test fixtures. The HE billets were cast and then machined to fit within the inner diameter of the test fixture. After machining, the condition of each billet was verified through x-ray inspection. This technique is used to expose subsurface flaws such as cracks, voids, and porosity. A vent disc with a hole drilled through its center was then inserted into one end of the fixture. For the small scale fixture, vent discs with vent holes ranging from 5.1 to 20.3 mm in diameter, were made so that the vent area could be changed from one test to the next. Similar scaled vent hole sizes were made for the large scale fixture. After, metal o-ring gaskets were inserted between the end flanges, 16 bolts were inserted and then torqued down in a star pattern to ensure a complete seal.

The finished assembly was normally placed vent side up on a ceramic tile inside of the heavy steel cylinder located in the test chamber. Ceramic tiles are used as insulation between the fixture and steel floor to make it easier to control the fixture temperature. A mirror and light are then aligned to allow a standard video camera (30 fps) to remotely record the vented side of the fixture through a viewing port located on the side of the test chamber. Figure 2 is a picture of the test set-up.

For melt cast formulations, the largest vent diameter reactions proceeded from melting with liquid formation at the top of the vent hole through bubbling to vigorous boiling and smoking and then on to burning. All hardware for large non-violent vent diameters has shown evidence of burning. For the non-violent tests, videos and surrounding evidence did indicate that burning had occurred, but the reactions were relatively benign resulting in no damage to both the test fixtures and the ceramic insulating tiles. Figure 16 shows Comp B small scale fixture testing during the vigorous bubbling and smoking phase. Small scale Comp B testing results indicate that a vent hole of 11.4-mm diameter is required in order to preclude a violent reaction. Large scale Comp B testing results with a scaled up vent hole (29.2 mm), as a function of total surface area, resulted in a benign response as can be seen in figure 17. Comp B large scale fixture testing using smaller vent hole sizes of 22.7 mm and 26.0 mm (equivalent to subscale 8.9 and 10.2 mm vent holes) resulted in full detonation and transition to detonation, respectively. Comp B small scale and large scale testing results are documented in table 3.

Figure 16
Small scale Comp B burn - 0.45-in. diameter vent

Figure 17
Large scale fixture - single vent hole

Table 3
Comp B scaled venting experiments - 27.8°C/hr

Scale	Go/no go	Vent size (mm)	Notes	T(°C)
Small scale	Go	2.5	Throttle plate blown out	187.8
Small scale	Go	5.1	Explode	204.4
Small scale	Go	5.1	Fixture on side, violent, bolts sheared, center burst	192.8
Small scale	Go	10.2	Explode, top end plate came off	191.1
Small scale	No go	10.2	Burn off	198.9
Small scale	No go	11.5	Burn off, fixture in one solid piece	193.3
Small scale	No go	12.7	Burn off	212.8
Small scale	No go	12.7	Burn off	190.6
Small scale	No go	12.7	Burn off	204.4
Small scale	No go	20.3	Fixture on side, burn off, fixture in one piece	192.2
Large scale	No go	29.2	Scaled up vent hole as a function of total surface area	
Large scale	No go	29.2	Deflagration, fixture intact	176.7
Large scale	Go	22.7	8.9-mm eq, full detonation	218.3
Large scale	Go	26.0	10.2-mm eq, transition to detonation	221.1
Large scale	Go	2.9/5	11.4-mm eq, surface area divided into five same size holes (0.512 in.)	221.1
Large scale	No go	2.9*2/10	2.9-mm diameter vent x 2, vent area divided by 10 same size holes (0.506 in.) burn. Initiated on heater band.	
Large scale	No go	2.9*2/10	2.9-mm diameter vent x 2, vent area divided by 10 same size holes (0.506 in.) burn	226.7

Further testing was conducted to determine the cook-off response and venting requirement for a single vent hole versus splitting the total vent surface area into five holes of equal size (13.0 mm). Testing of the five-hole configuration with the same total vent surface area resulted in a violent response (fig. 18).

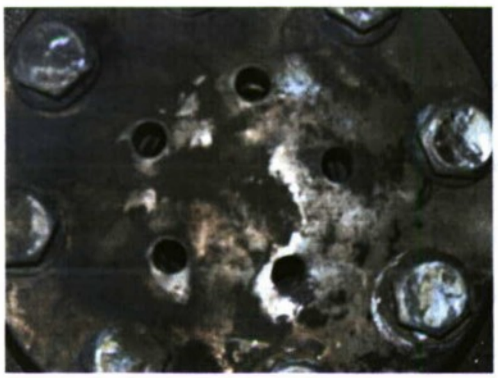


Figure 18
Large scale fixture - vent area split into multiple holes

Doubling the total vent surface area by adding five additional vent holes, for a total of 10 vent holes (12.9 mm) resulted in a benign response (fig. 19). This demonstrates that for Comp B, splitting the required venting into multiple vent holes would require increased total vent area.

Figure 19
Large scale fixture - vent area split into multiple holes

Testing results clearly indicate that a single-hole scaled configuration resulted in the same required scaled vent area. However, a five-hole configuration using the same scaled vent area resulted in a violent response.

CAST CURE LARGE SCALE LINER MATERIAL INVESTIGATION

A simple analytic burn model was developed under the IM warheads Army Technology Objective. This model assumes the entire explosive billet burns from its exterior surface, inwardly. The burn rate is a typical propellant pressure dependant rate form, with the addition of temperature dependence. The gas products are allowed to be released through the vent using a standard rocket nozzle mathematical representation. The calculations have shown a strong dependence to initial free volume (ullage) and initial pressure. Essentially, the calculations have shown that the result (violent or non-violent) is governed by the early burning conditions. Figure 20 shows that either rapid pressurization (violent) or depressurization (non-violent) occurs from the onset of burning. The analytic model has predicted that very small vent areas can be successful, but requires that the IM liner material melts away, providing both free volume and a clear vent path. For this reason, lower viscosity IM liner materials were investigated and found to provide successful mitigation using smaller vent areas.

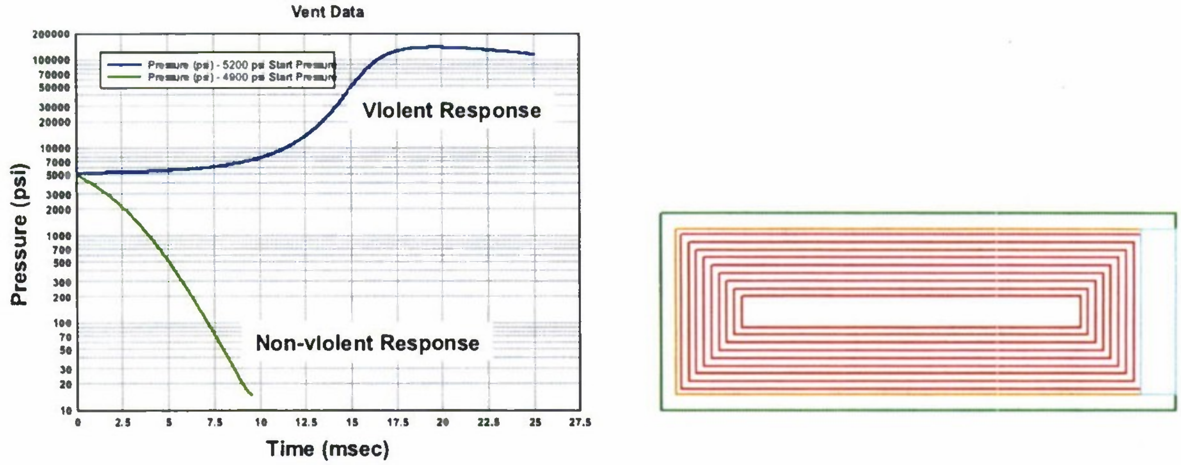


Figure 20
Analytic burn modeling of PBXN-109 large scale test fixture
[pressure response (left) and billet burn profiles at different times (right)]

Prior testing of PBXN-109 and other solid explosives has required the use of a melt liner to achieve consistent results. Liners typically encase the explosive billet within the warhead case and are incorporated in order to provide a path for explosive burning products to escape once the billet begins burning. A vent path is desirable to avoid a rapid increase in pressurize-tion, and the subsequent increase in burning rate that often results in a runaway violent reaction. It was noted from our experiments that HDPE liner material often does not leave the experi-mental test fixture until an explosive burning event is noted. As a result, an initial high pressure could be produced by the expansion of the explosive billet and compression of the unreleased HDPE. Additionally, very little or no free volume would exist if the HDPE remains in the test fixture up until the time of explosive ignition. One conjecture is that due to the high viscosity (melt index) of the HDPE used, the HDPE did not have sufficient time to flow out of the test fixture. HDPE is available in a variety of different melt indexes; however, the HDPE used for the experiments was not one of the lowest melt index HDPEs available. In order to address this hypothesis, a very low viscosity material was chosen for experimentation. Asphaltic hot melt (AHM) is a basic tar that has been used for HE applications and it has a very low viscosity upon melting (similar to water).

As seen in figure 21, AHM was clearly flowing from the experimental fixture before explosive ignition. The AHM lined test figure produced a non-violent result with the very small venting area (12.7-mm diameter); whereas, the HDPE produced a violent result with the same vent area. Selection of appropriate low melt index liner material, such as HDPE or AHM, which would flow out of the vent holes, would provide a vent path for the explosive burning product to escape. Hence, for munitions loaded with solid explosives, selection of an appropriate liner material with a low melt index and appropriate vent area would allow for a low order reaction.

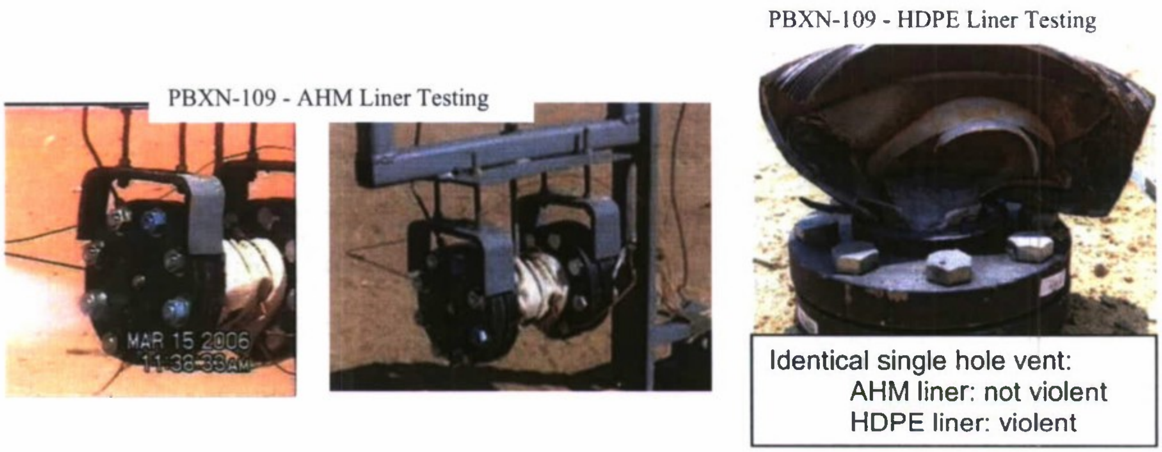


Figure 21
AHM versus HDPE liner materials - PBXN-109

FULL-SCALE SLOW HEATING RATE EFFECT

The Joint IM Test Standards and Passing Criteria, including slow heating, were issued via Office of the Under Secretary of Defense (OUSD) Acquisition, Technology & Logistics/ Portfolio Systems Acquisition/Land Warfare & Munitions on 14 May 2007. These standards resulted from a collaborative effort between the Joint Weapons Safety Technical Panel and the Joint Service Insensitive Munitions Technical Panel. The slow heating test under the 2006 Joint IM Standards specifies a heating rate of 3.3°C/hr (6°F/hr) and passing criteria of type V (burn) response. Prior to the Department of Defense's implementation of these Joint Standards the U.S. Army managed programs normally conducted slow heating at 27.8°C/hr (50°F/hr) (ref. 12).

As part of an effort to reduce SCO violence, full scale testing was conducted using PBX-N9 filled 155-mm warhead prototypes with various thickness liners using both 27.8°C/hr and 3.3°C/hr. A mass mock fuze was included in the testing to simulate thermal mass. Previous testing showed that liners with smaller thickness than the 4.7 mm all resulted in a Type III response. Two tests were conducted with HDPE liners using a thickness of 4.7 mm, which resulted in one type V and one type III response at 27.8°C/hr (fig. 22). Based on these results, subsequent testing was conducted using 5.7-mm single thick liners. The two tests conducted at 27.8°C/hr resulted in violent explosive responses. The 5.7-mm liner was also tested at the 3.3°C/hr slow heating rate, which resulted in a type I mass detonation of the test item (fig. 23). Solid Works Simulator (COSMOS Works) was used to model the warhead to predict pre-ignition, when the warhead is subjected to SCO test at heating rates of 27.8°C/hr versus 3.3°C/hr. The thermal modeling results clearly suggest that the lower heating rate, 3.3°C/hr, causes ignition to occur in the center of explosive billet; whereas, at a heating rate of 27.8°C/hr, the ignition occurs on the surface of the explosive billet. This modeling effort is presented in figure 24 showing the results of the Excalibur warhead when it is subjected to 27.8 and 3.3°C/hr heat rate.

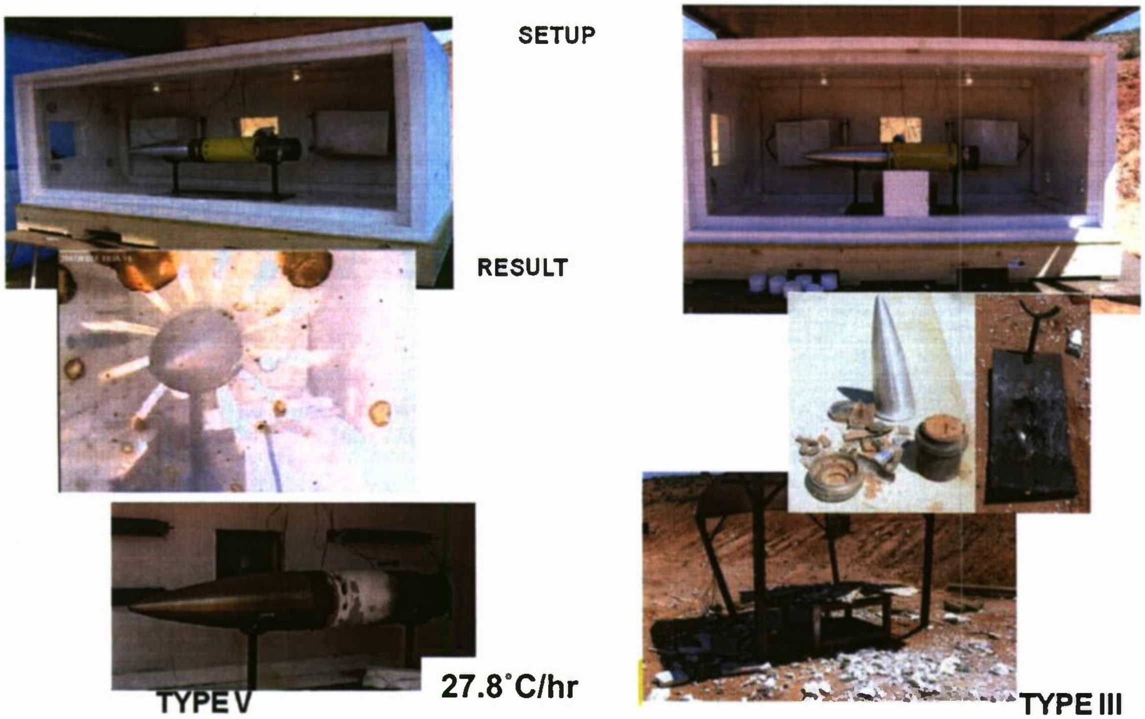


Figure 22
Full scale reactive double thickness liner (4.7 mm) - post test

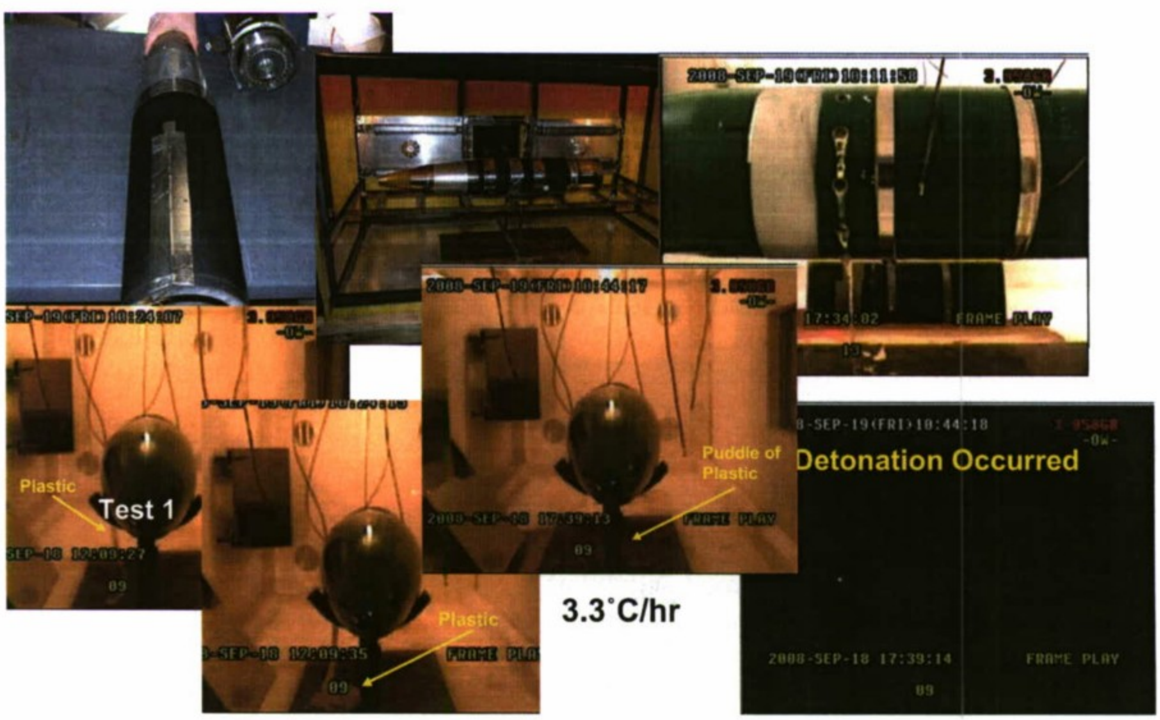


Figure 23
Full scale reactive double thickness liner (5.7 mm) - post test

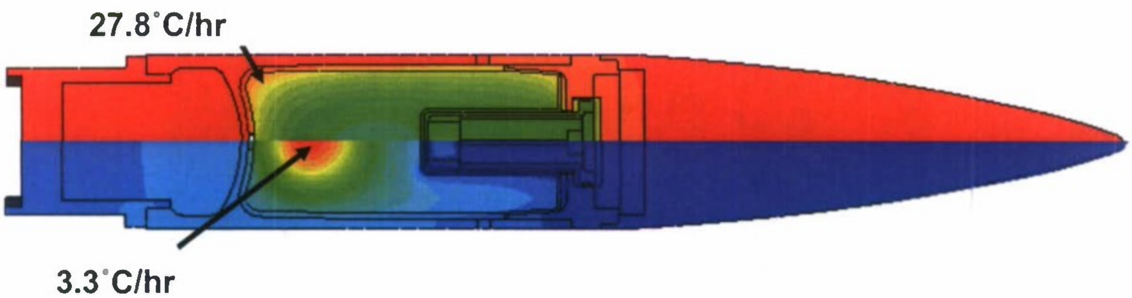


Figure 24
Munition baseline modeling - 27.8°C/hr versus 3.3°C/hr

IGNITION VENT PLUG MATERIALS AND TEST RESULTS

As the effect of the 3.3°C/hr heat rate was shown to require a significantly different or increased warhead venting for larger warheads, an ignition vent plug approach is now a focus of technology development. This approach aims to assure that deflagration ignition during cook-off occurs near or at an engineered venting system; this is to assure release of reaction products in order to prevent significant pressurization and associated violent reaction. Figure 25 presents a depiction of an ignition vent plug that incorporates a reactive material. The reactive material ignition pellet must be chosen and designed so as to ignite the main charge explosive before it will self ignite, but also maintain a high enough temperature to provide a reasonable temperature margin above service requirements.

A variety of reactive materials were investigated for appropriate ignition characteristics to assure appropriate auto-ignition when subjected to a slow heating environment at 3.3°C/hr heating rate. In particular, four tests were conducted with downselected ignition material pellets in stacks of three using a closed bomb inside a SCO oven. Two of these tests were bare pellet tests. One stack of three was tested in an ultem shell; another was tested in an aluminum shell. Figure 26 shows the pellet configuration, confinement, and test set-up. Testing was conducted at 3.3°C/hr. All pellet configurations ignited at about 143.3 to 148.9°C. Figure 27 is a comparison between thermocouple data (directly above pellets) on all four tests. Peak flame temperatures reach over 1093°C and should be sufficient to initiate surface burns on explosive billets.

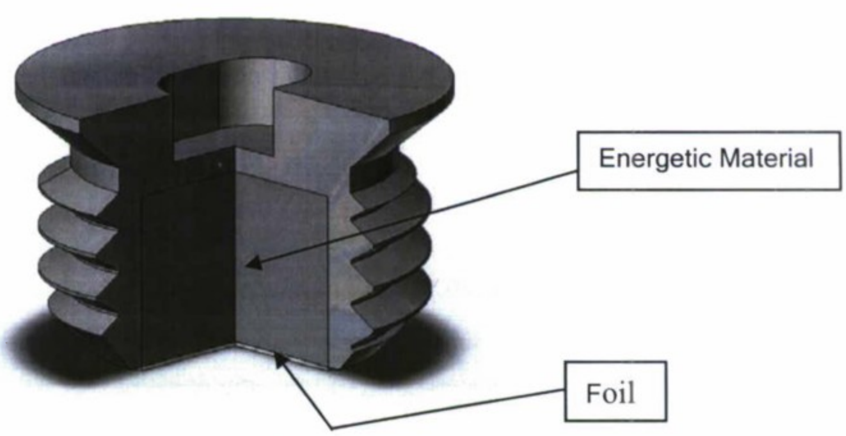


Figure 25
Reactive vent plug

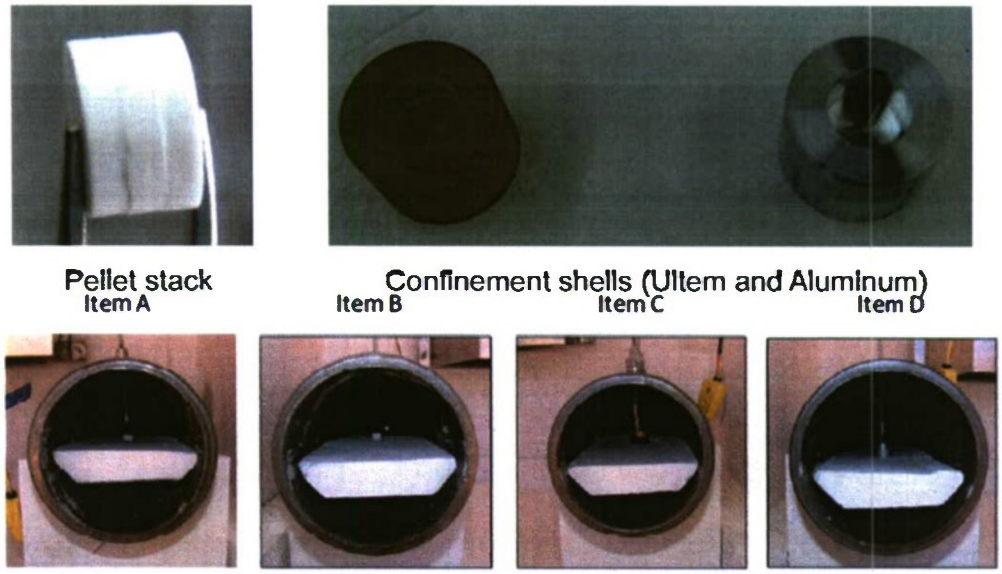


Figure 26
Ignition pellets test configuration and Set-Up

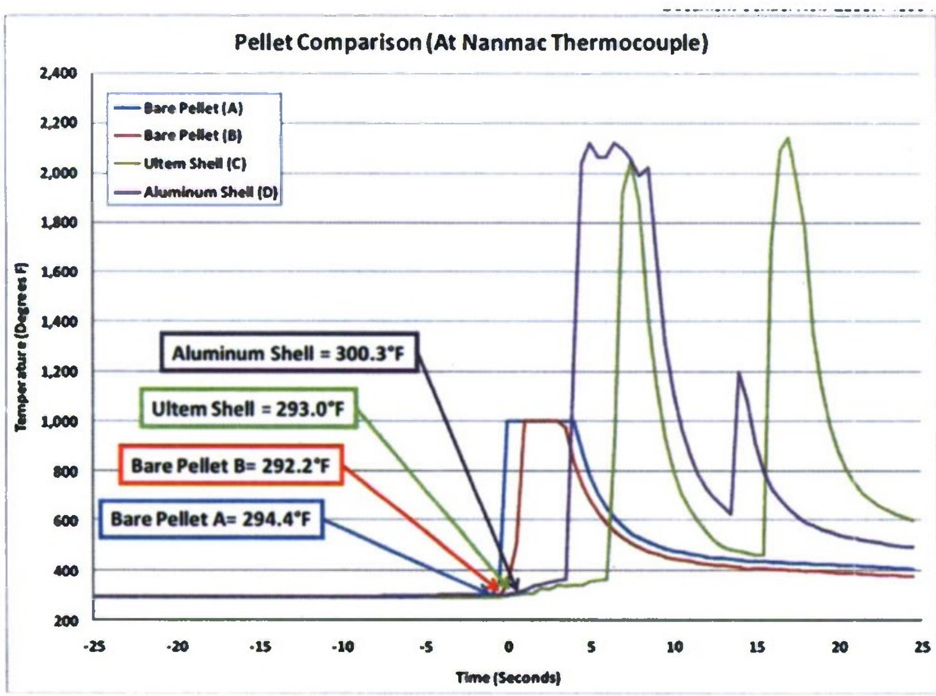


Figure 27
Ignition material thermocouple data

CONCLUSIONS

To date, a variety of melt pour, cast cure, and pressed explosives have been tested including Comp B, PAX-28, PBXN-109, and PBXN-9. These experiments were conducted with and without insensitive munitions (IM) venting liners. Thermal modeling was conducted using ALE-3D. Vent burn modeling was conducted using a simple analytic burn model that is currently under development. Vent area requirement using subscale and large scale fixtures is being used to develop venting solutions for full sized ordnance systems. For solid and melt pour explosives, direct scaling based on billet surface area for the required vent area determination have been successful. However, the required vent area increased, as did the number of vent holes. For solid explosives, our results demonstrate that the viscosity of the melted IM liner is a critical factor in reducing the vent area required. The results show that low viscosity materials allow significant reductions in the vent area required.

Efforts clearly show that cook-off mitigation using venting of solid explosives can be significantly more difficult at heating rates of 3.3°C/hr compared to 27.8°C/hr. The study suggests that ignition occurs near the billet surface for the higher 27.8°C/hr rate. For this reason, sub-detonative responses were achieved for the double thickness liner at 27.8°C/hr. Specifically, two tests of double thickness liner at 27.8°C/hr resulted in a violent explosive response, whereas, a mass detonation resulted when heated at the lower 3.3°C/hr rate. The hypothesis is that at the lower heating rate, ignition occurs near the center of the explosive billet and the subsequent burning produces temperatures and pressures internal to the billet that produce a deflagration to detonation transition as the reaction product gases cannot easily escape. This hypothesis is supported by thermal kinetics modeling that predicts the internal ignition for full scale munitions at 3.3°C/hr. For this reason, an ignition pellet approach is being pursued in order to assure ignition near or at vents. The use of reactive vent plugs (vent plugs filled with reactive material) is one such concept.

REFERENCES

1. Baker, E.L.; DeFisher S.; Madsen T.; Pfau D.; Al-Shehab N.; and Fuchs B., "Warhead Venting Technology Development for Cook-off Mitigation," NDIA Insensitive Munitions Symposium, Bristol, U.K. April 2006.

2. DeFisher S.; Baker E.; Madsen T.; Pfau D.; Pham J.; Al-Shehab N.; Wilson A.; and Fuchs B., "Development of Venting Technology for Cook-off Response Mitigation of Confined Explosives," 13th Detonation Symposium, Norfolk, VA, July 2006.

3. Johnson J., Kim S., and Nolder M., "Improved Insensitive Munitions Performance of an HE Rocket Warhead," NDIA Rockets and Missiles Symposium, San Antonio, TX, 15 May 2001.

4. United States Department of Defense, Acquisition Manager's Handbook for Insensitive Munitions, Revision 01, January 2004.

5. Maline R., "Navy Insensitive Munitions - A Record of Success," Proceedings of PARARI 99 (im03), 12 Nov 1999.

6. Swierk T., "Cookoff Mitigation Concepts for Ordnance System Applications," NSWC TR19930299-207, Naval Surface Warfare Center, Dahlgren, VA, 23 June 1993.

7. Wardel J.F. and Maienschein J.L., "The Scaled Thermal Explosion Experiment," Proceedings of 12th International Detonation Symposium, Office of Naval Research, San Diego, CA, 2002.

8. DeFisher S.; Madsen T.; Pham J.; Fuchs B.; Baker E.; and Potucek J., "Sub-scale Testing of PAX-28 for Vent Area Determination to Mitigate Slow Cook-off Response", U.S. Army Armament Research Development Engineering Center Technical Report, April 2006.

9. Nichols III, A.L.; Anderson, A.; Neely, R.; and Wallin, B., "A Model for High Explosive Cookoff," Proceedings of 12th International Detonation Symposium, Office of Naval Research, San Diego, CA, 2002.

10. McGuire, R.R. and Tarver, C.M., "Chemical Decomposition Models for the Thermal Explosion of Confined HMX, TATB, RDX, and TNT Explosives," Proceedings of 7th International Detonation Symposium, Naval Surface Weapons Center, Annapolis, MD, pp. 56-64, 1982.

11. Yoh J., et al., "Simulating Thermal Explosion of Cyclotrimethylenetrinitramine-based Explosives: Model Comparison with Experiment," Journal of Applied Physics 97, 083504, 2005.

12. Frey R., "Appropriate Slow Cookoff Heating Rates," U.S. Army Research Laboratory Memorandum, 18 January 2000.

DISTRIBUTION LIST

U.S. Army ARDEC
ATTN: RDAR-EIK
RDAR-GC
RDAR-MEE-W (7)
Picatinny Arsenal, NJ 07806-5000

Defense Technical Information Center (DTIC)
ATTN: Accessions Division
8725 John J. Kingman Road, Ste 0944
Fort Belvoir, VA 22060-6218

Commander
Soldier and Biological/Chemical Command
ATTN: AMSSB-CII, Library
Aberdeen Proving Ground, MD 21010-5423

Director
U.S. Army Research Laboratory
ATTN: AMSRL-CI-LP, Technical Library
Bldg. 4600
Aberdeen Proving Ground, MD 21005-5066

Chief
Benet Weapons Laboratory, WSEC
U.S. Army Research, Development and Engineering Command
Armament Research, Development and Engineering Center
ATTN: RDAR-WSB
Watervliet, NY 12189-5000

Director
U.S. Army TRADOC Analysis Center-WSMR
ATTN: ATRC-WSS-R
White Sands Missile Range, NM 88002

Chemical Propulsion Information Agency
ATTN: Accessions
10630 Little Patuxent Parkway, Suite 202
Columbia, MD 21044-3204

GIDEP Operations Center
P.O. Box 8000
Corona, CA 91718-8000