LA-UR-12-22394

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Intended for: L2 milestone for science campaign
Report

SUMMARY OF BOOSTER DEVELOPMENT AND QUALIFICATION REPORT

UNITED STATES/UNITED KINGDOM ENHANCED COLLABORATION
FOR INSENSITIVE EXPLOSIVES
DOE/NNSA CAMPAIGN 2: DYNAMIC MATERIALS PROPERTIES

June 30, 2012

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Abstract

This report outlines booster development work done at Los Alamos National Laboratory from 2007 to present. The booster is a critical link in the initiation train of explosive assemblies, from complex devices like nuclear weapons to conventional munitions. The booster bridges the gap from a small, relatively sensitive detonator to an insensitive, but massive, main charge. The movement throughout the explosives development community is to use more and more insensitive explosive components. With that, more energy is needed out of the booster. It has to initiate reliably, promptly, powerfully and safely.

This report is divided into four sections. The first provides a summary of a collaborative effort between LANL, LLNL, and AWE to identify candidate materials and uniformly develop a testing plan for new boosters. Important parameters and the tests required to measure them were defined. The nature of the collaboration and the specific goals of the participating partners has changed over time, but the booster development plan stands on its own merit as a complete description of the test protocol necessary to compare and qualify booster materials, and is discussed in its entirety in this report.

The second section describes a project, which began in 2009 with the Department of Defense to develop replacement booster formulations for PBXN-7. Replacement of PBXN-7 was necessary because it contained Triaminotrinitrobenzene (TATB), which was becoming unavailable to the DoD and because it contained Cyclotrimethylenetrinitramine (RDX), which was sensitive and toxic. A LANL-developed explosive, Diaminoazoxyfurazan (DAAF), was an important candidate. This project required any replacement formulation be a drop-in replacement in existing munitions. This project was timely, in that it made use of the collaborative booster development project, and had the additional constraint of matching shock sensitivity. Additionally it needed to be a safety improvement, and a performance improvement, especially at cold temperatures. The requirements of this project necessitated novel test development and a different approach to ranking booster qualities. Results of this project have been documented to the DoD and the relevant portions are included within.

The third section of this booster report outlines testing related to main charge initiation merit. Initiability can be evaluated by looking at critical diameter, run distance, and shock sensitivity. Once a booster is initiated, it needs to be powerful enough to initiate the main charge symmetrically and evenly. Main charge initiablility is evaluated directly by observing detonation wave symmetry, curvature, and first break out over the surface of a charge. Furthermore it must be insensitive to accidents and insults, and safe and reliable across a range of temperatures. These effects, tests, and results will be discussed individually in the context of DAAF and other explosives similarly tested.

The last section provides a conclusion and summary of our experimental work and recommendations for the path forward. References and additional supporting documentation and results are provided in the appendices at the end of this report.

1 List of Formulations and Explosives

PBX 9407	94% RDX, 6% Oxy-461
PBX 9501	95% HMX, 2.5% BDNPA/F, 2.5% Estane
PBX 9502	95% TATB, 5% KelF-800
PBX 9504	70% TATB, 25% PETN, 5% KelF-800
LX-07	90% HMX, 10% Viton-A
LX-17	92.5% TATB, 7.5% KelF-800
EDC-29	95% HMX, 5% HTPB
KD-5	98.5% UF-TATB, 1.5% Viton-A
RX-55-AY	94% LLM-105, 6% Viton
PBXN-7	60% TATB, 35% RDX, 5% Viton-A
PBXW-14	50% HMX, 45% TATB, 5% Viton-A
LAX-117-10	60% DAAF, 35% HMX, 5% Viton-A
LAX-118	95% FOX-7, 5% KelF-800
LAX-120.1	50% HMX (50:50 mix of class 1 and class 5), 45% DAAF, 5% Viton-A

DAAF	Diaminoazoxyfurazan
FOX-7	Diaminodinitroethylene
HMX	Cyclotetramethylenetetranitramine
HNS	Hexanitrastilbene
LAX-112	Diaminotetrazinedioxide
LLM-105	Diaminodinitropyrazine
PETN	Pentaerythritoltetranitrate
RDX	Cyclotrimethylenetrinitramine
TATB	Triaminotrinitrobenzene

2 Introduction

The Insensitive High Explosive (IHE) Enhanced Collaboration (EC) activity was initiated to enable the participating laboratories to share the responsibilities of establishing and maintaining the capabilities for the development of novel explosive materials. During the first evaluation phase, this collaboration endeavored to understand the requirements, processes and facilities that underpin the explosive development programs. To this end, the Sustainable Insensitive Booster (SIB) strand of the EC has thus far delivered a review of the current testing techniques across all of the participating laboratories and a requirement definition for the explosives under consideration.

This section summarizes the development of a standardized testing approach and matrix of experiments. The approach detailed in this report will develop a union of peers and facilities/capabilities that will result in an increased scientific rigor for the experimental and modeling activities. Furthermore, this common access to capabilities and technical expertise will ensure the most efficient and effective route for developing common explosive materials to support all laboratory programs. It should be noted that each of the individual laboratories lack the resources to develop multiple candidate materials to the level of maturity proposed as part of this matrix.

The standardized testing procedure has been developed bearing in mind the need to fully characterize the candidate booster materials against component requirements. However, it should also be noted that the matrix focuses on those tests that deliver crucial information for the development of booster materials and omit some areas of interest for specific applications or programs, which do not necessarily fit in with the agreed top-level booster requirements.

The goal of modern booster development is not solely focused on performance and safety; it includes sustainability as well. This concept encompasses raw material availability, and environmentally conscious manufacturing practices. All ingredients required for synthesis and formulation are readily available from national sources. The goal is to avoid materials available only from foreign companies, materials that are sole-source and materials that are environmentally unfriendly.

2.1 Standardized Testing Procedure

A particular area of interest for the development of IHE systems is the integration of an explosive train that fulfills all of the performance criteria without compromising the safety of the main charge. As part of this, the development of an insensitive booster that fully meets the performance requirements is particularly demanding.

Historically, booster components have been fabricated from conventional high explosives, which have been shown to meet the performance requirements but struggle to fulfill certain safety demands. Switching from a conventional high explosive (CHE) to sustainable insensitive booster is likely to fulfill more of the safety criteria, such as sensitivity to impact, friction, shock, and temperature excursions. However, these improvements can come at the cost of performance; indeed, detonation speed, CJ pressure, initiability, and cylinder energy are typically lower in an IHE or reduced sensitivity material.

Booster development in today's environment requires a reduced sensitivity component where the safety enhancements outweigh any reduced performance. The goal of the technical programs, and indeed this Enhanced Collaboration activity, is to find a replacement booster candidate with improved performance and safety properties, which also fulfills the requirement for a long-term sustainable manufacturing path. These new booster formulations will fall into a new class of "sustainable insensitive boosters" (SIBs).

The expected range of performance and safety characteristics for a new SIB can be bounded by the established behavior/response of current IHE and CHE booster formulations. Ultra-fine TATB defines the high safety, low performance end, whilst HMX-based formulations can set the high performance, lower safety boundary; within this EC activity, the community has suggested that LX-07 (90% HMX, 10% Viton-A) and EDC29 (95% HMX, 5% HTPB) will be used as a lower safety bound that should not be passed for any future SIB. These formulations can be used to serve as bookends to bound the targeted performance and safety envelope for future SIBs under this Enhanced Collaboration. Indeed, a set of performance and safety metrics could be developed that measure candidate materials against known standards, using existing testing protocols. These will serve as the performance-and-safety-characterization screening tool for carrying materials to the next phase of this project.

2.2 Booster Development Test Matrix

The approach of the booster development Program is to subject booster candidates to a systematic testing regime. When the testing is complete, a thorough evaluation of new booster candidates against the component requirements will exist. The plan can include explosive materials in various stages of development with a range of known physical, mechanical and performance characteristics. The goal, ultimately, is to evaluate an identical set of characteristics for each material so that a direct comparison can be made.

Tests are broken into functional areas: Performance, Impact and Shock, Thermal, and Thermo-Mechanical. Furthermore, each functional area has three levels of test: Evaluation, Development, and Demonstration. Evaluation tests are ubiquitous and every explosive included in the booster development effort will need undergo these tests. Development is higher fidelity and frequently utilizes a test available at only one location. Demonstration tests are extremely high fidelity (translation: expensive) and are for likely candidates.

2.2.1 A. Performance testing

Evaluation	Development	Demonstration
Rate stick/plate dent	Cylinder	Onionskin, Half Peach, Snowball
Polyrho	ITraC (front curvature, P_{CJ})	PRad
Floret	Bare Booster	Size effect, failure diameter
Calorimetry		

Table 1: levels of performance testing.

2.2.1.1 Rate stick/plate dent

This is an easy test requiring relatively simple diagnostics and returns a measure of the detonation velocity and the CJ pressure. The density of the pellets affects the velocity, so some measure of the pressing characteristics of the material is collected when this shot is made. The detonation speed is measured through the rate stick with pins or switches between pellets of material pressed to the same density. The test usually requires L/D (ratio of length to diameter) of 5 or 6. Measuring the depth of a dent made by the detonation in a steel witness plate, or via a velocimetry diagnostic collects the CJ pressure.

All labs possess this capability
Test requires less than 30 g

2.2.1.2 Polyrho

The polyrho is similar to the rate stick in that switches placed in between each pellet measure the velocity along a stack of pellets. The difference is that the density varies from pellet to pellet, starting with low density (usually 82-85% TMD) and progressing to as high a density as possible (usually 98% TMD). This gives a measure of the effect of density on the detonation velocity and can be in conjunction with Cheetah to model the material.

All labs possess this capability
Test requires ~60 g of material

2.2.1.3 Floret

The floret test is a detonation-spreading test requiring only a small amount of material and is valuable in early explosive development. A measure of the corner-turning ability of an explosive can be realized from this test. The test pellet is pressed with a length much shorter than its diameter, and is initiated by the impact of a detonation-driven thin, small diameter flyer plate. The behavior of the detonation can be measured in the dent on a copper witness block. Density, particle size and binder effects can be measured in the dent analysis from this test. The critical diameter to support initiation can be evaluated by reducing the flyer plate diameter until the sample fails to initiate.

All labs possess this capability

Test requires 100 mg-1g per shot (depending on specific design)

2.2.1.4 Calorimetry

Heats of combustion, as determined in an oxygen bomb calorimeter, are measured by a substitution procedure in which the heat obtained from the sample is compared with the heat obtained from a standardizing material. In this test, a representative sample is burned in a high-pressure oxygen atmosphere within a metal pressure vessel or “bomb”. The energy released by the combustion is absorbed within the calorimeter and the resulting temperature change is recorded. From the measured heats of combustion, stoichiometric relations can be used to determine the heats of formation of the molecules of interest. These values serve as essential input to current performance estimators, such as the CHEETAH code developed at LLNL.

This capability exists at LLNL and LANL
Test requires 3 g per shot

2.2.1.5 Cylinder Test

The Cylinder Test consists of a precision-machined copper pipe filled with the sample explosive to be evaluated. The explosive is detonated at one end and the velocity of the expanding copper wall is measured over time. This wall velocity data is used to determine the energy of detonation at some volume of expansion. For the standard 1-inch diameter shot (12.7 mm explosive radius), the instantaneous copper wall velocities at the three expansion positions of 6, 12.5 and 19 mm are reported, and used to determine the output energy at the relative expansion volumes, v/v0, of 2.2, 4.4 and 7.2. The square of the copper wall velocity is related to the output energy of the explosive. These values are compared to values obtained for a standard set of explosives (HMX, PETN, RDX). This test also gives a high fidelity measurement of detonation velocity.

All labs possess this capability
Test requires 250 g of material

2.2.1.6 ITraC Test or Front Curvature

ITRaC

The Initiation Train Characterization Test has been developed to provide a reproducible, flexible and low cost capability to study the performance of explosive train materials and initial design configurations. The test utilizes a 1” diameter sample of various lengths to characterize the basic performance parameters – such as velocity of detonation, output pressure and reaction front curvature – along with initial screening of initiation train design configurations. The unconfined nature of the test allows multiple diagnostics to be applied to every experiment, including time of arrival probes, velocimetry probes, pressure gauge packs and high-speed cameras (streak and imaging).

AWE possesses this capability
Test requires less than 50 g per shot

Front Curvature

Front curvature evaluates the detonation front breakout profile. The front curvature is a relative measure of the burn kinetics of the explosive – higher curvature is indicative of lower burn rates and larger failure diameters.

All labs possess this capability, but differences exist in the test implementation.
Sample size depends on specific shot geometry

2.2.1.7 Bare Booster

There is a recognized need to quantitatively evaluate booster output over and above what is achieved with a measurement of the detonation front breakout profile and velocimetry. A variety of methods exist, with the goal being observation of the breakout as a function of time. This test can be used to evaluate the effects of temperature, density, binder content, etc. It is generally analogous to the Onionskin / Snowball / Half Peach, but lacks the main-charge covering at the booster output surface.

All labs possess this capability, but differences exist in the test implementation.
Requires 10-15 g per test

2.2.1.8 Onionskin/ Snowball/ Half Peach

This test evaluates the corner-turning ability and transit time and can be performed at various temperatures of interest. The test is made up of an outer hemisphere of IHE main charge formulation containing an inner booster material in either a hemispherical or cylindrical geometry. As the shot is detonated, the surface of the outer shell is filmed with a streak camera or measured with velocimetry, where the time, location and pressure of the detonation front across the output surface is recorded. This translates to a wave shape and breakout angle. An explosives ability to turn corners can be assessed as well as the transit time. Transit time is the time from detonation to breakout and is a measure of the speed at which the booster runs up to detonation and its ability to swiftly light the main charge.

Onionskin Test (LANL) utilizing PBX 9502
Snowball (LLNL) utilizing LX-17
Half-Peach (AWE) utilizing EDC35
Each test requires 12-50 g booster material and 150 g TATB-based material

2.2.1.9 PRad

Proton Radiography (or PRad) is a unique LANL capability. PRad radiographs are used to track the progression and symmetry of the detonation wave through the initiation train and have proven a good method for detecting three-dimensional phenomena in this geometry. The booster is placed into a PBX 9502 puck and the detonation progression, corner turning and symmetry are filmed at any temperature desired.

LANL capability
Test requires 12-50 g booster material and 800 g TATB-based PBX

2.2.1.10 Critical Diameter or Size Effect or Failure Diameter

Every explosive has a diameter where the attenuation from the edge effects overwhelms the detonation wave and the detonation fails. The critical/failure diameter correlates with the inherent safety of an explosive formulation. CL-20 has a critical diameter in microns and TATB has a critical diameter close to 10mm. A variety of critical diameter tests exist, from a cone test, to a series of rate sticks at progressively smaller diameters. Independently, the size-dependent detonation velocity is a measure of a material's burn kinetics, and can be used as a basic modeling parameter or performance metric. Preliminary evaluation of this phenomenon can be measured using the floret test.

All labs possess this capability, but differences exist in the test implementation.
Requires 100mg-50 g per test.

2.2.2 B. Impact and Shock

Evaluation	Development	Demonstration
Drop Hammer, Rotter F-of-I	Gap	Low velocity impact
LABSET	Shock run-to-detonation	Embedded-gauge Gas Gun

Table 2: Levels of impact and shock testing.

2.2.2.1 Drop Hammer

The drop hammer test is a small-scale sensitivity test performed on every explosive as part of baseline safety testing. A weight is dropped from measured heights until a height is found where an explosive will detonate 50% of the time. Insensitive high explosives will usually not exhibit any reaction to this test even at the maximum height. LANL has a maximum height of 320 cm while LLNL has a maximum height of 177 cm.

This is used by LLNL and LANL.
This test uses 1-2 g of material

2.2.2.2 Rotter (Figure of Insensitiveness) Test

The Rotter test is a standard small-scale powder hazard test that is used to indicate how sensitive an energetic material is to a nipping high-shear impact. In the test a 5 kg weight is dropped from a series of heights onto a small amount of energetic material held in an inverted brass cap. Gas that evolved as a result of reaction is measured and this, together with any visual signs of decomposition, is used to judge the degree of reaction in the sample. The result from the experiment is then used to determine the initial drop height for the subsequent test run, using a Bruceton Staircase approach, on 50 caps. Upon completion of the '50 cap' run, the mean height of a positive response (or 'go') is calculated and then compared against a standard RDX result to yield the figure of insensitiveness (F of I) for that material, relative to an RDX standard (RDX = 80).

AWE uses the Rotter test.
Test uses 2 g of material for series

2.2.2.3 LabSET

The Laboratory Scale Explosiveness Test (LabSET) was developed to characterize the explosiveness of energetic materials to a combined drop weight impact and thermal heating insult, mimicking a simple Oblique Impact (Skid) test scenario. The test utilizes a small (~17 g) explosive pellet mounted in cylindrical steel confinement. The explosive is subjected to a shaped impact pulse that originates from a 22.7 kg drop weight and a simultaneous heating effect from a wire in contact with the sample (heated as a capacitive discharge during the loading phase). The test is used to give an early indication of how the formulation will respond to combined impact and friction stimuli delivered from the large-scale oblique impact test. Results from the test have been shown to correlate well with responses from large-scale oblique impact tests.

AWE uses this test.
This test uses 17 g of material

2.2.2.4 Gap Test

The gap test is a shock sensitivity test where the explosive of interest is separated from the initiation train by an inert gap. The thickness of the gap is varied until the acceptor explosive detonates 50% of the time. The thicker the gap required, the more sensitive the explosive is to shock, as the attenuation of the input shock pulse is affected by the gap thickness. There are a variety of gap tests using different amounts of confinement, attenuation materials in the gap, different initiation trains, and different amounts of materials. As a result, data from the gap test are only meaningful when compared to materials tested in the exact same test. An event is evidenced by a dent on a witness block. Results from this test complement the wedge test, or gas gun run distance to detonation.

All labs possess this capability
Each Test Requires ~12 g of material, series is 8-20 tests

2.2.2.5 Shock run-to-detonation

The goal is to measure the run distance to detonation as a function of pressure. Pressure is varied by attenuation of the input pressure pulse using attenuation material between the plane-wave generator explosive source and the sample. These data are used to generate a Pop plot, which plots the run-to-detonation distance as a function of input pressure on a logarithmic scale. The resulting plot lines are then used to evaluate the relative sensitivity to shock between energetic materials.

This test varies in design specifics at each site
Sample sizes typically are 100-500 g

2.2.2.6 Low-speed Impact

This refers to a category of tests designed to investigate the response of candidate materials to credible non-shock mechanical impacts representing tooling or transportation accidents on cased assemblies. The most common tests are derivatives of the LLNL Steven Test. In general, a consolidated disc of explosive is mounted in heavy steel confinement in the center of an internal annular support ring. A thin steel plate covers the front of the assembly. The assembly is impacted at the front cover plate by a steel projectile fired from a gas gun. Various projectile nose shapes have been used. Target samples are usually ~12.7 mm thick and either 120 mm (US) or 70 mm (UK) in diameter. The results are typically reported as a threshold projectile velocity for the onset of detectable reaction and a measure of explosiveness that is determined by blast gauges for higher velocities.

Capability exists at LANL, AWE and LLNL
Sample sizes are 50-250 g

2.2.2.7 Embedded-gauge Gas Gun

Powder and gas gun experiments are designed to measure the detailed initiation response of explosives to well-defined high-pressure shock loading. The guns deliver a planar (1D), long-pulse shock wave to the sample over a range of input pressures – determined by the impedance and velocity of the projectile. Gauge packages are inserted in the interior volume of the explosive sample, and can measure either pressure or particle velocity. Gauge records serve two purposes: (1) as a safety response to shock insults determined from the run-distance to detonation (indicated by a change in the shape of the pressure pulse from any gauge record) as a function of input pressure; and (2) as input data for building initiation burn models.

All labs possess this capability
Test Requires 1000 g of material

2.2.3 C. Thermal tests

Evaluation	**Development**	**Demonstration**
DSC, C_p	Cook-off: DDT, Fast, Slow, VCCT	Large-scale cook-off
TGA	Strand burner	
	ODTX	

Table 3: Levels on Thermal testing.

2.2.3.1 DSC, C_p

Differential Scanning Calorimetry (DSC) is used to characterize the thermal stability of materials. The energy required to maintain a given temperature profile is monitored. The onset of decomposition, melting temperature, decomposition temperatures, and material purity (at percent levels) can be easily read off the graph by significant deviations from the baseline energy input. This test can be combined with TGA and yields a complete picture of the decomposition of materials evaluated. Heat capacity (C_p) can be measured using DSC.

All labs possess this capability
Test requires ~5 mg of material

2.2.3.2 TGA

Thermo gravimetric analysis is a standard powder characterization test where the sample is heated and the mass loss as a function of temperature is measured. Its principal uses include measurement of a material's thermal stability and composition.

All labs possess this capability
Test requires ~5 mg of material

2.2.3.3 Cook-off

The cook-off test is a thermal stability test where the temperature and violence of reaction can be evaluated. A variety of cook-off tests exist: variable confinement, fast heating, slow heating and extremely heavy confinement. These various designs address a continuum of conditions and behaviors. By varying the confinement and heating rate, the transition from deflagration to detonation (DDT) can be investigated.

All labs possess this capability
Test requires 5-100 g of material depending on test

2.2.3.4 Strand Burner

Pressure-dependent laminar burn rates are measured using the LLNL high-pressure strand burner. Sample columns are initiated using a thermal source (igniter wire, $BKNO_3$ and a thin HNS pellet), and the monitored via silver break wires that are embedded within the sample. A typical sample consists of nine individual pellets and 10 burn wires. The sample is pre-pressurized to a desired pressure using argon. As the burn progresses, the pressure around the sample column increases. This is due to the limited volume of the test chamber. The subsequent rise in pressure is on the order of 3-5 times the initial pressure. The change in burn rate with pressure is then monitored. Many towers may be burnt in order to investigate a pressure range of 10-600 MPa. Materials having high burn rates generally exhibit high thermal sensitivity and explosive violence under thermal loads.

This test is performed by LLNL
Test requires ~50 g of material

2.2.3.5 ODTX

One-dimensional time to explosion (ODTX) is a thermal stability test where the time to explosion is monitored as a function of temperature. A 12.7 mm diameter pressed sphere, initially at room temperature, is inserted into a heated isothermal sample holder under confinement (150 MPa). The sample holder is made up of a pair of anvils, each with a hemispherical cavity, 12.7 mm in diameter. The time to explosion is the elapsed time between insertion of the sample and rupture of the containment. The test is repeated over a wide range of temperatures.

This test is performed by LLNL and AWE
Test requires 20 g of material

2.2.3.6 Large-Scale cook-off

This test characterizes the cook-off behavior of the system rather than simply evaluating individual materials. The propensity of one explosive to react violently and ignite a neighboring explosive is evaluated.

All labs possess this capability
Test requires variable amounts of material

2.2.4 D. Thermo-Mechanical

Evaluation	Development	Demonstration
Pressing/ dimensional stability	Compression	Tensile
CTE	Brazil	
Friability Tumble test		

Table 4: Levels of Thermo-Mechanical testing.

2.2.4.1 Pressing/Dimensional Stability

The pressed part density is an important variable affecting an explosive material's performance and safety. The higher the density, the faster the detonation velocity, and the lower the shock sensitivity. Investigating the ease with which a material can be pressed to a high density is important in the early stages of formulation/part development. An initial understanding of dimensional stability can be gained in these studies.

All labs possess this capability
Test requires 10-100 g of material

2.2.4.2 Coefficient of Thermal Expansion (CTE)

The volumetric expansion of a material is one of a set of thermo-mechanical parameters that describe the mechanical behavior and heat transport of a material when the thermal environment of that material changes. These parameters are critical to estimating important chemical-physical responses, such as the mechanical behavior during thermal cycling or cook-off behavior in a fire. CTE measurements are usually done with dilatometry methods in which the length of a cylindrical sample is measured as a function of temperature during a constant rate thermal ramp.

All labs possess this capability
Test requires 3 g of material

2.2.4.3 Friability Tumble Test

The friability tumble test is a pharmaceutical industry standard test developed to investigate the mechanical integrity of small pellets or tablets. The test consists of a rotating drum that repeatedly lifts and drops a number of pellets through a 15 cm drop height. The pellet weight is determined before and after the test has been completed to determine the extent of damage caused through calculation of the weight loss. This test is a useful tool to be used during the early stages of formulation development allowing different binders, fillers and weight fractions to be screened.

This capability exists at AWE
This test requires ~10 g of material

2.2.4.4 Compression

The compressional stress-strain test is one of the important figures of merit for mechanical performance. In compression testing, a cylindrical sample is placed between two platens and mechanically loaded at a relatively slow rate. The load at failure and the strain at failure are both used to evaluate the mechanical quality of the material and to compare to other materials. Compression testing is often carried out over a range of different temperatures. Long term creep testing under low loads is also relevant information that can be gathered in a compression testing geometry. Finally, a last parameter known to effect mechanical properties, and especially in compression, is the bulk density of the specimen. In order to provide a full picture of the compressive properties, especially in support of a comparison of different materials, it is important to understand how these properties depend on pressed density.

All labs possess this capability
Test requires 250 g of material

2.2.4.5 Tensile testing

Tensile testing provides the same information as compression testing but in the opposite stress state. In this case, samples are in a dogbone shape that permits the ends to be gripped symmetrically and with a low load so that the response is due primarily to the center, narrower portion of the sample. In this test, extensometers mounted in this central region must be used to measure strain. The tensile modulus and strengths over a range of temperatures are usually measured. Again, density is a parameter that must be measured and used in the comparison of materials.

All labs possess this capability

Test requires 160 g of material

2.2.4.6 Brazil Test

This test is an alternate means of measuring the tensile strength of a material. A thin disc of material is diametrically compressed until it fails in tension through the axis of the material. Its usefulness is in the simpler geometry of the samples and reduced quantity of material necessary for the part.

This capability exists at AWE and Pantex
Test requires <5 g per part.

2.3 Reduced Test Plan for Round Robin Testing

The purpose of this report is to recommend a suite of tests that would develop the performance and safety data to facilitate the characterization and down-selection of future candidate insensitive booster explosives. This testing plan attempts to develop a reasonably complete picture of the necessary performance and sensitivity characteristics. We have identified and described those tests that produce data that we feel is accurate, reliable and relatively free of artifacts. They are a subset of all of the available tests across the Enhanced Collaboration laboratories. Given a shorter timeline, we suggest below a reduced subset of tests that would permit an early assessment of the viability for further development of the candidate materials (Table 5). The reduced test plan therefore consists of approximately eleven tests that cut across their most essential performance, mechanical and safety characteristics. The testing is divided up among the labs to share the cost, burden and expertise in the most judicial manner.

Performance	Mechanical	Thermal Sensitivity	Impact & Shock Sensitivity
Floret	Load curves (density versus load, cycles)	DSC	Drop Hammer
½-in rate stick + dent block	Stress-strain compression	TGA	IHE Gap Test
½-in rate stick + PDV		ODTX	LabSET
ITraC: curvature + PDV			

Table 5: reduced test plan.

The testing was distributed across the four sites:

Pantex:	Pressing characteristics, load curves, compression tests
AWE:	Floret, ITraC, LabSET
LLNL:	PDV rate stick, ODTX
LANL:	Dent rate stick, IHE Gap test

The drop hammer, DSC and TGA tests were to be performed at all sites. Unless otherwise specified, part preparation for each test was to be done at the sites performing the test. However, formulated material for each candidate was drawn from a single lot where possible. This required shipment of materials and/or pressed parts for explosives that did not have Department of Transportation EX-numbers. For this reason, we used the twice-yearly US-UK military transport exchanges that occur in the Fall and Spring. An initial exchange of materials was completed in November 2010. In this shipment KD-5 was received from the UK at all US labs. DAAF formulated with 3% KelF-800 was received by the UK. For the May 2011 transport, RX-55-AY was shipped to the UK. The US labs exchanged materials without incident. Testing began in January 2011 but was abandoned for lack of support.

2.4 Candidate materials and their properties

Based on previous testing a short list of explosives and their compelling characteristics has been assembled:

CHE formulations: LX-07 (90/10 HMX/Viton) and **EDC-29** (95/5 HMX/HTPB)
(1) Minimum safety baseline
(2) High energy, HMX based explosives
(3) Highly tested and characterized as booster or main charge materials

SIB candidate: DAAF (3,3'-diamino-4,4'-azoxyfurazan)
(1) Insensitive (like TATB) to impact and friction
(2) Sensitive to shock (like HMX)
(3) Green synthesis route

SIB candidate: FOX-7 (1,1-diamino-2,2-dinitrothylene)
(1) Considered an IHE in Europe, but not highly investigated in the US
(2) Performance similar to RDX
(3) Less shock sensitive than RDX

SIB candidate: LLM-105 (2,6-diamino-3,5-dinitropyrazine-1-oxide)
(1) Intermediate impact sensitivity
(2) High thermal insensitivity
(3) Widely tested, development of material is mature.

IHE formulation: ultrafine TATB
(1) Minimum performance baseline
(2) Very insensitive, TATB based booster material
(3) Performance issues at below-ambient temperatures

Formulation	TMD (g/cc)	D_v (km/s)	P-CJ (kbar)	Exotherm, (°C)	DH50 (cm)	Production scale
LX-07	1.9	8.67	346	284	64	10 kg
EDC-29	1.82	8.77	360	259	59*	125 kg
FOX-7	1.88	8.34	340	240; 285	-	-
DAAF	1.75	7.93	306	262	>177	1 kg
LLM-105	1.91	7.8-7.9	280-300	350-360	114	1 kg
μf-TATB	1.94	7.50	250	375-385	>177	10 kg

Table 6: properties of candidate materials

* Figure of Insensitivity from UK Rotter Test: PETN = 40, RDX = 80.

3 LANL Booster work to support the DoD Joint Insensitive Munitions Technology Program (JIMTP)

In 2009 the DoD funded a new LANL project to investigate replacement formulations for PBXN-7, an explosive formulation widely used as a booster in munitions. Many problems exist in PBXN-7 and it was felt most could be solved by using DAAF in replacement formulations. Through this project, it was possible to explore and understand the testing and acceptance criteria associated with Insensitive Munitions (IM), the requirements of a booster in DoD munitions, and development of new tests to compare physical phenomena.

3.1 Introduction

PBXN-7 is an explosive formulation widely used in fuzes by the DoD. The formulation consists of 60% TATB, 35% RDX and 5% Viton. It was developed to fulfill certain Insensitive Munitions (IM) requirements, but suffers from a number of shortfalls: the inclusion of TATB hampers performance, and exacerbates poor cold temperature performance; it contains TATB, which can be precious, and contains RDX, which is environmentally unfriendly. The original goal of this project was to find a better IM formulation with DAAF as the backbone. DAAF was chosen because it possesses many insensitive traits similar to TATB, with better performance. A variety of formulations with DAAF and TATB, DAAF and RDX, DAAF and HMX, were evaluated. A wide variety of performance and safety advantages were expected, although not in the same formulation: the performance of a formulation containing DAAF and TATB would maintain performance of PBXN-7 with increased insensitivity, and a formulation with DAAF and RDX would be expected to perform better, with similar sensitivity. Formulations were planned with DAAF and HMX to further increase performance and aid thermal stability.

DAAF synthesis was investigated in the 1980s by Russian scientists [1], and its synthesis development was performed at LANL and patented by Hiskey, Chavez, et al. [2] Initial performance and sensitivity testing revealed an explosive that was remarkably insensitive to impact and friction, but had favorable performance characteristics, tiny critical diameter [3] of ~1 mm, which is unprecedented in an insensitive high explosive, and was more sensitive to shock than TATB. The shock sensitivity revealed by wedge testing and the resulting Pop-plot showed the run distance to detonation as a function of pressure to be similar to HMX. Small-scale gap testing on DAAF of different particle sizes showed shock sensitivity could be affected by particle size and synthesis method. The least sensitive DAAF has been used in this study [3, 18].

DAAF has showed promise as a booster or a main charge ingredient. DAAF's booster capabilities have been tested in the onionskin [4] test and with proton radiography (PRad). The onionskin tests examine the breakout wave on the surface of an acceptor explosive as a measure of the booster's ability to reliably and uniformly initiate the acceptor explosive at cold (-54°C) temperatures. This was the first observation that DAAF performed well cold, where it's corner turning outperformed all other explosives tested, including the conventional high explosive (CHE) LX-07. Cold temperature performance is an area where TATB does not excel, and utilizing DAAF as an ingredient was expected to provide a distinct advantage.

3.2 Formulation and testing approach

DAAF was selected as the main ingredient for the formulations based on its safety and performance. Other explosives were included to enhance performance **or** safety. Safety and performance are usually mutually exclusive in explosives. Formulation included DAAF with TATB, RDX or HMX. For simplicity, a formulation of just DAAF and Viton was included to see if PBXN-7 could be improved upon with a single-explosive system. In all formulations, the binder was fixed at 5% Viton to allow

Formulation	Predicted Dv (km/s)	Predicted Pcj (kbar)	Density (g/cc)
PBXN-7	7.870	274	1.830
PBXW-14	8.263	306	1.859
95% DAAF, 5% Viton	7.778	282	1.702
80% DAAF 15% RDX 5% Viton	7.889	287	1.711
80% DAAF 15 % HMX 5% Viton	7.928	292	1.720
80% DAAF 15% TATB 5% Viton	7.765	279	1.727
60% DAAF 35% RDX 5% Viton	8.040	293	1.720
60% DAAF 35% HMX 5% Viton	8.132	304	1.750
60% DAAF 35% TATB 5% Viton	7.749	276	1.784
50% HMX 45% DAAF 5% Viton	8.289	314	1.774

Table 7: Cheetah 5.0 performance calculations for booster candidates and benchmarks.

comparison to PBXN-7.

Both PBXN-7 and PBXW-14 are included as benchmarks. Early in the project the goal was only to look at replacing PBXN-7 but the scope was increased to include PBXW-14 as TATB availability to the DoD decreased. All formulations were compared at 97% TMD, which was chosen because it was an achievable density with favorable performance. Later it was found that most of the existing data on PBXN-7 was at a density of 94.3% TMD. All tests and modeling were adjusted to the lower density to allow apples-to-apples comparison.

The first step in formulation development is performance modeling using the LLNL explosive performance estimation tool: Cheetah 6.0. Explosive performance and the performance of mixtures can be evaluated with this tool. It contains a number of different product libraries, which are based on different equations of state. Because Cheetah is a model, it needs understanding and calibration to be used effectively. Cheetah over-predicts TATB so all formulations listed in Table 7 were made regardless of subpar performance when compared to PBXN-7.

3.3 Testing:

Once the formulations were made, tests relevant to booster performance were chosen. The tests were chosen to represent comparative performance and safety traits to allow down-selection. The goal was: include tests that were relatively easy to perform in a timely manner, weren't excessively expensive and gave useful booster data. The approach detailed in the EC report was largely used, two exceptions are the use of the

Test	Location	What does this test yield?	Finish date
Ambient Rate stick	LANL	Detonation Velocity, Pcj	Dec 2009
Polyrho	LANL	Detonation velocity as a function of density; Calibration of Cheetah	Jan 2010
Variable Confinement Cook-off Test	NSWC-IHDIV	Cook-off violence as a function of confinement	June 2010
IHE gap test	LANL	Shock sensitivity, comparison to DoD library of explosives.	July 2010
Cold Temperature rate stick	LANL	Detonation velocity at low temperatures, Pcj	July 2010
Front curvature (ambient)	LANL	Detonation wave curvature, detonation velocity, temperature effects, diameter effects	Oct 2010
Front Curvature (cold)	LANL	Detonation wave curvature, detonation velocity, temperature effects, diameter effects	Oct 2010

Table 8: Test Plan for PBXN-7 replacement project

IHE Gap Test and the Variable Confinement Cook-off Test. These were used to make use of a thorough database of comprehensive DoD data. See Table 8 for a complete list of tests.

At the start of this project, DAAF cook-off response had not been evaluated. If DAAF exhibited excessive thermal violence, the project would come to a halt, so this was performed first. The data were extremely favorable (see Appendix 1 and 2). While evidence exists to show DAAF has reasonable cold temperature performance, a comprehensive test had not been developed and performed. Through this project a new test was developed where velocity and front curvature could be investigated as functions of temperature and diameter.

Each test series will be described and the results and down-selection (if applicable) discussed individually. In the end two formulations were chosen and moved forward to 6.3 (applied munitions testing and pilot scale production).

3.3.1 Ambient Rate Stick

Figure 1: Rate stick fixture used. Time of arrival data is generated from magnet wire between pellets. Detonation wave completes circuit and sends time information to scope where it is read and imported to Igor for analysis.

Explosives are ranked by performance, and performance is largely evaluated by detonation velocity. Rate sticks were fired to measure the detonation velocity of the formulations and compare the results to Cheetah 6.0 calculations. The shots consisted of ½" diameter pellets with an L/D (ratio of length to diameter) of 10. **Error! Reference source not found.** shows the configuration used.

Previous PBXN-7 data published [6] has been largely tested at a density of 1.78g/cc or 94.3% TMD. To allow direct comparison, all replacement formulations were pressed to the same percent TMD. This does not allow the full performance to be realized, and causes the material to be more shock sensitive, as shock sensitivity is a function of porosity [8]. Magnet wire inserted between the pellets was used to transmit time of arrival of the detonation front. All tests were fired at ambient temperature, and the velocity was ascertained using the time-of-arrival scope data. The results are shown in Table 9.

Formulation	Impact Height (cm)	Detonation Velocity (Ambient) km/s	Cheetah 6.0 calculation at 94.3% TMD	IHE Gap test results (inches)	Product Library
PBXN-7- IH **60% TATB, 35% RDX 5% Viton**	**77**	**7.680 ± 0.004**	**7.761**	**2.05**	**Exp6.2**
PBXW-14-IH **50% HMX (3:1 Class 1 to Class 5) 45% TATB 5% Viton**	**57.8**	**7.956 ± 0.004**	**8.007**	**2.14**	**Exp6.2**
LAX-117-4 **80% DAAF, 15% Fine RDX 5% Viton**	**297.2**	**7.756 ± 0.003**	**7.721**	**1.84**	**BKWC**
LAX-117-6 **60% DAAF, 35% Fine RDX 5% Viton**	**159.9**	**7.906 ± 0.003**	**7.869**	**2.00**	**BKWC**
LAX-117-8 **80% DAAF, 15% Fine HMX 5% Viton**	**>320**	**7.764 ± 0.003**	**7.758**	**1.74**	**BKWC**
LAX-117-10 **60% DAAF, 35% Fine HMX 5% Viton**	**159.5**	**7.974 ± 0.009**	**7.959**	**1.96**	**BKWC**
LAX-117-13 **95% DAAF, 5% Viton**	**>320**	**7.659 ± 0.002**	**7.700**	**1.59**	**BKWC**
LAX-120 **50% HMX (class 5), 45% DAAF, 5% Viton**	**60.4**	**8.121 ± 0.002**	**8.113**	**1.87**	**BKWC**
LAX-120.1 **50% HMX (25% Class 1, 25% Class 5), 45% DAAF, 5% Viton**	**55.1**	**8.121 ± 0.002**	**8.113**	**2.08**	**BKWC**

Table 9: Impact height measurements and rate stick results for all formulations. Cheetah 6.0 Library, which best fits the data is also included. IHE gap test results are included. Calibration of DAAF Cheetah libraries using Polyrho data found BKWC gave the best approximation. Agreement between experiment and model was very good.

3.3.1.1 Rate stick discussion

Not surprisingly, the larger weight percent RDX or HMX in the studied formulations, the better performing the explosive. This is diametrically opposed to the small-scale safety testing results. Optimizing the formulations was a trade off between safety and performance. This series of experiments allowed a useful evaluation of Cheetah modeling. Table 9 contains ambient velocities for all materials, impact heights measured with type 12 DWI impactor, detonation velocities from Cheetah 6.0 representing the closest fit, and the library used.

3.3.2 Polyrho

When a new material is made, only two pieces of data are needed to generate Cheetah calculations: crystal density and heat of formation. This allows some indication of an explosives performance to be made with very little material, but the accuracy of Cheetah's calculations is unknown, so some sort of calibration for detonation velocity is crucial. To calibrate Cheetah, two mindsets exist: 1) do a number of rate sticks at different densities to develop a detonation velocity as a function of density curve and use that to calibrate Cheetah and it's various libraries or 2) Do a polyrho test where a number of density/velocity points are measured for a single rate stick. While 1) is definitely more thorough, 2) allows a density/velocity curve with only one shot. The inherent error in the Polyrho shot is greater, and therefore it must be done with care. We elected to perform three polyrhos: neat DAAF, DAAF and 0.5% KelF-800, DAAF and 3% KelF-800. These formulations were chosen to evaluate the inclusion of binder on the detonation velocity/ density relationship.

3.3.2.1 Polyrho Testing Improvements and Results

The Polyrho has been used for decades and studied and perfected using the equipment and diagnostics available at the time. The original test used single pellets of each density allowing 12-15 different densities to be tested [7, 12]. They were arranged from low to high density and initiated with an SE-1 detonator. Foil switches were used to collect time of arrival scope data. We found these data to be erratic and the velocity between pellets was inconsistent. See figure 2 for representative foil switch scope trace.

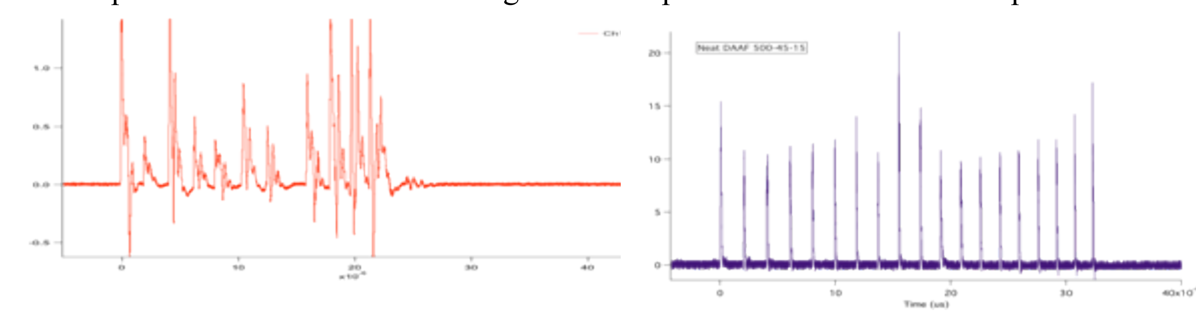


Figure 2: Left trace is foil switch data, Right trace is scope data from polyrho utilizing magnet wire. This data was exceptionally clean, easy to read and the results were consistent with calculations. The rise time associated with each pulse measurement was 3-4ns as compared with 20-60ns with the foils switches.

3.3.2.2 Test Improvements

It was determined the foil switches introduced too much noise to the scope trace and the rise time associated with each switch measurement was too slow to allow a high fidelity measurement to be made. Owing to the difficulty analyzing the data from foil switches, the measurement technique was redesigned. One density pellet per measurement was too uncertain, so two similar pellets measured each representative density. This allowed the velocity at each density to reach a more steady state. Low-

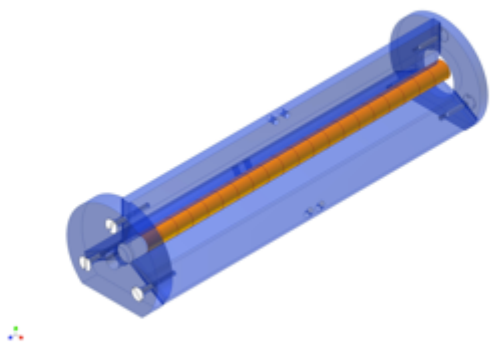


Figure 3: New Polyrho fixture.

density velocities did not agree well with Cheetah and we hypothesized that the PBX 9407 pellet was overdriving the first six pellets. Streak imaging was employed to test this hypothesis. Additionally, the data from the streak image could be analyzed to corroborate the switch data. Later tests used 3-4 lowest density pellets to allow the detonation to approach an initial steady state. A new fixture was designed to hold twenty pellets (see **Error! Reference source not found.**). The foil switches were replaced with .002” magnet wire with a polyamide coating. An example of the time of arrival scope data from the magnet wire can be seen in Figure 2. The wire was sandwiched between each pellet and the pellets were held together with vacuum grease. Holding the pellets in place with thin vanes minimized confinement. Tension on the pellets was applied with the detonator holder screw. The shot was initiated with an RP-2 detonator.

The formulations included in the new polyrho experiments were neat DAAF, DAAF and 0.5% KelF-800, and DAAF and 3% KelF-800. Two pellets identical in density to within 0.002 g/cc represented each density. The shots were painted with aluminum fluorosilicate paint to enhance the amount of light to the streak camera. This greatly improved the clarity of the streak image.

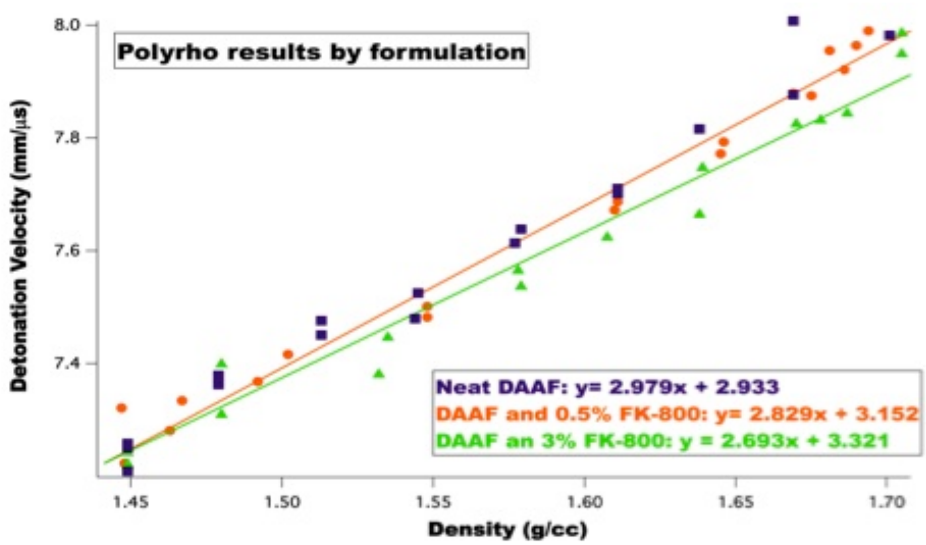


Figure 4: Polyrho results for each DAAF formulation. DAAF and 3% FK-800 shows a much greater reduction of velocity at high density than the other two formulations.

3.3.2.3 Polyrho Results

Figure 4 shows the velocity vs. density results for the three DAAF formulations tested. The effect of adding a larger amount of binder can clearly be seen with the velocity being compromised at higher density. The 0.5% binder formulation showed very little

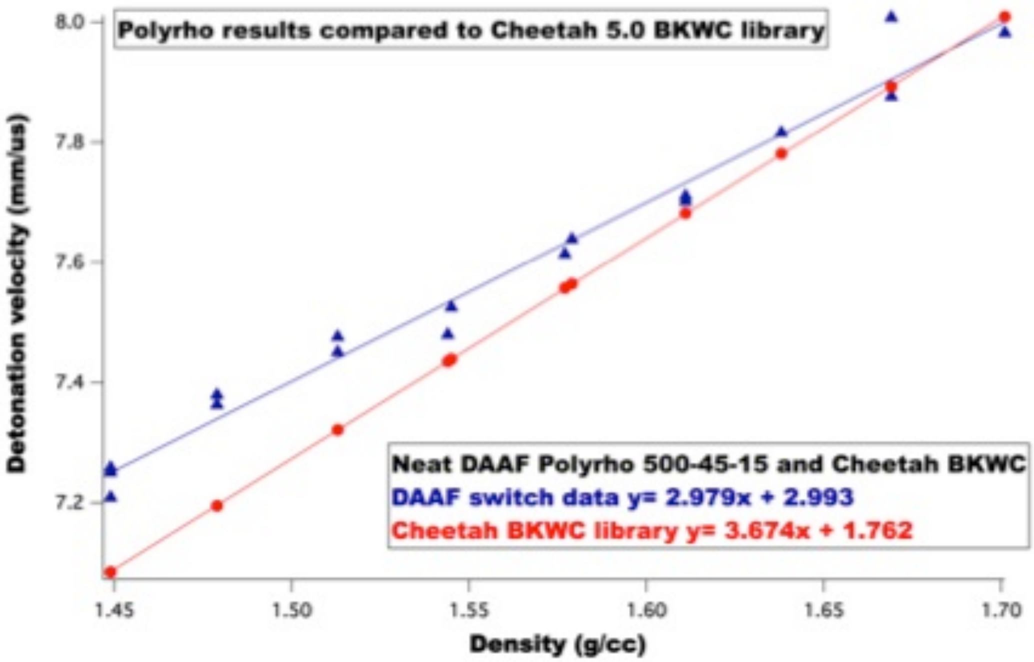


Figure 5: Polyrho results for neat DAAF and compared to Cheetah 5.0 BKWC library results.

Effect of the binder on the velocity, but it was the most difficult formulation to press. Interestingly, neat DAAF was significantly easier to press; the pellets held together and it was possible to create sturdy pressed pieces. The 0.5% formulation did not hold together at the low %TMD pressings, and the corners broke off the pellets with little provocation. It is curious that a small amount of binder is worse than no binder at all at low densities. At higher densities the 0.5% FK-800 formulation pressed well, producing solid pieces. With these data at different densities, a valuable opportunity to validate Cheetah exists. The switch and streak data was compared to Cheetah 6.0 calculations from all libraries. There was poor agreement. **Error! Reference source not found.** shows the polyrho data for neat DAAF and the Cheetah library exemplifying the closest fit: BKWC. The agreement between model and reality is less than ideal, showing a much higher disparity at low density, but reaching a close approximation at high density. Cheetah and

Figure 6: VCCT fixture after test. This represents the results of DAAF at the thickest confinement (0.120 inches). The sleeve is ruptured and the fixture is intact.

experiment agree well in the density range of 1.65-1.70 g/cc using the BKWC library. Fortunately this is the useful pressed density for DAAF, and all existing experimental data is in this density range.

3.3.3 Variable Confinement Cook-off Testing (VCCT)

The VCCT was developed to be a low cost measure of an explosive behavior to confinement during slow or fast heating. Because little was known about DAAF response in a slow cook-off test, samples were sent to Indian Head for VCCT. If DAAF reacted violently in this test, the project would come to a halt. To save time and money, it was prudent to evaluate this as soon as possible. Pellets were pressed and shipped to Indian Head for testing. Care was taken to create high quality pellets because it was suggested that the test is sensitive damage on the edges of the pellets. Crack, dings, flakes, or divots were to be avoided.

DAAF did not react violently in any confinement. **Error! Reference source not found.** shows an example of the fixture after the test. The results and the time to reaction can be seen in Table 10. DAAF and 5% Viton is compared to PBXN-7 which begins to react violently at 0.09" as shown in Table 11

Confinement	Reaction Temperature	Time to Reaction	Reaction Type **DAAF**	Reaction Type **PBXN-7**
0.060"	225.9 °C	46.65 hours	burn	Pressure rupture
0.075"	228.9 °C	46.65 hours	Pressure rupture	Pressure rupture/deflagration
0.090"	222.1 °C	44.79 hours	burn	Deflagration
0.105"	232.4 °C	38.53 hours	burn	
0.120"	229.5 °C	38.29 hours	burn	

Table 10: DAAF and 5% Viton VCCT results compared to PBXN-7 results. DAAF shows a significantly less violent reaction at higher confinements than PBXN-7 does, suggesting it is thermally more stable.

Based on this success, the project continued. All formulations under investigation sent to Indian Head by the spring of 2010.

Formulation	Response at 0.030"	Response at 0.045"	Response at 0.060"	Response at 0.075"	Response at 0.090"	Response at 0.105"	Response at 0.120"
PBXN-7			Pressure Rupture	Pressure rupture/ Deflagration	Deflagration	NT	NT
PBXW-14			Burn	Pressure Rupture	Burn	Pressure Rupture	Burn
80% DAAF, 15% RDX, 5% Viton	Deflagration	NT	Explosion	Deflagration	Explosion	Deflagration	Deflagration
60% DAAF, 35% RDX,	NT	Burn	Deflagration	Deflagration	Explosion	NT	Deflagration

5% Viton							
80% DAAF, 15% HMX, 5% Viton	NT	NT	NT	NT	Burn	Burn	Burn
60% DAAF, 35% HMX, 5% Viton	NT	NT	Pressure Rupture	Burn	Pressure Rupture	Pressure Rupture	Burn

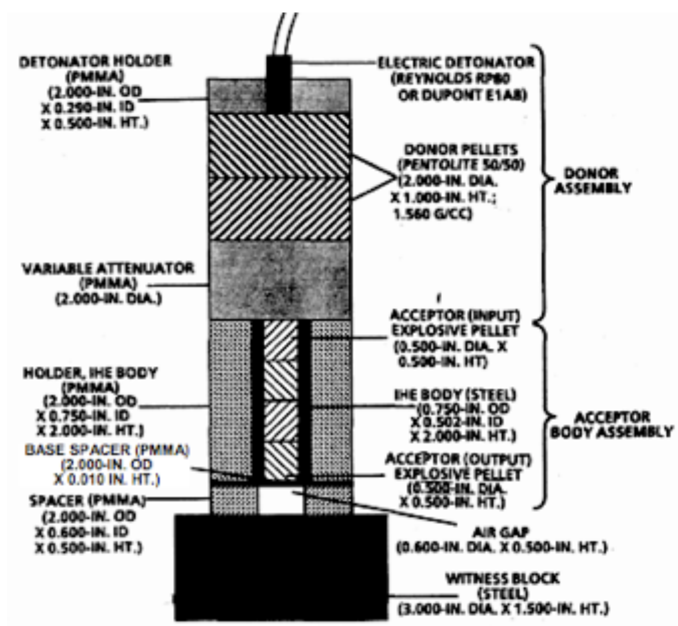
Table 11 highlights the results. Inclusion of RDX did cause a violent reaction with DAAF, as similar to PBXN-7. Based on this outcome all formulations containing RDX were abandoned. HMX does not show this trait and all formulations comprised of DAAF and HMX passed VCCT. A passing grade was a burn or pressure rupture, as these are outcomes acceptable to the JIMTP. A complete description of the test and the results can be found in appendices 1 and 2.

Formulation	Response at 0.030"	Response at 0.045"	Response at 0.060"	Response at 0.075"	Response at 0.090"	Response at 0.105"	Response at 0.120"
PBXN-7			Pressure Rupture	Pressure rupture/ Deflagration	Deflagration	NT	NT
PBXW-14			Burn	Pressure Rupture	Burn	Pressure Rupture	Burn
80% DAAF, 15% RDX, 5% Viton	Deflagration	NT	Explosion	Deflagration	Explosion	Deflagration	Deflagration
60% DAAF, 35% RDX, 5% Viton	NT	Burn	Deflagration	Deflagration	Explosion	NT	Deflagration
80% DAAF, 15% HMX, 5% Viton	NT	NT	NT	NT	Burn	Burn	Burn
60% DAAF, 35% HMX, 5% Viton	NT	NT	Pressure Rupture	Burn	Pressure Rupture	Pressure Rupture	Burn

Table 11: Results of VCCT for entire project compared to PBXN-7 and PBXW-14. Formulations containing DAAF and RDX reacted violently and were abandoned.

3.3.4 IHE gap test

Because PBXN-7 is used in fuzes, matching the shock sensitivity was critical to allow a new formulation to be a drop-in replacement. No changes to the initiator would be necessary if we could match the shock sensitivity of PBXN-7. To achieve this evaluation, the IHE gap test was used. A significant amount of data on



PBXN-7 and PBXW-14 IHE gap tests has been published [6,7] allowing a direct comparison to be made. The test configuration can be seen in **Error! Reference source not found.**, and the results are shown in Table 12. PBXN-7 and PBXW-14 were included to serve as benchmarks, and validate the test against existing data. In all cases the replacement formulations were less sensitive to shock than the benchmarks, and effort was required to make these formulations shock sensitive enough to be drop-in replacements.

3.3.4.1 IHE gap test discussion

Once the testing was complete and the results were compared, the shock sensitivity of PBXN-7 was surprising. The inclusion of TATB contributes very little to making this formulation insensitive to impact or shock. The goal to make this new formulation a drop-in replacement was challenged by these results. Historically, shock sensitivity of PBXW-14 was dialed in using HMX particle size. To achieve the desired shock sensitivity a combination of class 1 and class 5, in a ratio of 3 to 1, was chosen. The inclusion of large particle size (class 1) HMX enhances the sensitivity to shock [8]. We adopted the same approach in the analog formulation to PBXW-14: LAX-120 which, consists of 50% class 5 HMX, 45% DAAF and 5% Viton. The IHE gap test results showed it to not be shock sensitive enough. The goal was a gap thickness near PBXN-7 (2.05 inches) and not exceeding PBXW-14 (2.14 inches); the result of 1.87 inches was deemed too insensitive. To mitigate this, a new formulation was made: LAX-120.1, which contained equivalent amounts of each ingredient, but the HMX was evenly divided between class 1 and class 5. This improved the shock sensitivity enough: 2.08 inches: enough to make it a drop-in replacement for either PBXN-7 or PBXW-14.

Figure 7: IHE Gap Test fixture.

Formulation	Inches/Cards	Input Pressure (kbar)
PBXN-7- IH 60% TATB, 35% RDX 5% Viton	2.05/ 205	19.6
PBXW-14-IH 50% HMX (3:1 Class 1 to Class 5) 45% TATB 5% Viton	2.14/ 214	17.9
LAX-117-4 80% DAAF, 15% Fine RDX 5% Viton	1.84/ 184	25.1
LAX-117-6 60% DAAF, 35% Fine RDX 5% Viton	2.00/ 200	20.7
LAX-117-8 80% DAAF, 15% Fine HMX 5% Viton	1.74/ 174	28.4
LAX-117-10	1.96/ 196	21.7

60% DAAF, 35% Fine HMX 5% Viton		
LAX-117-13 95% DAAF, 5% Viton	1.59/ 159	34.4
LAX-120 50% HMX (class 5), 45% DAAF, 5% Viton	1.87/ 187	24.2
LAX-120.1 50% HMX (25% Class 1, 25% Class 5), 45% DAAF, 5% Viton	2.08/ 208	19.0

Table 12: IHE Gap Test results for all formulations including PBXN-7 and PBXW-14. Shock sensitivity needed to be similar to allow any new formulation to be a drop-in replacement.

3.3.5 Cold temperature performance- rate sticks

One of the complaints against TATB is that it does not perform well cold (-55^{o}C). This sentiment also applies to PBXN-7 because it contains 60% TATB. In order to evaluate the temperature effect, a series of cold rate sticks was performed where the setup was housed in a Styrofoam box and cooling was provided though a mixture of liquid nitrogen and dry nitrogen. The cooling rate was controlled to 0.5 degree/minute and the fixture was soaked at -55^{o}C for 30 minutes to allow thermal equilibrium. Velocity data was collected in the same manner as the ambient rate stick. The results are shown in Table 13.

Formulation	Detonation Velocity (km/s) at ambient temperature	Detonation Velocity (km/s) at -55^{o}C	Density increase (%TMD)
PBXN-7- IH **60% TATB, 35% RDX 5% Viton**	**7.68**	**7.79**	**1.6**
PBXW-14-IH **50% HMX (3:1 Class 1 to Class 5) 45% TATB 5% Viton**	**7.96**	**8.07**	**1.6**
LAX-117-4 **80% DAAF, 15% Fine RDX 5% Viton**	**7.76**	**7.92**	**2.6**
LAX-117-6 **60% DAAF, 35% Fine RDX 5% Viton**	**7.91**	**8.01**	**1.7**
LAX-117-8 **80% DAAF, 15% Fine HMX 5% Viton**	**7.76**	**7.92**	**2.5**
LAX-117-10 **60% DAAF, 35% Fine HMX 5% Viton**	**7.97**	**8.08**	**1.9**
LAX-117-13 **95% DAAF, 5% Viton**	**7.66**	**7.77**	**1.8**

LAX-120 **50% HMX (class 5), 45% DAAF, 5% Viton**	**8.12**	**8.22**	**1.6**

Table 13: Detonation velocity comparison at ambient temperatures and at -55^{o}C. Perceived density increase evaluated with Cheetah 6.0.

3.3.5.1 Cold temperature rate stick discussion

The results of this test were unexpected but interesting. All formulations including PBXN-7 and PBXW-14 had a higher detonation velocity at -55^{o}C than they did at ambient. One could dismiss previous statements about TATB's cold temperature performance problems based on these results, but that would be in error. What the test revealed was an increase in density due to thermal contraction. All materials showed a velocity increase because they were denser. Table 13 shows velocities at ambient compared to velocities at -55^{o}C and the density increase that is assumed to account for that as modeled with Cheetah 6.0. All are largely similar owing to the identical binder content of each, and similar particle sizes of each formulation.

This is was not the best choice of tests to exhibit performance degradation due to temperature. The error in this test lies in the assumption that "TATB performs poorly cold" associates "performance" with detonation velocity. Through a peer review of the results it was decided that detonation front curvature would be a better assessment of temperature effects [16].

3.3.6 Cold Temperature Performance- Front Curvature Experiments

A test series was developed to evaluate two candidate replacement formulations: LAX-120.1 (50% HMX, 45% DAAF and 5% Viton) and LAX-117-10 (60% DAAF, 35% HMX and 5% Viton) with the benchmarks of PBXN-7 and PBXW-14. In this series the four formulations were evaluated for velocity and curvature at three diameters: 6.35mm, 5mm and 3.81mm. In the case of PBXN-7 the smallest diameter is near to the failure diameter, and curvature effects should be obvious. Similar to previous rate sticks, the velocity was measured with magnet wire with time of arrival data collected from oscilloscopes. The curvature was observed using a Hamamatsu C7700 HPD-TA digital streak camera oriented to the end of the rate stick. This allowed the detonation front

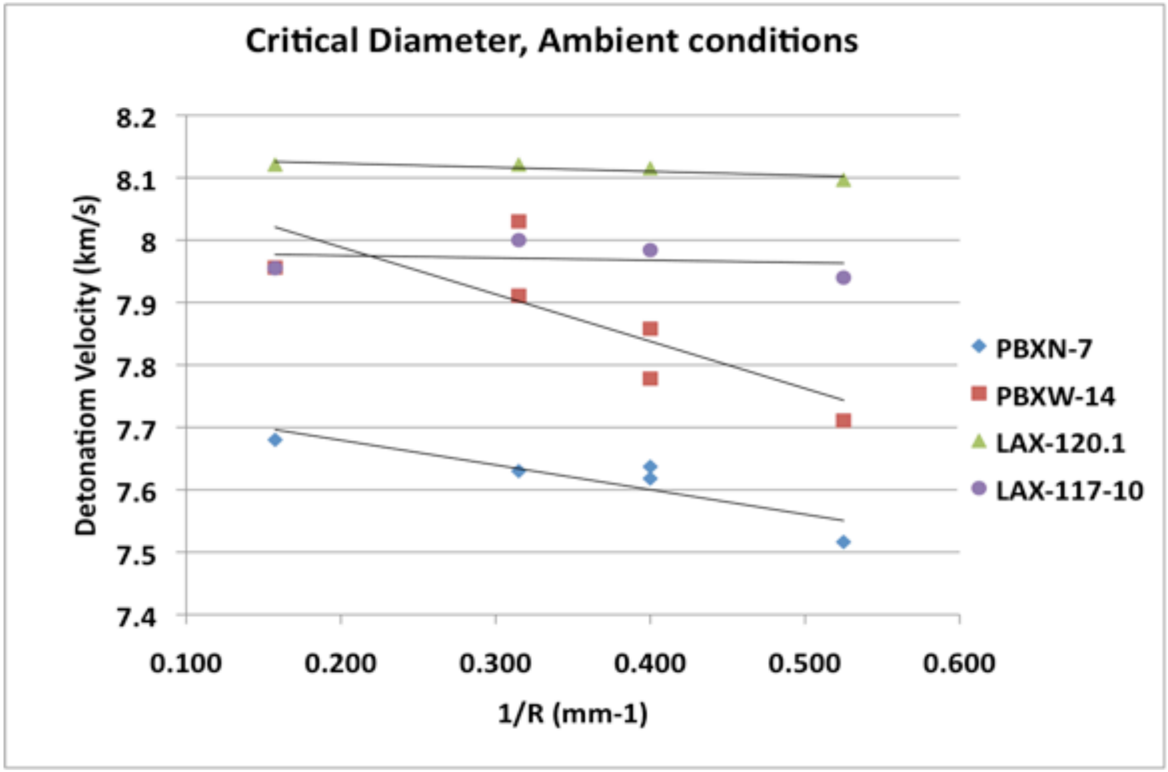


Figure 8: Detonation velocity as a function of diameter at ambient conditions. TATB containing explosives (PBXN-7 and PBXW-14) show velocity degradation as the diameter shrinks. DAAF containing explosives (LAX-117-10 and LAX-120.1) do not.

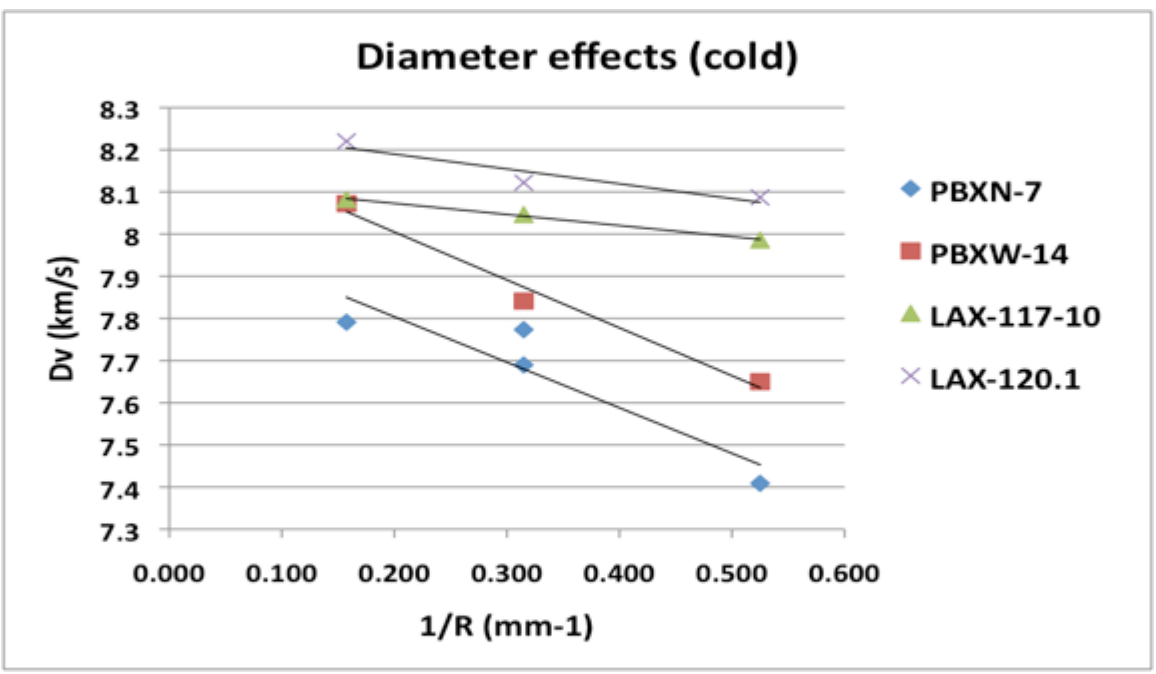


Figure 9: Diameter effects on detonation velocity at cold (-55^{o}C) temperatures. All formulations show increased velocity (over ambient) at larger diameters due to increased density. At smaller diameters edge effects predominate as the critical diameter is neared.

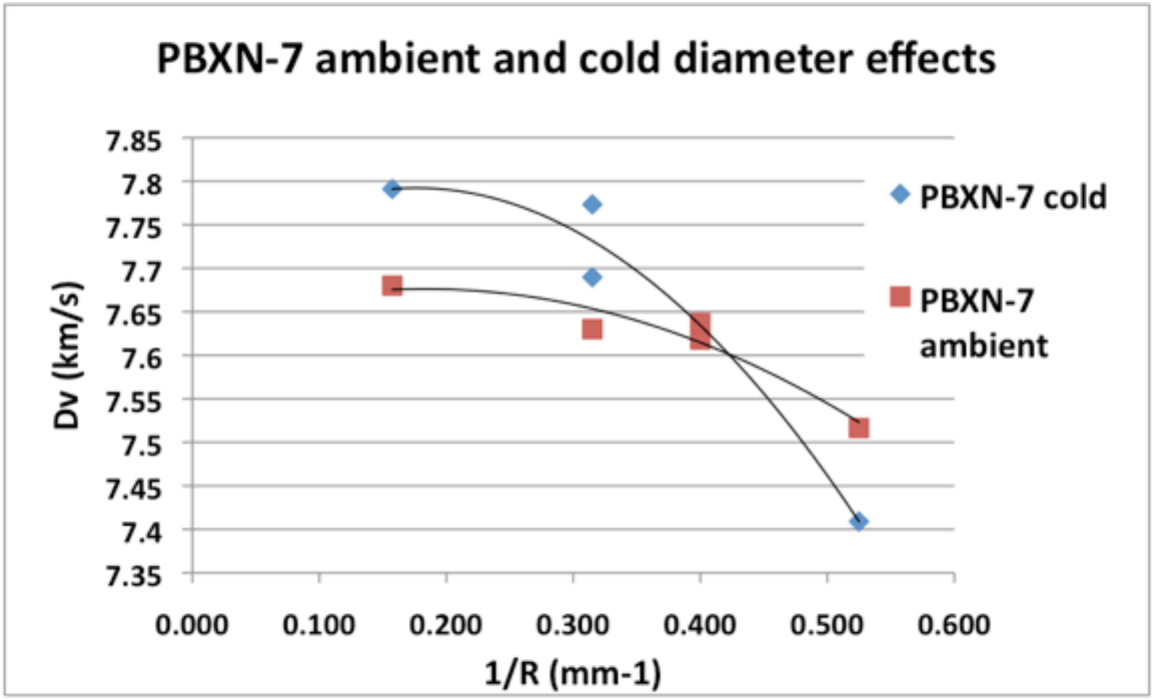


Figure 10: Comparison of PBXN-7 diameter effects at ambient and cold temperature. The critical diameter actually increases at -55°C. Extrapolation suggests an increase from 3.33mm to 4mm.

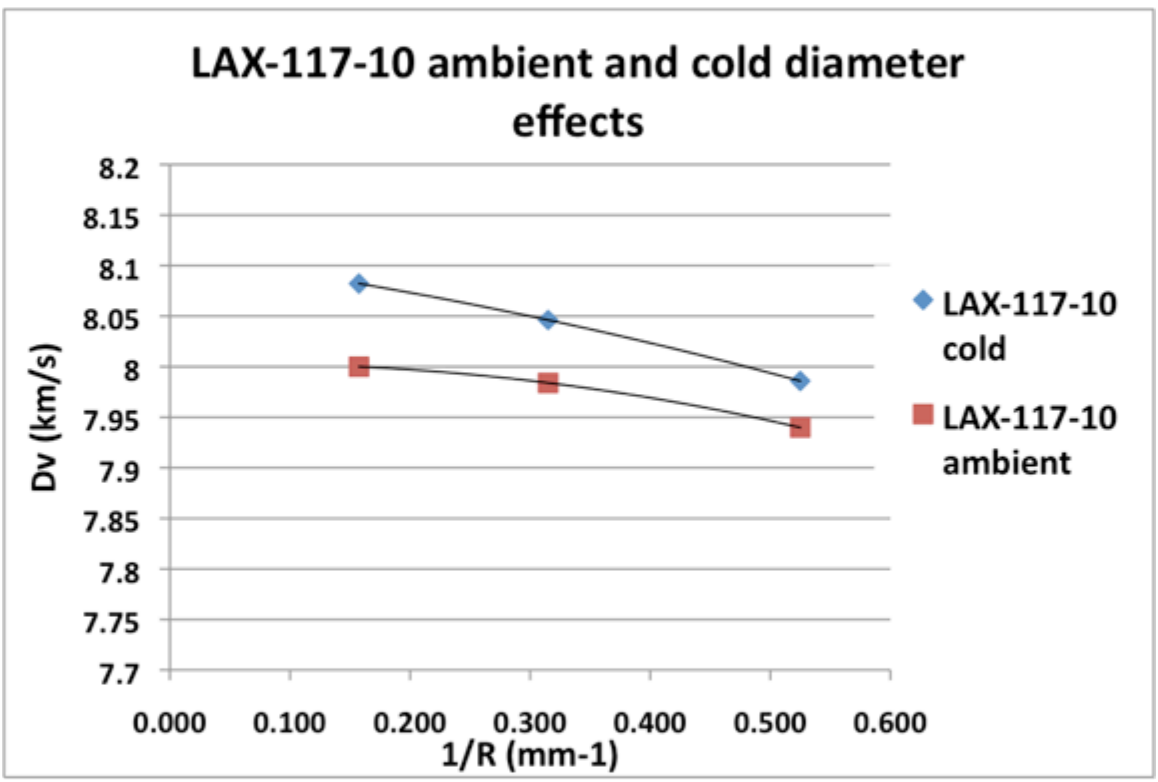


Figure 11: Comparison of the DAAF analog to PBXN-7. Temperature effects on the critical diameter are much reduced. This suggests DAAF is not affected by temperature.

across the face to be observed and qualitatively compared. The materials were tested at ambient conditions first, and the diameter extremes (6.35 mm and 3.81 mm) were tested cold (-55°C). The velocity data was integral to convert the streak image, a distance vs. time record, to distance and allow a radius of curvature to be calculated. The test yielded several important data sets: velocity as a function of diameter; relative curvature from material, diameter, and temperature; and radius of curvature based on material, diameter and temperature. This test allowed the statements to TATB's temperature behavior to be evaluated and the replacement formulations advantages to be observed.

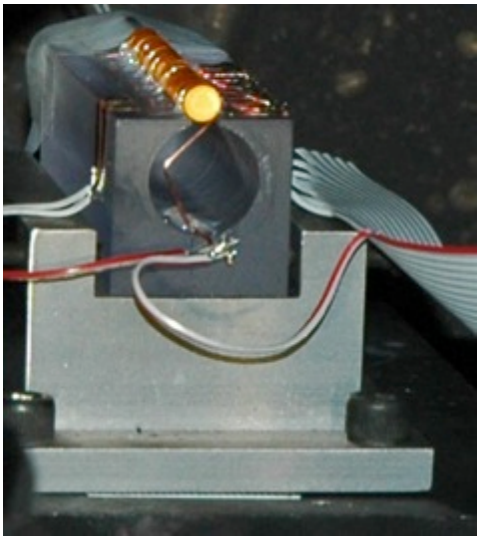


Figure 12: Front curvature test fixture showing the orientation as seen by the streak camera.

Velocity as a function of diameter can be seen in Figure 8. It is clear that PBXN-7 and PBXW-14 are nearing their failure diameter and the velocity is being hampered by edge effects. This is not seen in the replacement formulations, which contain explosives with much smaller critical diameters than TATB. DAAF has a critical diameter near 1.25 mm [3].

At cold temperature the diameter effects are even more obvious. Figure 9 shows the detonation velocity as a function of diameter for the same materials at the same range of diameters when cooled to -55°C. Similar to the cold rate sticks, an increase of velocity at larger diameters is seen. This can be attributed to an increase in density when the material contracts.

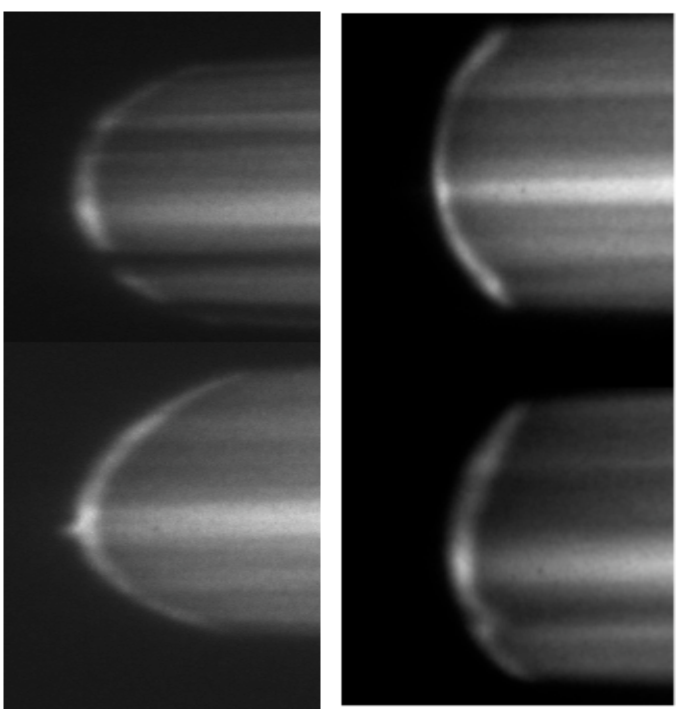


Figure 13: PBXN-7 (left) and LAX-117-10 (right) curvatures compared at ambient (top) and -55°C (bottom). Curvature of TATB containing materials clearing increases with decreasing temperature

Comparing the velocity of the smallest diameter rate sticks for all materials at both temperatures some interesting trends are revealed. PBXN-7 and PBXW-14 are slower at cold temperatures; whereas LAX-117-10 and LAX-120.1 are faster. This suggests that the densification at cold temperature is still a prevalent effect in the DAAF containing formulations, but the attenuation from edge effects in the TATB containing formulations predominates. This supports the statement that DAAF performs well cold, and is at least as effective cold as it is at ambient temperatures, unlike TATB.

The effects of temperature are dramatically illustrated in Figure 10, where PBXN-7 trends at ambient and cold can be compared. It is apparent that the critical diameter increases with decreasing temperature. This behavior is not observed for LAX-117-10, which is shown in Figure 11. LAX-117-10 is not being tested near its critical diameter, which is expected to be around 1.5 mm [3, 13] and shows much less velocity attenuation from edge effects.

Curvature results can be seen in **Error! Reference source not found.** where streak images of PBXN-7 and LAX-117-10 can be seen for diameter of 3.81 mm at ambient and cold temperatures. From a strictly qualitative perspective the curvature in the detonation front can be seen to vary with temperature in the formulation containing TATB. This illustrates how side losses cause a detonation wave to propagate more slowly and contribute to the curvature observed.

3.4 Conclusions

The formulations studied under this program ranged from largely DAAF (DAAF and 5% Viton) to the main ingredient shifting to HMX (50% HMX and 45% DAAF, 5% Viton). The more HMX a formulation contains, the faster the detonation velocity, but at the expense of safety. Cold temperature behavior was excellent for formulations containing DAAF, and easily surpassed formulations containing TATB. The observation that cooling HE to -55^{o}C caused the density to increase and the detonation velocity to increase was made for all explosives, unless the diameter was small enough for edge effect to dominate. TATB-containing formulations exhibited this trend, whereas DAAF-containing formulations did not. This behavior is attributed to the fact that TATB-containing formulations are being tested near the critical diameter, but DAAF, and HMX formulations were well above the critical diameter. Farther from the critical diameter (6.35mm) PBXN-7 still showed a decrease in radius of curvature at cold temperature.

Overall, the inclusion of DAAF increases performance at ambient and cold temperature, while maintaining excellent safety characteristics. The small critical diameter of DAAF may give pause, but there is mounting evidence that DAAF has a shock induced phase change at ~4 GPa [14]. Below this threshold it exhibits very shock *insensitive* behavior, and above this initiates easily. This also explains the dichotomous behavior where DAAF is insensitive to impact but exhibits a Pop-Plot similar to HMX.

Based on this project's results a recommendation was made to the DoD to continue at the 6.3 level. A new project headed by NSWC-IHD was started with the intention of scaling up the synthesis and formulation to the multi-kilogram level and performing scaled munitions testing.

4 Applied Booster Testing Methodology

The Holy Grail of explosive research is an energetic material with performance better than HMX and safety better than TATB. Since such a material has not yet been found, the initiation train of detonator, booster, and main charge has remained largely unchanged. A prevailing trend to make the main charge as insensitive as possible has been adopted by bombs, munitions and nuclear warheads. The safety inherent in tremendously insensitive materials overshadows their performance limitations. As a result, much research over the years has focused on the booster. More output is required to initiate the increasingly insensitive main fills, but it is also of interest to have an insensitive booster. Various materials have been investigated to fill these dichotomous roles: high performance and low sensitivity: DAAF, LLM-105, FOX-7, CL-20, RS-RDX, Spherical HMX etc. DAAF can be used to illustrate the applied booster testing methodology.

Russian chemists discovered Diaminoazoxyfurazan (DAAF) in 1981. The molecule and synthesis method was adopted quickly by LANL chemists, documented and patented in 1999. It largely looked to be a higher performance TATB-like material. Initial testing showed it to be insensitive like TATB, but with more energy and a faster detonation velocity. Problems with the synthesis method, material characteristics and purity diminished interest in this molecule until a new synthesis method was discovered in 2007 and most of these problems were fixed. Interest in this molecule as a booster or a main charge has been growing ever since.

The booster needs to be easily initiated, but safe. Booster initiability can be evaluated by looking at critical diameter, run distance, and shock sensitivity. Once initiated it needs to be powerful enough to initiate the main charge symmetrically and evenly. The booster's effect on the main charge initiability and spreading is viewed directly by observations of detonation wave symmetry, curvature, and first break out over the surface of a charge. For safety and performance considerations, a booster must be insensitive to non-initiation insults, and insensitive to cold temperature effects. These effects, tests and results will be discussed individually in the context of DAAF and other explosives similarly tested.

4.1 Initiation Characteristics

The booster needs to initiate promptly and run up to full detonation quickly with a wide variety of detonators. Initiability can be investigated with several critical tests: Shock run-to-detonation experiments yield the Pop-Plot which relates run distance to detonation as a function of input pressure and an explosives' sensitivity to shock, the Gap Test which investigates shock sensitivity, and critical diameter which defines the minimum diameter an explosive charge needs to have to sustain a detonation. Each test will be discussed.

4.1.1 Shock run-to-detonation (Pop-Plot)

The goal is to measure the run distance to detonation as a function of pressure. Pressure is varied by attenuation of the input pressure pulse using attenuation material between the plane-wave generator explosive source and the sample. These data are used to generate a Pop plot, which plots the run-to-detonation distance as a function of input pressure on a logarithmic scale. The resulting plot lines are then used to rate the relative sensitivity to shock between energetic materials.

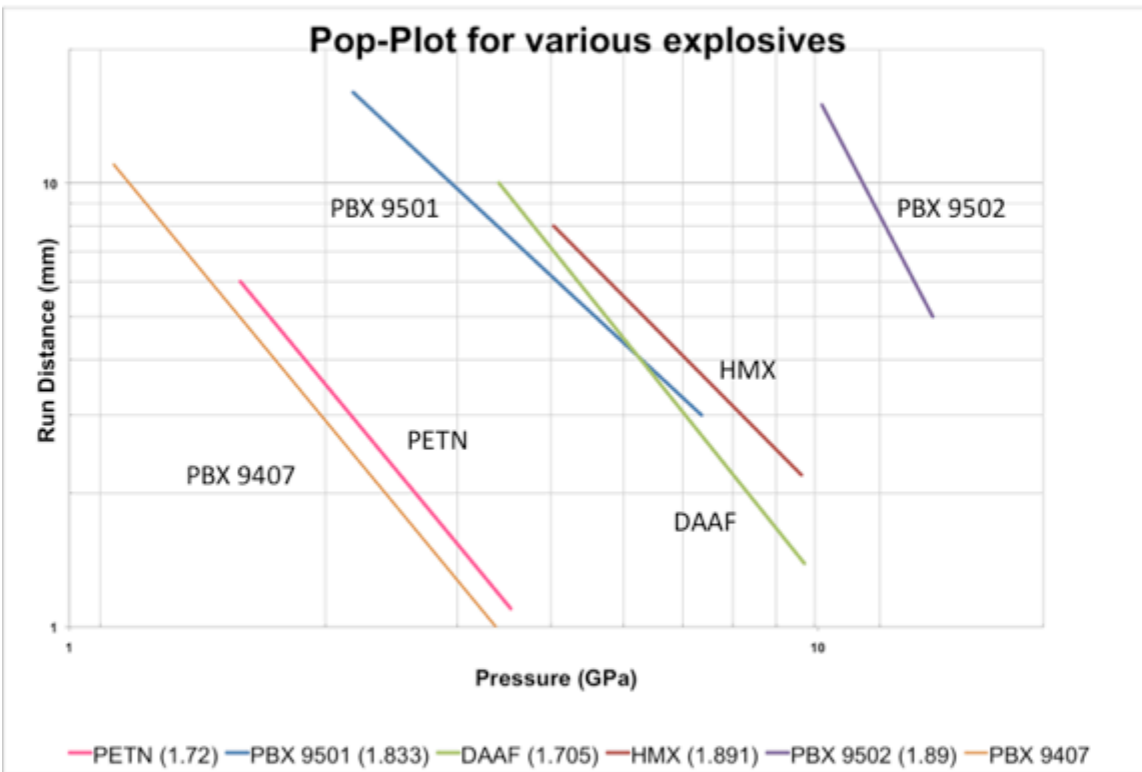


Figure 14: Pop-Plot for various popular explosives. Highly shock sensitive explosives are on the left. Sensitivity decreases to the right.

Figure 14 shows a Pop-plot for various explosives from those that are shock sensitive (left) to those that are shock insensitive (right). DAAF exhibits similar shock sensitivity to HMX and PBX 9501. This is surprising because DAAF is insensitive to impact, showing characteristics similar to TATB in the Drop Weight Impact tests. These data were produced using a mini wedge test [2] and while indicative of a particular behavior, do not possess the fidelity of embedded gauge test results. To verify these results, a series of single stage and two- stage gas gun shots were performed in 2010-

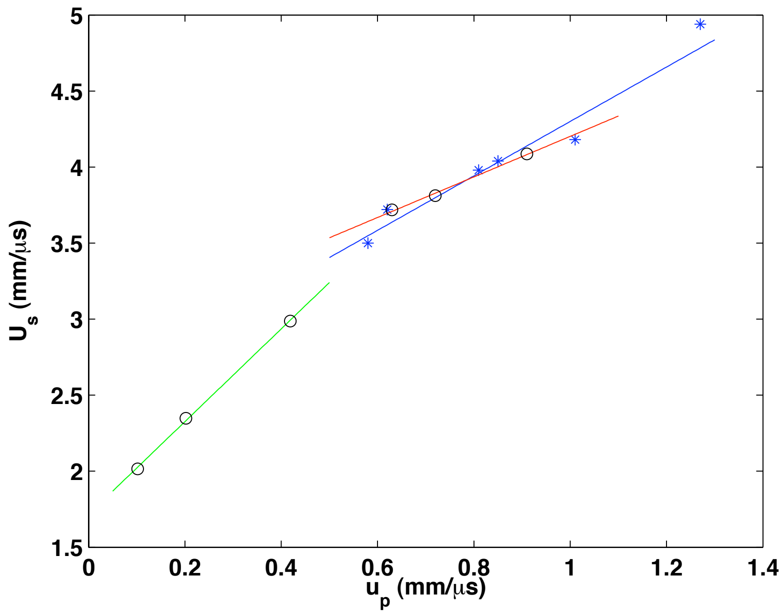


Figure 15: Particle velocity vs. Shock velocity Hugoniot for DAAF showing discontinuity at 40 kbar.

2011. The single stage test series was developed to see low pressure effects on the shock sensitivity of DAAF. It was of interest to see if DAAF transitioned at some pressure from being insensitive to low impact shocks to more sensitive to high impact shocks. Interestingly a transition was found. It appears DAAF has a shock induced phase transition at ~40 kbar (Figure 15). Anecdotal evidence has existed for years that DAAF does not exhibit a failing detonation. It simply goes or does not go at all. The existence of this asymptote at 40 kbar may support these observations and explain some of the asymmetric behavior seen in other tests [3,4,17,18].

While all explosives will exhibit the capacity to not initiate below a certain pressure threshold, the location of this asymptote at ~40 kbar is what makes this explosive interesting. This is reasonably common input shock magnitude. If below this threshold the explosive cannot initiate because it is in the wrong phase, this may have tremendous value in surviving bullet impact, fragment impact and shape-charge jet munitions tests.

4.1.2 Gap Testing

Two gap tests have been used to evaluate DAAF. Both give a measure of an explosive's sensitivity to shock by using a known input shock (donor) to initiate the test explosive (acceptor). Sensitivity is evaluated by varying the thickness of a solid "gap" to find where the explosive transitions from a "go" to a "no-go". The thinner the gap, the less sensitive an explosive is to shock. Both the LANL Small Scale Gap Test (SSGT) and the DoD IHE gap test were used. The IHE gap test was chosen because a wide variety of DoD explosives have been tested with this test and the data compiled [6]. This allows comparisons to be made between materials. Furthermore the IHE gap test gap thicknesses have been calibrated to an input pressure [6] allowing a more meaningful measure. IHE gap test results can be seen in 3.3.4. Further IHE gap testing is planned for 2012 where two particle sizes of DAAF will be evaluated with this test for the effects of porosity independent of density.

4.1.2.1 LANL SSGT

The LANL SSGT is shown in **Error! Reference source not found.** and measures the brass gap thickness required to allow an acceptor stack of explosive to "go" 50% of the time given an input stimulus from a RP-1 detonator and a PBX 9407 (94% RDX, 6% oxy-461) donor pellet. We wished to correlate DAAF shock sensitivity to the statistical data from previous LANL SSGT data for other common explosives. For these experiments DAAF of three particle sizes (80 μm, 40 μm and <5 μm) was pressed to two densities: 97% TMD (high density) and 91% TMD (low density) and tested for shock sensitivity. The <5μm particle size DAAF could not be pressed above 91% TMD and was not included in the high-density tests.

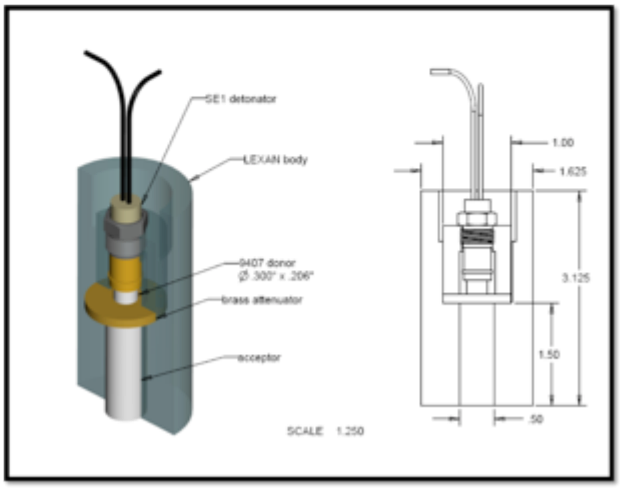


Figure 16: LANL SSGT fixture

To investigate the shock velocity and pressure required to initiate DAAF, a custom fixture was made. The detonator, donor explosive, and brass gap were the same as those used in the gap test; the area where the acceptor is normally placed was filled in with solid polymethyl methacrylate (PMMA). When backlit, the shockwave through the PMMA could be seen (**Error! Reference source not found.**). The velocity was read off of the streak image, and used to construct P-u Hugoniots for brass and relate them to PMMA and DAAF (Figure 18)

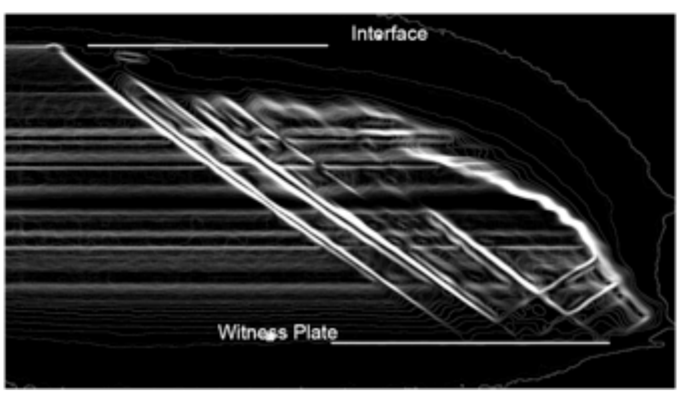


Figure 17: Streak image of shockwave through PMMA. The velocity at the brass-PMMA interface is measured and used to calculate the input pressure as a function of gap thickness. This is used to construct the P-u Hugoniot.

At high density (97% TMD) DAAF is less sensitive to shock, and the difference between the 80-micron DAAF and the 40-micron DAAF was dramatic (Table 14). At lower density (91% TMD) all materials were more sensitive than the high-density series, and slight differences based on particle size could be seen. The 50% point indicates a relative measure of the acceptor material's sensitivity to shock; the thinner the gap, the less sensitive the material. Table 14 LANL SSGT shows results for DAAF and a number of well-characterized explosives. HMX and PBX 9501 are included largely because Pop-plot data for DAAF (Figure 14) has shown it to be similar to HMX in shock sensitivity, and it can be seen that the brass gap thickness is comparable for low density DAAF and HMX. It is interesting to note that the brass gap thickness for PBX 9501 is around half the thickness for HMX, indicating that the 5% addition of binder has a dramatic effect on shock sensitivity. Future gap tests on DAAF will include a binder, and the desensitizing effects of binder inclusion will be evaluated. Furthermore, this behavior was seen in the floret testing, where larger amounts of binder caused the critical diameter to increase.

Material	Density (g/cc)	50% point (mm)	Initiation Pressure (GPa)
DAAF 40μm	1.69	1.91	**8.3**
	1.59	3.12	**4.5**
DAAF 80μm	1.69	2.74	**4.8**
	1.59	3.35	**4.5**
DAAF <5μm	1.69	NA	
	1.59	3.02	**4.5**
HMX (hot pressed)	1.84 1.79	3.43 4.27	
PBX 9501 (hot pressed)	1.843 1.825	1.3-1.8 1.52	
PETN	1.757	5.21	
RDX (hot pressed**)**	1.735	5.18	

Table 14: LANL SSGT results

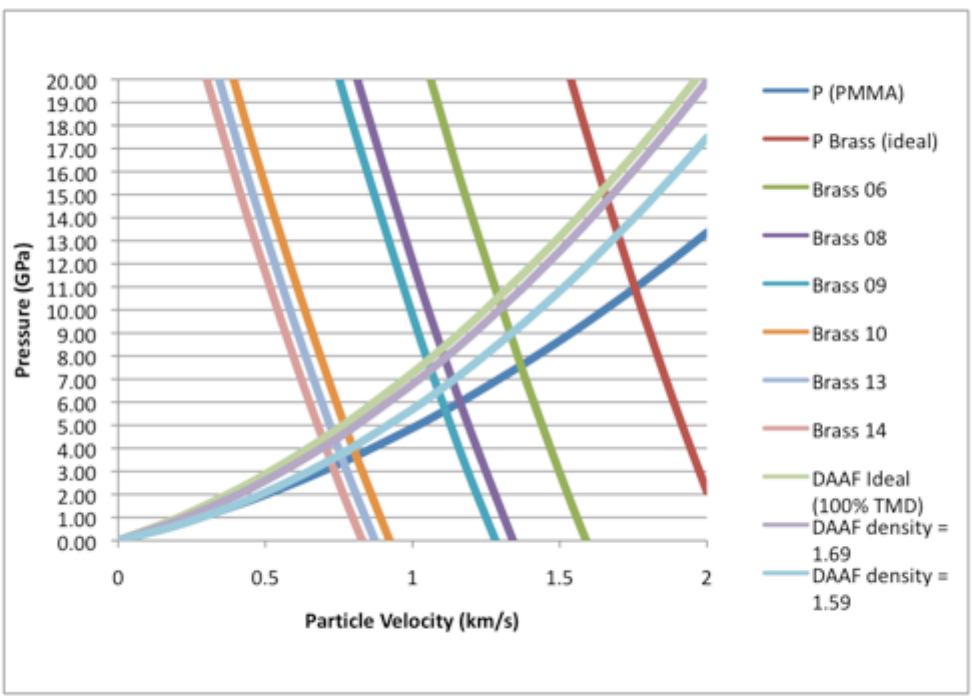


Figure 18: P-u Hugoniot for DAAF-Brass-PMMA interactions.

4.1.3 Critical Diameter

Critical diameter is an important trait for any explosive as it can be connected to safety characteristics and performance characteristics. Large critical diameter materials are safe, but more difficult to initiate and more material is required to sustain a steady state detonation. Small critical diameter materials are easier to initiate, require less material to sustain a detonation, but are considered less safe.

Losses of detonation velocity to edge effects exist for any explosive at any diameter, but don't predominate until a sufficiently small diameter is reached. Eventually a diameter is reached where edge effects predominate and the detonation velocity cannot be sustained causing failure. This diameter is called the failure or critical diameter. The easiest way to measure this threshold is with rate sticks of increasingly small diameters. However, high performing materials have small critical diameters (less than 2mm) and rate sticks of this size are difficult to make and field. Previous information on DAAF stated its critical diameter was less than 3mm due solely to limitations on available die sizes for pressed pellets. Based on DAAF's insensitivity to impact, experimenters were originally surprised that is had such a small critical diameter. Recently the critical diameter has been approximated as 1.32 mm using the floret test. Diameter effects and resulting detonation front curvature observations in booster materials were discussed in 3.3.6.

4.1.3.1 Floret Test Overview

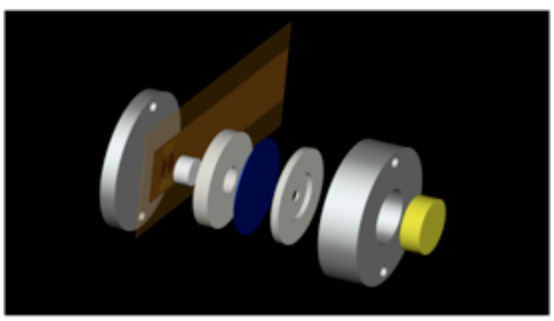


Figure 19: Exploded view of floret test fixture.

The floret test measures divergence and can suggest a "spot-size" or initiation point diameter to support full detonation. The "spot-size" can be used to approximate critical diameter. The Floret test is advantageous especially in early explosive development because it uses tiny amounts of material to evaluate detonation spreading. The test consists of an explosively driven flyer of a controlled diameter, which initiates the test explosive (**Error! Reference source not found.**). The completeness of the reaction is measured by a dent profile in a copper block. The minimum flyer size to allow a complete detonation can be correlated with the critical diameter. The floret test has proven useful when comparing IHE materials like TATB, PBX 9502, LX-17, and UF-TATB in several densities [20, 22, 23] and has been used to compare LLM-105 to TATB [21, 22]. Successful discrimination of particle size effects in TATB led us to believe the floret test could complement particle size work done with the LANL SSGT on DAAF. In addition, DAAF had been formulated with a variety of binders and amounts, and we wanted to observe the effects of binder content on divergence. In an effort to understand the effects of thermal and mechanical damage on PBX 9501, the floret test was redesigned to provide relevant data for more sensitive explosives than previously tested.

4.1.3.2 Floret Test Results

A set of parameters that allows divergence in DAAF to be compared has not yet been found. DAAF demonstrates an on/off behavior where, under these conditions, it either goes completely, or fails to start at all. The perfect set of parameters is still being sought. PBX 9501 has proven much more amenable to this test. The critical diameter of PBX 9501 is known to be less than 1.52 mm [13]. In order to develop a baseline for future damaged/aged PBX 9501 floret tests, a test matrix was performed to determine the parameters where divergence differences could be readily observed. The parameters investigated included density: PBX 9501 pellets were pressed to a density of 1.834 g/cc and 1.78 g/cc; Flyer material: aluminum and stainless steel; Flyer Diameter: 1mm, 1.32 mm, 1.5 mm, and 2 mm; Acceptor Diameter: ¼" and ½"; and Acceptor Height: 2 mm and 4 mm. The results for the ¼" tests can be seen in Figure 20 and demonstrate examples of a go and no-go, in addition to partial detonations where divergence can be compared. A 1.32 mm stainless steel flyer was chosen for the experiments because it showed similar divergence traits at high and low density.

To verify the test yielded meaningful results, a series was fired where the only parameter varied was density. All other parameters were fixed as follows: Flyer size: 1.32 mm; Flyer Material: stainless steel; Acceptor size: ¼" x 2 mm. Two pellets represented each density (Figure 21). The dent depths and profiles were measured and compared for shape, depth and width at half height. The higher density pellets were not able to react completely under these constraints and exhibited a smaller dent than low- density pellets. The best divergence is seen with a lower density pellet (1.774 g/cc) where the porosity facilitating lateral spreading of the detonation wave allowed the entire pellet to react. This should be compared to the high density pellet where performance should be better, but the lack of porosity causes poor divergence and the pellet is shattered by the flyer before it can react. Plotting dent depth as a function of density shows a local maximum at 1.774 g/cc (Figure 22) and will allow useful comparison when other parameters like damage and aging are introduced.

4.1.3.3 Floret Test and Approximations of Critical Diameter

The critical diameter of DAAF has been approximated to be 1.32 mm using the Floret test. Some comments on the veracity of this approximation are warranted. Using PBX

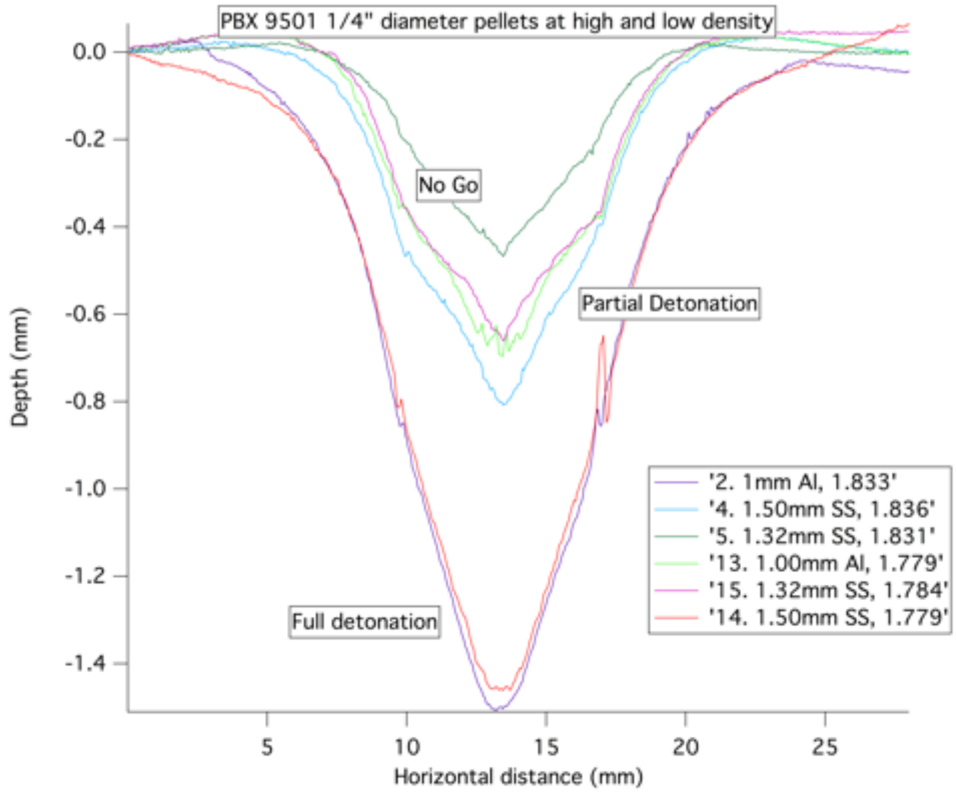


Figure 20: PBX 9501 parameter scoping series. Most favorable input parameters found when flyer is 1.32mm in diameter and made of stainless steel.

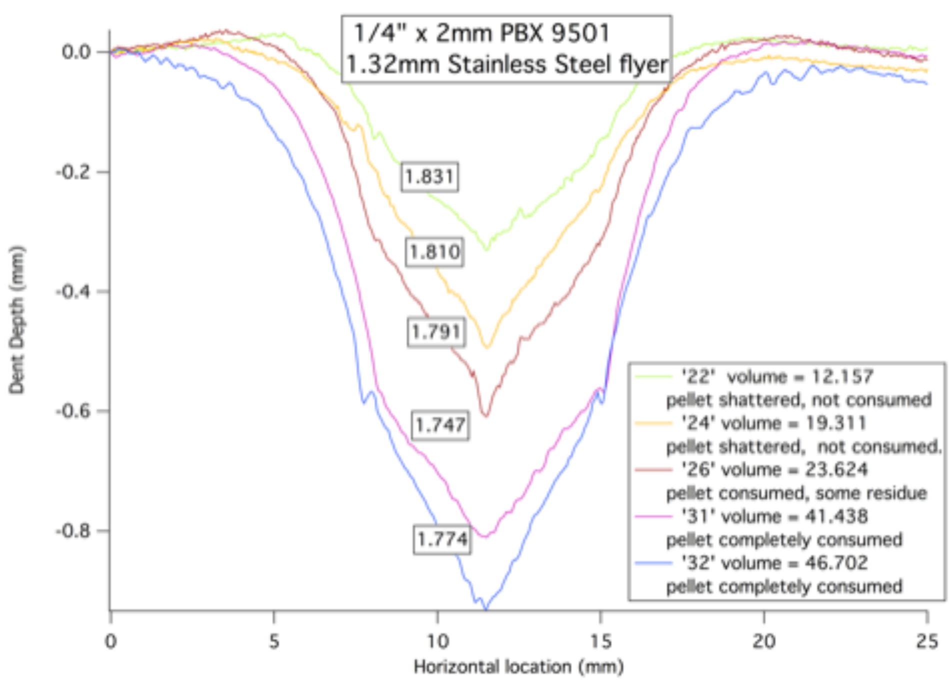


Figure 21: Using favorable input parameters exhibited in figure 18, density was varied to see the effect on detonation spreading. Greatest effect seen at density = 1.770g/cc

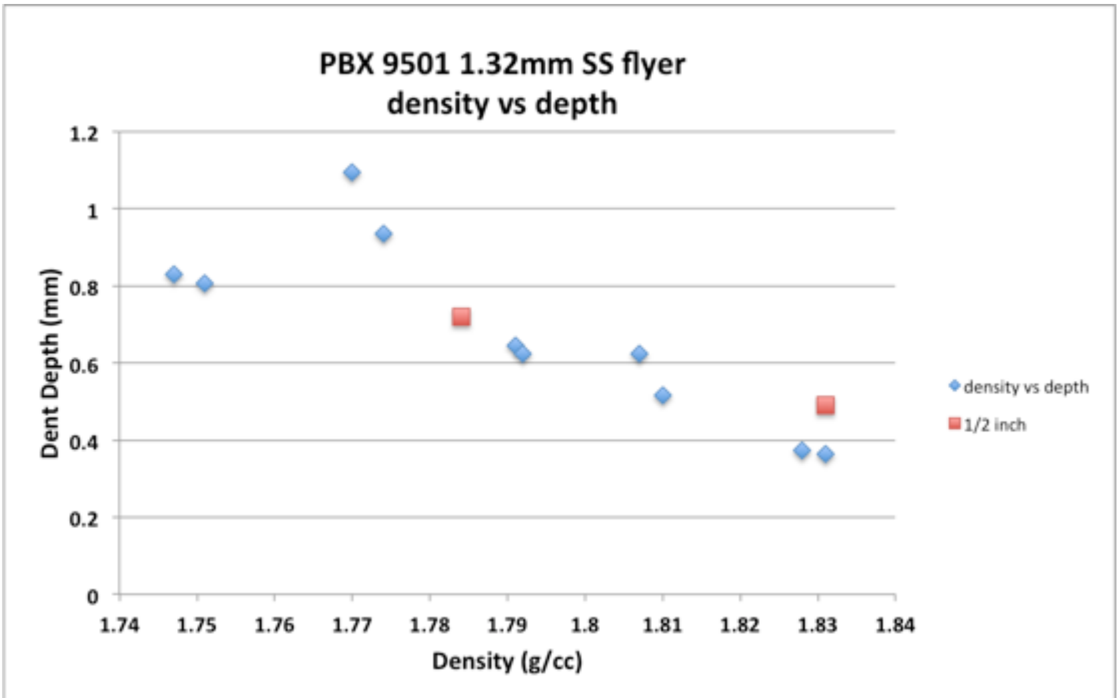


Figure 22: Dent depth as a function of density. Blue points represent 1/4" x 2mm pellets. Red points represent 1/2" x 2mm pellets. Maxima at 1.774 g/cc represents best divergence.

9501 as an example, it is stated that the "experimentally determined failure diameter is slightly less than 1.52 mm" [13] at a density of 1.832 g/cc. Figure 21 shows the difference in energy between a density of 1.831 g/cc (which is close to failure) and a density of 1.774 g/cc (which is detonating completely) using a 1.32 mm stainless steel flyer. Figure 20 shows the effect on a pellet of 1.836 g/cc hit with a 1.50 mm stainless steel flyer. It reacts more completely but still shows poor divergence, suggesting a failing detonation. One could surmise the largest flyer demonstrating poor divergence may approximate the failure diameter *at that density*. Using similar logic on DAAF at high density (1.685-1.689 g/cc) shows complete failure to initiate with a 1mm stainless flyer, and close to a complete detonation with a 1.32 mm stainless steel flyer. Based on these results the critical diameter is approximated to be ~1.32 mm *at this density*.

4.2 Main-Charge Initiation Characteristics

Ultimately the goal of all explosives is to do work. The booster serves as a vital step to initiate the main charge and do the required work. How well the main-charge initiates and how well the reaction propagates and spreads requires an evaluation of behavior over a surface or through a volume. Evaluation of the detonator, booster and main charge can be seen with the Onionskin test, which is a surface detonation wave breakout test. It serves as the quintessential booster evaluation test, but what is actually observed is the main-charge. This section will discuss Onionskin results and test improvements.

4.2.1 Main Charge Initiation Merit

The Onionskin test is a hemispherical wave breakout test used to evaluate the corner turning performance of booster materials, to qualify lots of PBX 9502, and evaluate novel detonator designs against historic test results. This test has existed for decades and evaluates the performance of the initiation train by observing breakout over a small, one-dimensional slice of a hemispherical surface. It can be used to ascertain temperature effects on the initiation train and has been fielded over a wide temperature range: +70^{o}C through -55^{o}C. It has been stated that this test allows "quick" comparison of booster materials based on performance metrics such as breakout angle, spreading efficiency and excess transit time [17]. However, "quick" only applies to the comparison of data, the Onionskin test is fairly complex to field. The Onionskin is a LANL test and, in general, refers to a hemispherical breakout test 50-50.8 mm in diameter utilizing PBX 9502 as the main charge and a variety of boosters in different sizes and shapes [17]. LLNL has an analogous test called the Snowball, which can use Ultra-Fine TATB as the booster and LX-17 as the main-charge. The Snowball uses a larger booster and subsequently, a larger main-charge to allow full run up to detonation [2].

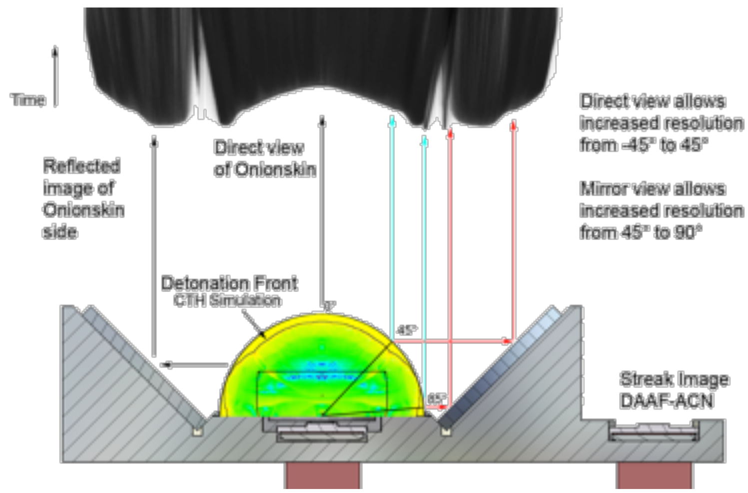


Figure 23: Onionskin fixture and resulting streak image. Mirrors are used to capture the breakout behavior from 45 degrees to the equator. Direct view can be used from pole to 45 degrees.

The standard to which all LANL boosters are compared is a LX-07 hemispherical booster housed inside a PBX 9502 shell. There is some variation in shell thickness and shape depending on the test design and detonator choice. The detonator can vary from an Exploding Bridge Wire (EBW) to a slapper. A streak camera captures the breakout of the detonation front as oriented to the pole of the HE hemisphere, and the results and fixturing can be seen in **Error! Reference source not found.**. Mirrors on the side capture the wave breakout from 45 degrees to the equator. With these two types of views, detonation behavior can be seen over a 180-degree swath, but limited by the constraint that the data collected is just a narrow line over the surface (**Error! Reference source not found.**).

4.2.1.1 *Previous Onionskin Work on Replacement Boosters*

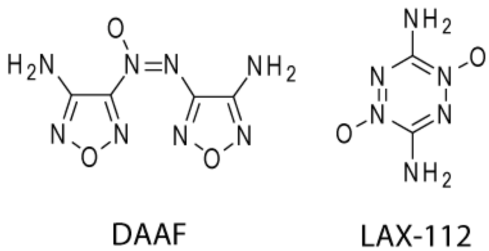


Figure 24: DAAF and LAX-112 molecules.

In order to increase the safety margin in existing systems, replacement of existing boosters (LX-07) with something less sensitive is discussed periodically. The last time this issue was raised, a modified onionskin was developed and fired to evaluate more insensitive materials. The modification was replacing the 30 mm diameter hemispherical booster with a 30 mm diameter by 10 mm tall cylindrical booster. The materials tested in this configuration included LX-07 (with and without orange dye), DAAF, PBX 9504 (70% TATB, 25% PETN, 5% KelF-800), UF-TATB, LAX-112 and 5% KelF-800, LAX-112 and 10% Viton. The detonator used was an ER 400 in a flyer configuration. The detonator was set at a standoff distance of 1.651 mm from the booster pellet, and its 0.165 mm thick aluminum flyer was sheared by the fixture to a diameter of 5.766 mm. The velocity of the flyer at impact with the booster pellet was 3.75 ± 0.25 km/s. The booster pellet was mounted in a 50 mm outer diameter hemisphere of PBX 9502. The assembly was cooled to -55°C in an insulated chamber prior to firing by flowing nitrogen gas over liquid nitrogen with an inline heater for control. Ramp rates were controlled at 0.5°C/min. The temperature of the gas inlet and of four locations on the charge assembly were monitored and recorded, and the assembly was soaked at the final temperature for a minimum of 30 min. The low temperature of firing emphasizes variations in spreading performance and wave perturbations. The breakout from the fiducial detonator and the surface of the main charge was recorded on a Cordin model 132 streak camera operating at a write speed of 12 mm/μs. A still image of the experiment was taken on the same film prior to firing. The experiments were fired in an enclosed firing vessel.

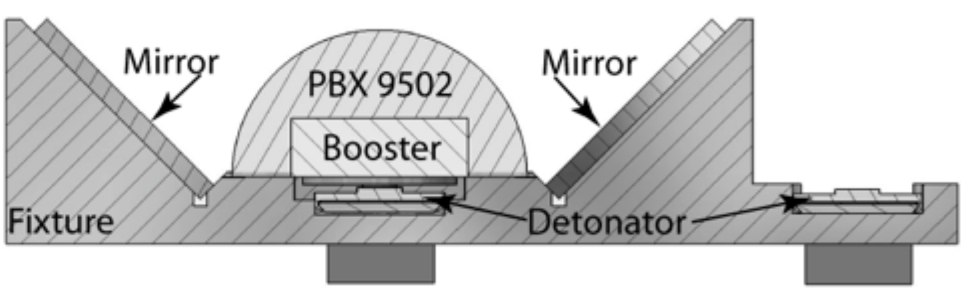


Figure 25: Cutaway view of the experimental assembly showing the complete charge on the aluminum fixture.

4.2.1.2 Modified Onionskin Test Results

The LX-07 booster performed the most ideally, as expected, and the addition of dye to the formulation made no observable difference. The DAAF showed very promising results in terms of detonation spreading, but exhibited slightly perturbed waves indicative of either material uniformity problems or detonation wave reflections at the corners of the booster pellet due to density and/or detonation velocity mismatch with the PBX 9502. The PBX 9504 also exhibited some small perturbations, and otherwise performed well. The UF-TATB exhibited hole-punching behavior, in which the center of the charge ignited but the detonation did not spread. This was to be expected, an UF-TATB booster at this temperature should be larger to allow the required run distance. Finally, both of the formulations including the LAX-112 molecule completely failed to ignite in the tested configuration, and therefore no data was obtained. A comparison of all streak records can be seen in **Error! Reference source not found.**. Comparisons of various figures of merit can be seen in Table 15.

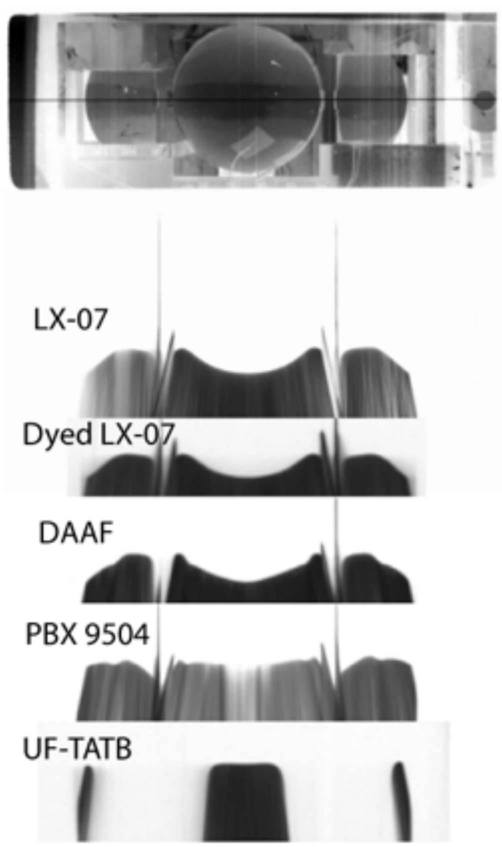


Figure 26: Scanned films for all successful experiments. Writing speed is 12 mm/μs

The simple change in experimental design from a hemispherical to a cylindrical booster had observable consequences. While the manufacture and assembly of parts was simplified, the analysis approach was complicated by the flattened waves.

The PBX 9504 and DAAF results were quite promising. Spreading performance and initiation of the PBX 9502 proved reliable even at the low temperature at which the tests were performed. However, the wave shape perturbations are of concern and merit more study. PBX 9504 has been known to be a challenge in formulation; the disparate solubility of PETN and TATB can cause uniformity issues in formulation and pressing. Purity, particle quality, and uniformity issues have been noted in DAAF as well [7, 8]. In fact, a new synthetic route and recrystallization procedure have been developed to improve these features. While these uniformity issues could be problematic, it is more likely that the perturbations were caused simply by wave reflections due to "impedance" (initial density and detonation velocity) differences. These differences may not matter as much if the geometry of the booster matches that of the desired wave spreading geometry. For this reason, future experiments will focus on formulation and pressing changes for PBX 9504 and DAAF in a hemispherical geometry.

Material	FBA (degrees)	Spreading Efficiency	COI (mm)	Excess Transit Time (ms)	Comments
DAAF	69.8	0.78	-3.64	0.27	Small Perturbation
PBX 9504	64.7	0.72	-0.74	0.14	Small Perturbation
Dyed LX-07	62.3	0.69	-4.77	0.27	Nominal
LX-07	64.5	0.72	-5.10	0.04	Nominal
UF-TATB	14.8	0.16	-1.38	.021	Hole Punching
LAX-112 / Viton A	---	---	---	---	Failure
LAX-112 / Kel-F 800	---	---	---	---	Failure

Table 15: Onionskin results showing figures of test merit. First Breakout Angle (FBA) measures where the detonation wave first exits the hemispherical surface. The closer to 90 degrees, the better the corner turning. Spreading Efficiency is the FBA divided by the ideal solution (90^o). Center of Initiation (COI) is an assumed initiation point based on Huygens wave reconstruction and is used to model the initiation train with out the complexities of actually modeling each component.

All cylinders for these shots were pressed to shape. Later it was discovered the cylinder ends were not parallel to each other. The significance and consequence of this is unclear, but it was decided all future shots would use more care with pressing and machining. A concern arose that the detonator was not normal to the booster face because of the wedge shape of the booster.

4.2.2 The next round of Onionskins

The next series of Onionskins was fired between 2008 and 2009. The goal of these shots was to examine the effect of booster geometry on the detonation wave shape, symmetry and FBA. PBX 9504 was not included in the test series because, although it had extremely favorable performance characteristics, it was too difficult to formulate and it aged poorly. For this series DAAF was formulated with 3% KelF- 800. This allowed the material to be machined, and still exhibit reasonable performance characteristics.

Shot name and material	Geometry	Density	FBA (degrees)	Comments
5-0020 DAAF	Hemispherical	NA	72.3	Machined Hemisphere. Asymmetrical breakout, slow pole
5-0026 DAAF	Hemispherical	NA	71.3	Machined Hemisphere. Asymmetrical breakout, slow pole
Assembly-2 DAAF	Hemispherical	1.6749	NA	Pressed hemisphere Large Asymmetry
Assembly-3 LX-07	Hemispherical	1.8421	74.9	Baseline Pressed Hemi
Assembly-4 LX-07	Cylindrical	1.845	66.2	Machined cylinder
Assembly-5 DAAF	Cylindrical	1.662	69.2	Machined cylinder
Assembly-6 DAAF	Cylindrical	1.684	68.4	Machined cylinder
Assembly-7 DAAF	Cylindrical	1.676	68.0	Pressed piece, machined ends

Table 16: Onionskin shot details

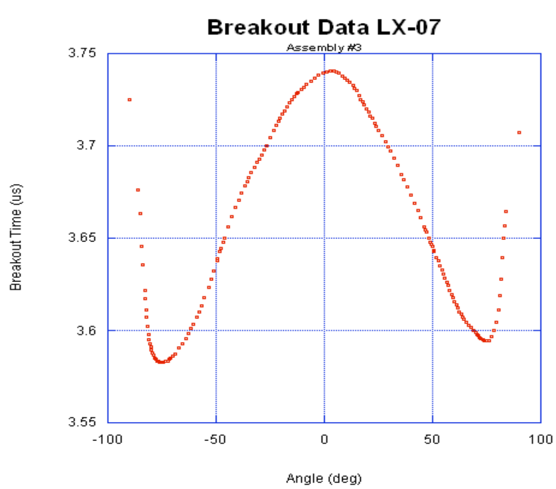


Figure 28: Hemispherical breakout timing plot. Difference in time from FBA to pole is approximately 0.16 us.

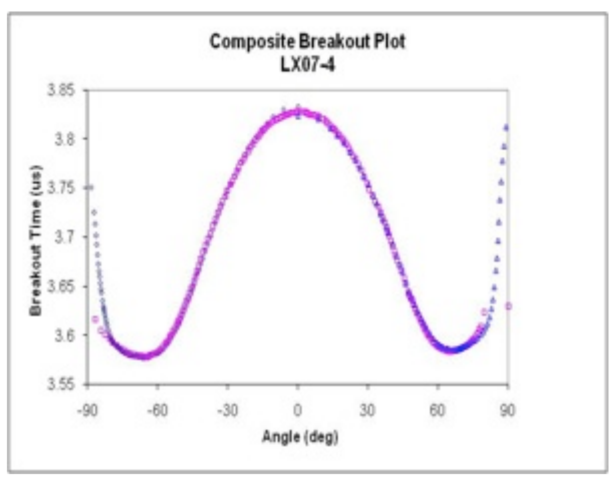


Figure 27: Cylindrical breakout timing plot. Difference in time from FBA to pole is 0.27us

4.2.2.1 Test details

Similar to previous onionskins, the current tests were fired cold at -55°C, and all used paired ER-400 slapper detonators to initiate the shot and serve as a timing fiducial. All machined cylinders were taken from a larger pressed piece. Density gradients existed from top (lowest density) to bottom (highest density). Table 16 lists the details and densities of each shot. Assemblies 5 and 6 came from the same piece and the density between them is significantly different. During the HE machining process all parts were radiographed. In the DAAF pellets, anomalous high-density regions existed. This suggests some inhomogeneity within the pellets, but the overall effect was impossible to ascertain as DAAF had never been radiographed before and that feature may be typical. Assembly 7 used a different approach, the part was pressed to shape, diameter-wise, and the ends were machined flat and parallel to each other.

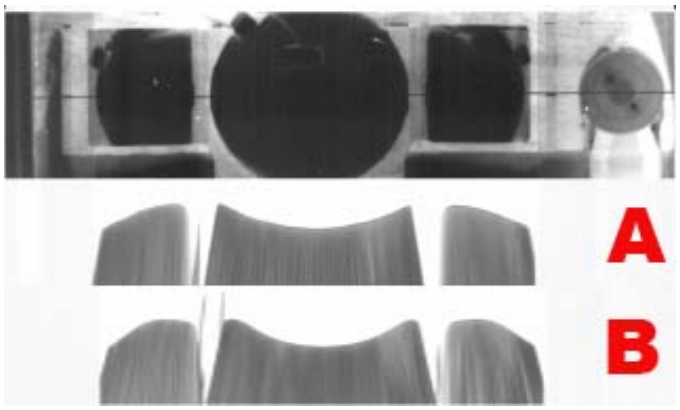


Figure 29: LX-07 geometry comparison. A represents a hemisphere, and B a cylinder. The detonation wave shape is slightly affected by geometry. First break out is also affected: 74.9° for A and 66.2° for B

The goal of the shot series was to compare the geometrical effects on the detonation wave breakout. In order for DAAF to be a suitable booster candidate, when compared to LX-07, the wave shape, timing, and FBA had to be within one standard deviation of each other. As a statistically significant sample had not been fired to allow a determination of the standard deviation, close similarity in the metrics of interest was sought. The effects of density on the detonation wave were also evaluated. Assemblies 3 and 4 were compared for geometry effects in LX-07; these in turn were compared to Assemblies 2 and 7 for geometry effects in DAAF. Assemblies 5 and 6 could be compared for density effects in DAAF. Assemblies 5, 6 and 7 were to be compared to see if homogeneity is important.

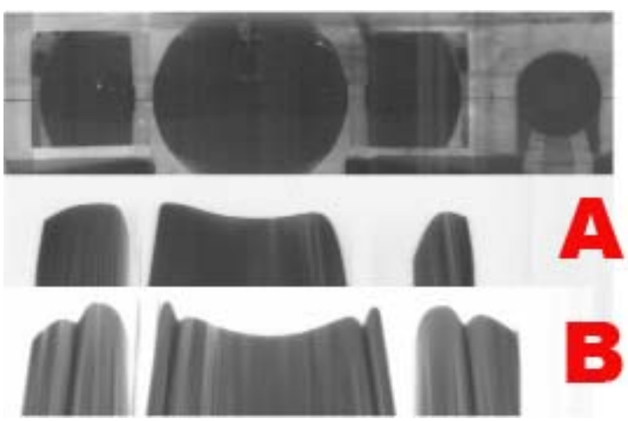


Figure 30: DAAF geometry comparison. A represents the hemispherical booster, and B the cylindrical booster. "Ears" seen in B correspond to interactions stemming from the booster corners.

4.2.2.2 Results of Geometry

Comparison of LX-07 in assemblies 3 and 4 shows a geometry effect (**Error! Reference source not found.**). While the timing for FBA was similar for cylindrical and hemispherical shots, the time difference between FBA and the lag at the pole was most favorable for a hemisphere. The observation is not surprising as there is more PBX 9502 in the cylindrical configuration at the pole for the detonation wave to move through before exiting the charge. From a design perspective this difference may add additional challenges.

It is more difficult to compare geometry differences in DAAF as seen when comparing assembly 2 and assembly 7. The results can be seen in **Error! Reference source not found.**. This result highlights the largest weakness in the Onionskin test: only a portion of charge is observed. The relevance of that asymmetry cannot be gleaned from this test. What if the charge were rotated in the fixture by 45^o, 90^o, etc.? Would the phenomenon look different, better, worse, be missed completely. Furthermore, what is causing the asymmetry? What contributions do material characteristics, assembly, detonator centering, density gradients etc. have on these observations?

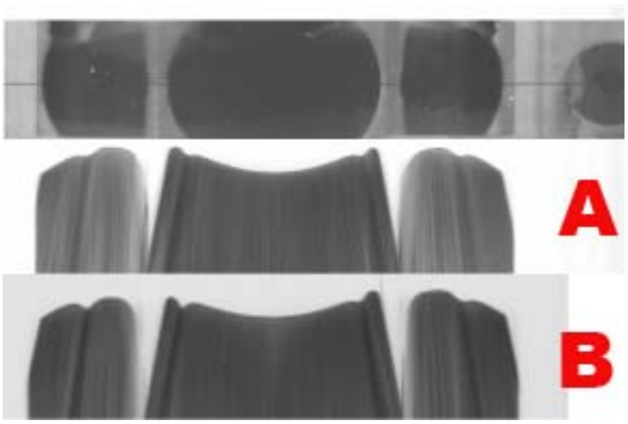


Figure 31: Density comparison of cylindrical DAAF pellets which were machined from the same larger piece. A shows the higher density cylinder (1.684g/cc) and B shows the lower density cylinder (1.662g/cc).

4.2.2.3 Results of Varying Density

Assembly 5 and assembly 6 used cylinders of DAAF machined from the same larger piece. Density gradients often exist in larger pressed pieces and this comparison was important to establish whether density had an effect on breakout wave characteristics, and whether parts from the same whole had similar characteristics. Assembly 6 had a density of 1.684 g/cc and was from the bottom of a 3” diameter by 2” tall pellet. Assembly 5 had a density of 1.662 g/cc. and was from

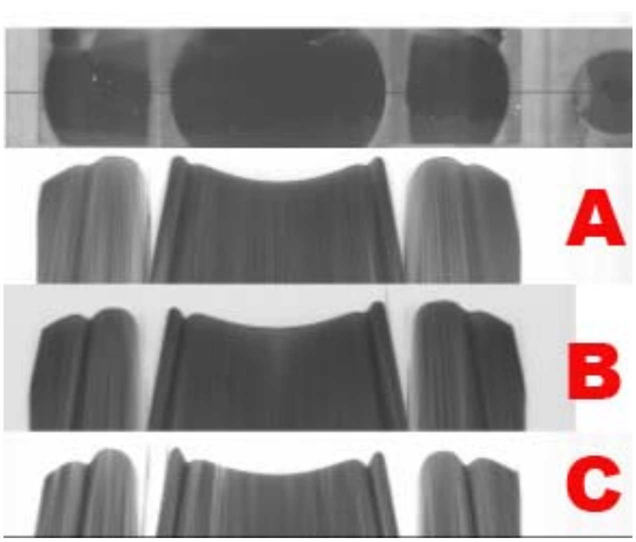


Figure 32: Comparison of results for homogeneity. Assembly 5 and 6 (A & B) did not have high-density regions. Assembly 7 (C) did. For the most part, in this testing method little difference is seen.

the top of the larger pellet. The results can be seen in **Error! Reference source not found.**. FBA is not affected significantly by density as seen in Table 16.

4.2.2.4 Results of Homogeneity

Assemblies 5, 6, and 7 can be compared for homogeneity. The observation that certain pellets had high density portions was a source of concern. The source of the high density regions was unknown. The binder in all examples was KEL-F 800, which has a density of 2.01 g/cc vs. DAAF, which, by itself, has a density of 1.747 g/cc, but this difference is too small to account for the observations. **Error! Reference source not found.** shows the comparison of Assembly 6 (A), Assembly 5 (B) and Assembly 7 (C). No appreciable difference stands out, leading to the conclusion that high-density regions have little or no effect on the output. The shape of the streak record in all cylindrical shots, DAAF and LX-07 suggests that some wave interaction is occurring at the booster corners. Other geometries have been proposed (taller, with a smaller diameter) but they will not be pursued at this time.

4.2.2.5 Conclusions

In almost every case involving an explosive other than LX-07, more information from this test is needed. The relevance of asymmetry, tilt, and unusual features cannot be adequately resolved or explained when only a small slice of the surface is observed. A new test is needed where detonation wave behavior over the entire surface is observed.

4.2.3 Onionskin Test Redesign

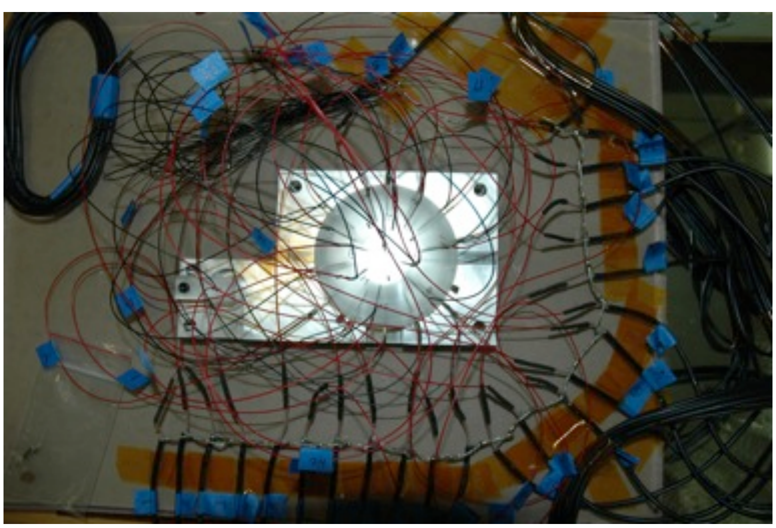


Figure 33: Hairball test fixture showing pin arrangement.

Two tests were developed using different diagnostics. First, the Hairball (**Error! Reference source not found.**) was designed as an array of shorting pins over the PBX 9502 hemisphere surface. Time of arrival data was collected from the pins with oscilloscopes. Second, the Furball was designed to use fiber optics arrayed over the surface. The diagnostic was a streak image of the fiber ends where the time of arrival could be spatially resolved.

Analogs to the Onionskin and Snowball tests were fielded. The Onionskin-type test was a 30mm diameter LX-07 hemispherical booster inside a 50 mm diameter PBX 9502 shell. The density of the LX-07 was 1.845 g/cc and the density of the PBX 9502 was 1.890 g/cc. The Snowball-type test was a 38 mm diameter UF-TATB hemispherical booster inside a 61 mm diameter LX-17 shell. The density of the UF-TATB was 1.80 g/cc and the density of the LX-17 was 1.90 g/cc.

4.2.3.1 Hairball test design

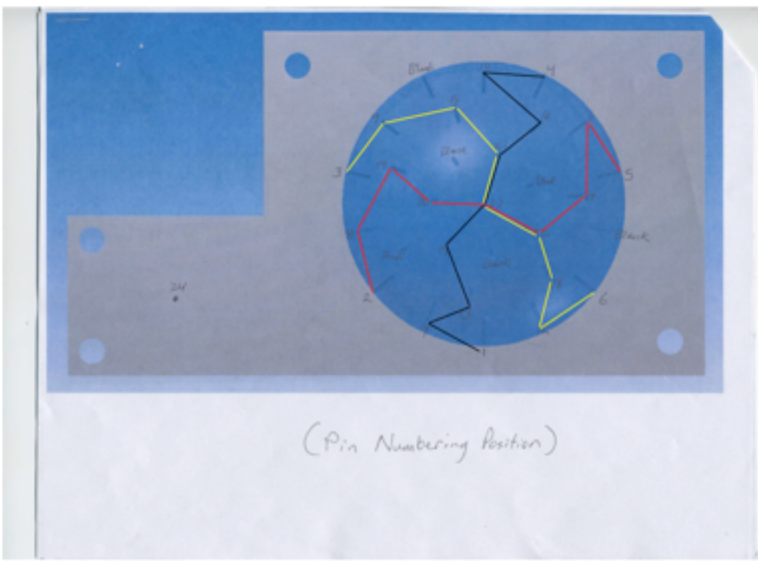


Figure 34: Pin arrangement to generate "w-plots". Tortuous path between the pins can be seen.

The test used ER-400 detonators in pairs: one as a fiducial, one to initiate the shot. This is a well-studied slapper detonator. A shorting pin was positioned above the fiducial detonator to establish T_o. We used Dynesen shorting pins, which were x-rayed to measure the internal standoff. Each test used pins with the same internal standoff to minimize timing errors.

Four Hairball tests were planned, all at ambient temperature. The first was intended to be a calibration shot where an Onionskin configuration was fired and the results were compared to similar historic data [17, 23]. Agreement within the data sets would demonstrate the test's validity. Three UF-TATB/LX-17 shots were fielded and the results compared. While the goal was to observe anomalous behavior, it was unclear what the magnitude of this behavior would be. As a result it was critical to understand, measure and account for all timing differences between the pins, cables, scopes, individual scope channels, patch panels, pin boards etc. Knowing the timing errors of all components provided confidence in the data. In general the magnitude of the error inherent in the system as a whole was +/- 10 ns.

4.2.3.2 Hairball Results

Originally, the easiest way to visualize the results was to plot the time of arrival data in the familiar "w-plot" where the timing associated with each pin is plotted against the polar angle. This can be accomplished by choosing points over the surface of the Onionskin that roughly describe an 180^o arc. The pin placement was not designed with this activity in mind so the path from one side to the other was tortuous. **Error! Reference source not found.** shows the paths associated with each w-plot. The results are shown in **Error! Reference source not found.**. In typical fashion, for a Snowball-type test, the first break out is around 45^o and the pole and equator lag. Some tilt and spatial asymmetry is seen. It is on the order of 20-30 ns and is within the measurement error.

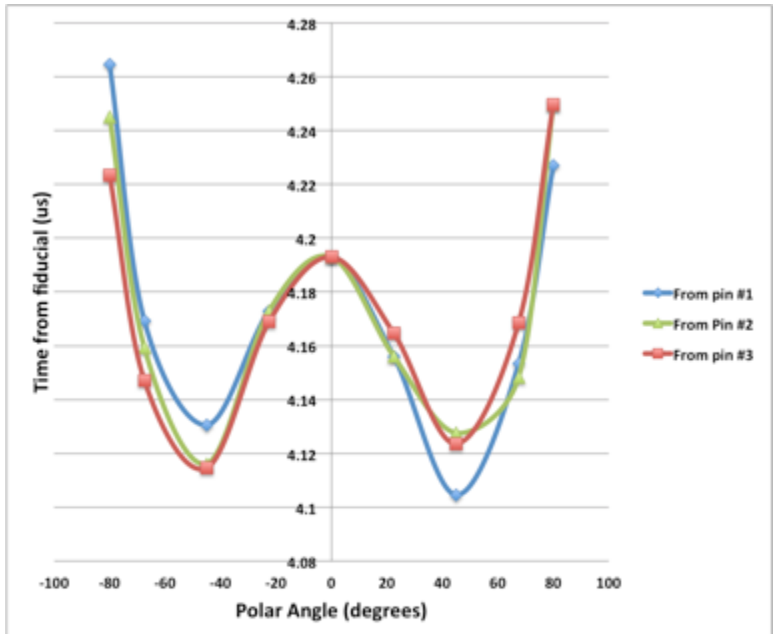


Figure 35: Results showing "w-plots" using the pin arrangements seen in Figure 34.

4.2.3.3 Furball Test design

The Furball test was designed using the logic: "If 3 tortuous w-plots based on a few points is good, 4-6 w-plots based on hundreds of points must be better". The Furball design used fiber optics to capture spatially resolved time of arrival data with a streak camera. For these shots 250 micron fishing line was used. A Lexan shell was machined with holes for the fibers spaced 5 degrees apart, pole to equator, and azimuthally 45 degrees apart for the Onionskin and 30 degrees apart

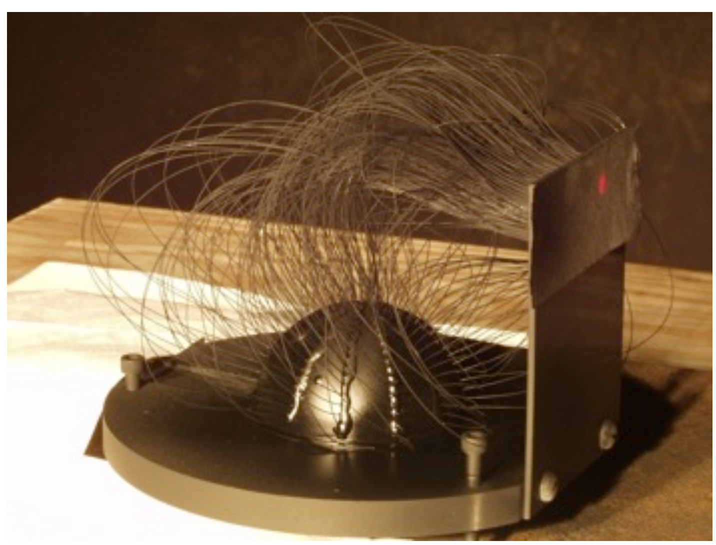


Figure 36: Furball test showing the fiber arrangement and the plane imaged by the streak camera. The shot was painted black to prevent some light loss.

for the Snowball. By arranging the points in bisecting lines through the pole, a family of w-plots was expected.

The ends of the fibers were pushed into the Lexan hemisphere until touching the surface of the HE charge. The other end was inserted into a plate oriented to face the streak camera (**Error! Reference source not found.**). The fibers were cut off flush to the fixture with a razor blade. Neither end was polished. Before firing, the shots were painted black to prevent light from escaping. Two tests were planned: one 50mm Onionskin test using a 30 mm LX-07 booster inside a 50 mm PBX 9502 shell, and a 61 mm Snowball test using a 38 mm UFTATB booster inside a 61 mm LX-17 shell. Both shots used paired ER-400 detonators.

4.2.3.4 Furball test results

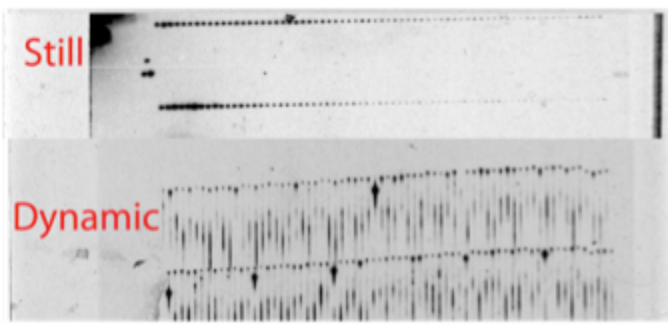


Figure 37: Streak records from a 50mm shot showing the still image compared to the dynamic image. A distinct spatial time lag can be seen.

Keep in mind that the intent of these shots was to record a relative time of arrival. The fiducial records T_o, and the data of interest is the time recorded at each location *relative* to the fiducial. Analysis of the streak record was fairly straightforward and can be seen in **Error! Reference source not found.**. The relative distance of each point to the fiducial, and from the still image, allows time of arrival at each discreet point to be determined.

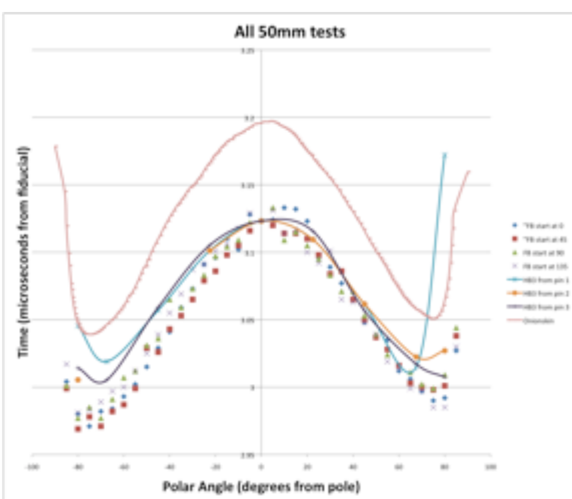


Figure 38: W-plots from 50 mm Furball shot (points). Also included is the Hairball results (overlaid solid lines) and historic Onionskin test (pink).

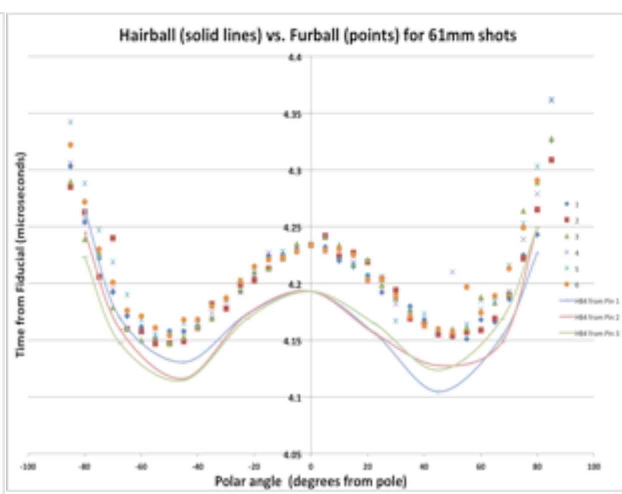


Figure 39: Results from 61 mm Hairballs and Furballs showing absolute time of arrival values. Comparable timing results for different diagnostic methods are favorable.

Similar to the Hairball analysis, w-plots are generated describing the surface.

The test results of the 50 mm Furball test can be seen in Figure 38. Aside from the tilt, which is thought to be due to shot orientation, the Hairball and Furball results agree extremely well. The results of the 61 mm Hairball and Furball can be compared in Figure 39. The data agreement from these two tests is especially favorable despite the very different diagnostics and fiducial measurement techniques. For comparison to a standard 1D Onionskin representation, it is adequate to plot the results as a series of w-plots (time vs. polar angle). It seems wasteful to collect data from the entire surface and then reduce it to a series of overlaying x,y plots. A 3D visualization tool was developed to address the breakout time as a function of location. The method used Matlab to fill in the surface on those plots. It uses a linear interpolation between the nearest points to come up with a new value for each location on the circle [3]. The locations are defined using phi and theta in spherical coordinates. The results for the 50 mm furball can be seen in Figure 38. Red defines early time, and blue late time. The temporal difference between the time extremes is 14 ns. The results for the 61 mm Furball are seen in Figure 39. First breakout clearly occurs around 45 degrees and breaks out evenly over the hemisphere. The difference between time extremes on this shot is 20 ns.

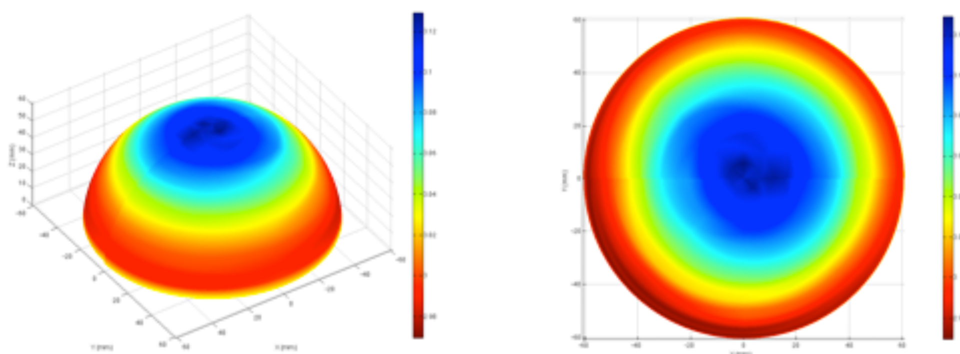
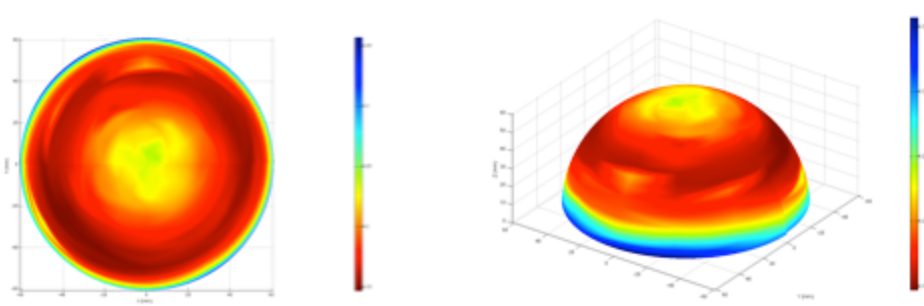


Figure 38: 3D visualization image of 50 mm Furball, showing symmetric breakout. Time axis shows early time events as red, and late time events as blue. First breakout Angle can be clearly seen near equator, suggesting corner turning advantages.

Figure 39: 3D visualization of 61 mm Furball showing small localized asymmetries, but largely symmetric behavior overall. FBA first seen at 45 degrees



4.2.3.5 Conclusions/Observations

Successful comparison of these data to a historic Onionskin test allows validation of these techniques and can be seen in Figure 38. A distinct difference between these tests and the historic Onionskin is temperature: the Hairball and Furball were tested at ambient and the Onionskin was tested at -55^{o}C. This may account for timing discrepancies. The shape of the W-plots is comparable, however. The Hairball and Furball Snowball-type test results compare extremely well, both in shape and arrival timing as shown in Figure 39. The need for a surface map of detonation breakout and symmetry in the Onionskin or Snowball tests has been recognized for decades and a considerable amount of research has been expended in this endeavor. We propose that either of these techniques are a valid solution. Significantly more involved tests exist that can give a measure of the internal behavior of the detonation wave through a charge: consider PRad or DARHT, but these aren't necessarily available early in the research of a new material. Further development of these tests will occur, and should shed light on the reliability and behavior of explosive systems through observation of symmetry over an entire surface. While the view of the first break out and detonation wave symmetry of the test has increased from 1D to 2D, the analysis method is similar to the onionskin. Additional analysis complexity is not introduced by these experimental designs.

5 Summary and Conclusions

When considering performance and safety changes to a nuclear weapon or standard munitions, the booster is often an obvious choice. It needs more energy, or the safety margin associated with it needs improving, or occasionally both. These can be daunting requirements, and a systematic approach is needed to evaluate any change of this nature.

This report introduced a test plan developed through collaboration between LANL, LLNL and AWE outlining the important parameters boosters needed for comparison. Much attention has been given to the fact that TATB based formulations (PBX 9502, LX-17) are qualified as Insensitive High Explosives (IHE) by the DOE Explosives Safety Manual (28), which results in lessened testing constraints to satisfy safety concerns. Much booster work is associated with showing newer materials are insensitive as well and the proposed test plan was designed to test all materials on a level playing field so they could be compared objectively. Previous test plans do exist which were used to qualify the existing IHEs and other explosives used in nuclear weapons. Many of the included tests are obsolete, so care was used in the development of this test plan that it addresses important booster traits, in addition to required tests. By identifying the parameter of interest (shock sensitivity, DDT propensity, etc.) and only suggesting a representative test, the test plan allows for change over time as the world modernizes.

The approach to booster development and qualification was tested in a 2009 DoD JIMTP project to seek a replacement formulation for PBXN-7, a booster widely used by the DoD. In this case, the booster requirements were much less stringent then they are for DOE weapons. The booster needed to perform better than PBXN-7 and PBXW-14 in velocity and cold temperature initiation characteristics. It needed to show favorable cook-off behavior. A burn result was sought at all confinements. Lastly it needed similar shock sensitivity to the materials it was replacing so it could be simply dropped into munitions and not require any changes to the detonator. This significantly reduced the amount of testing over what was suggested in the first section. It was possible to develop formulations, containing DAAF that showed improvement in all performance characteristics over the DoD explosives. The DoD found the conclusions of this project favorable enough to continue the development work on these formulations at higher levels of funding and oversight. The end result will be full-scale munitions testing with the formulations described in this report. Cold temperature performance test development was an area where great strides were made to understand the shortcomings of TATB and show improvement with DAAF. Future booster work will make use of these tests to show diameter effects on detonation velocity and detonation wave shape.

Booster material development requires addressing what happens previously in the initiation train, and what happens after. The final section of tis report addressed the testing done to investigate booster initiation, and the effects the booster has on the main charge. Much of the novel work has been done in these areas. Understanding the unique initiation behavior of DAAF, as seen in the gas-gun shots, may allow for the realization of an explosive with on/off capability. While all explosives cannot initiate when the input pressure is too low, the location of the DAAF on/off switch is in a very useful pressure regime. Many DoD explosives cannot pass a bullet impact test or a fragment impact test. Future tests on DAAF subjected to bullets and fragments of velocities between 6800 and 8000 ft/s with different amounts of shielding will be telling. Developments in 2D surface mapping of detonation behavior hold significant promise in understanding the initiability of insensitive materials used as boosters. The modeling community has expressed much interest in the results of these tests, and the visualization tool developed. The ability to look at the entire surface of a hemispherical test rather than a thin sliver, holds great promise for characterizing any change to the initiation train: not just the booster, but effects of the detonator and main charge can be evaluated as well.

6 References

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7 Appendix 1: DAAF Variable Confinement Cook-off Test Report

DEPARTMENT OF THE NAVY
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NAVAL SURFACE WARFARE CENTER
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INDIAN HEAD MD 20640-5150

8000
Ser R33/01
15 Oct 09

Los Alamos Laboratory
P.O. Box 1663
Attn: MS C-920 Elizabeth Francois
Los Alamos, NM 87545

Dear Ms. Francois:

Enclosure 1 you will find a copy of the test memorandum for the Slow VCCT (Variable Confinement Cook-off Test). Each test in the series contained three pellets averaging 60g total. Each test was conducted at a different confinement level. The standard VCCT was conducted, which soaks the test hardware at 75°C for a minimum of two hours prior to a 3.3°C/hour increase for the duration of the test.

Test Results Summary:

All tests resulted in a burn. For each test, all witness plates had no deformation, no bolts were broken, and the confinement sleeve was either intact or split open into one large piece.

There was one 'no test' at the 0.105" confinement level since the hardware failed out of order, making the results invalid. This test was repeated.

Pictures and graphs are included within the memo.

If there are any questions, please contact Erin Marx, Code R33EM at 301-744-1203 or Kevin Gibson, Code R33KG at 301-744-1303.

Sincerely,

ROBERT E. KACZMAREK
Director, Research Development
Test & Evaluation Department
By direction of the Commander

Enclosure: 1. Test Memorandum

MEMORANDUM

1OCTOBER2009

From: E. Marx
To: E. Francois

Subj: Slow VCCT (Variable Confinement Cook-off Test) on DAAF

1. Variable Confinement Cook-off Testing was performed on the DAAF formulation at several confinement levels, tested per the VCCT standard. See Table 1 for corresponding burst pressure for a particular confinement level. The standard test soaks the test hardware at 75 °C for a minimum of 2 hours prior to a 3.3 °C/hour increase for the duration of the test.

Confinement Sleeve Thickness (in)	Calculated Burst Pressure (psi)	Measured Burst Pressure (psi)
.015" steel	2507	2350
.030" steel	5150	5230
.045" steel	7795	7725
.060" steel	10270	10000
.075" steel	12999	12700
.090" steel	15305	---
.105" steel	17634	---
.120" steel	19963	---

2. At the .060" confinement level, the DAAF resulted in a burn. The reaction occurred at 225.9 °C at 46.65 hours from when the material started its temperature ramp. The confinement sleeve buckled and split. Also, explosive material was left after the test.

3. At the .075" confinement level, the DAAF resulted in a burn. The reaction occurred at 228.9 °C at 46.65 hours from the end of the soak period. Once again, the confinement sleeve split and opened into one large piece. Material remains were also present.

4. At the .090" confinement level, the DAAF resulted in a burn. The reaction occurred at 222.1 °C at 44.79 hours from when the material left soak temperature. There was scorching visible on the top witness plate with a dark residue. Also, the confinement sleeve remained in one piece, yet bulged/expanded, bluing in color by the temperature and pressure of the material completely reacting.

5. At the .105" confinement level, the DAAF resulted in a burn for the second test. The first test was defined as a 'no test' since the bolts broke before the confinement sleeve. ¼" bolts were used and failed. The reaction of the second test occurred at 232.4 °C at 38.53 hours. The initial temperature ramp prior to soak time was 100 °C, to shorten the test cycle, hence why the reaction time is lower than previous times. This test showed slight bending in one bolt and the

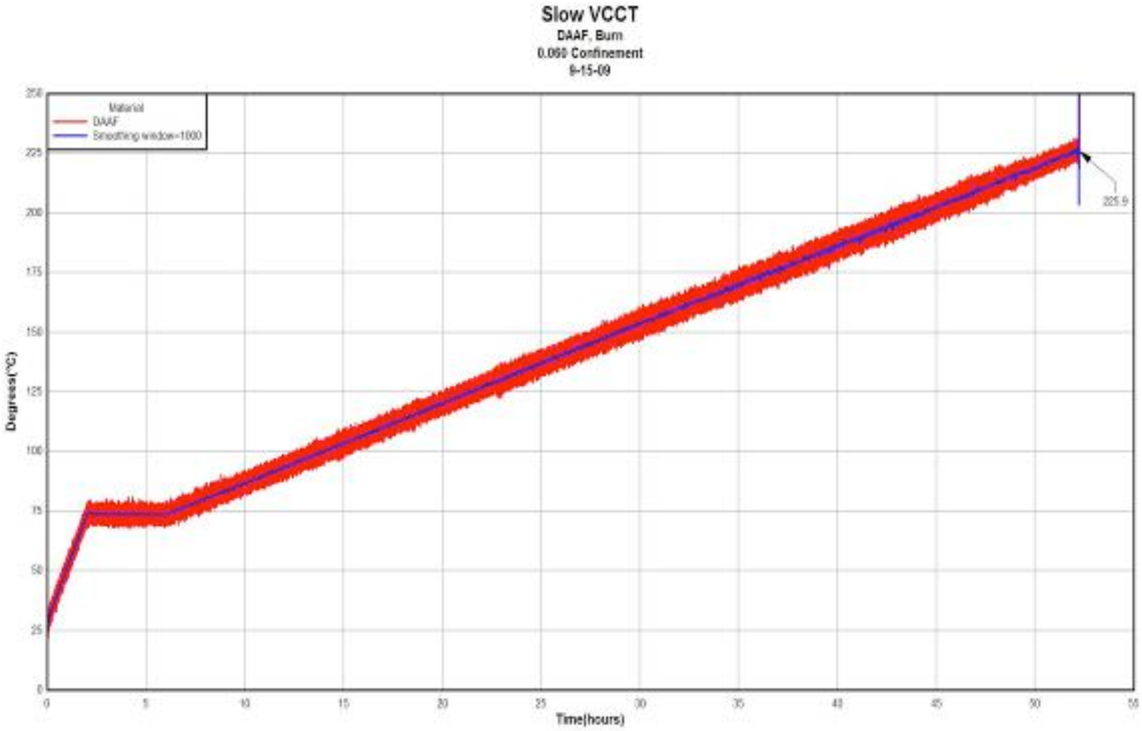
confinement sleeve split open, but was still in one piece. ⅜" bolts were used and the sleeve failed first, making the test valid. Material remained after the test.

6. At the 0.120" confinement level, the DAAF resulted in a burn. The reaction occurred at 229.5 °C at 38.29 hours. The soak temperature was raised to 100 °C. Two of the bolts were slightly bent, and the confinement piece split, yet remained whole. There was also material remaining.

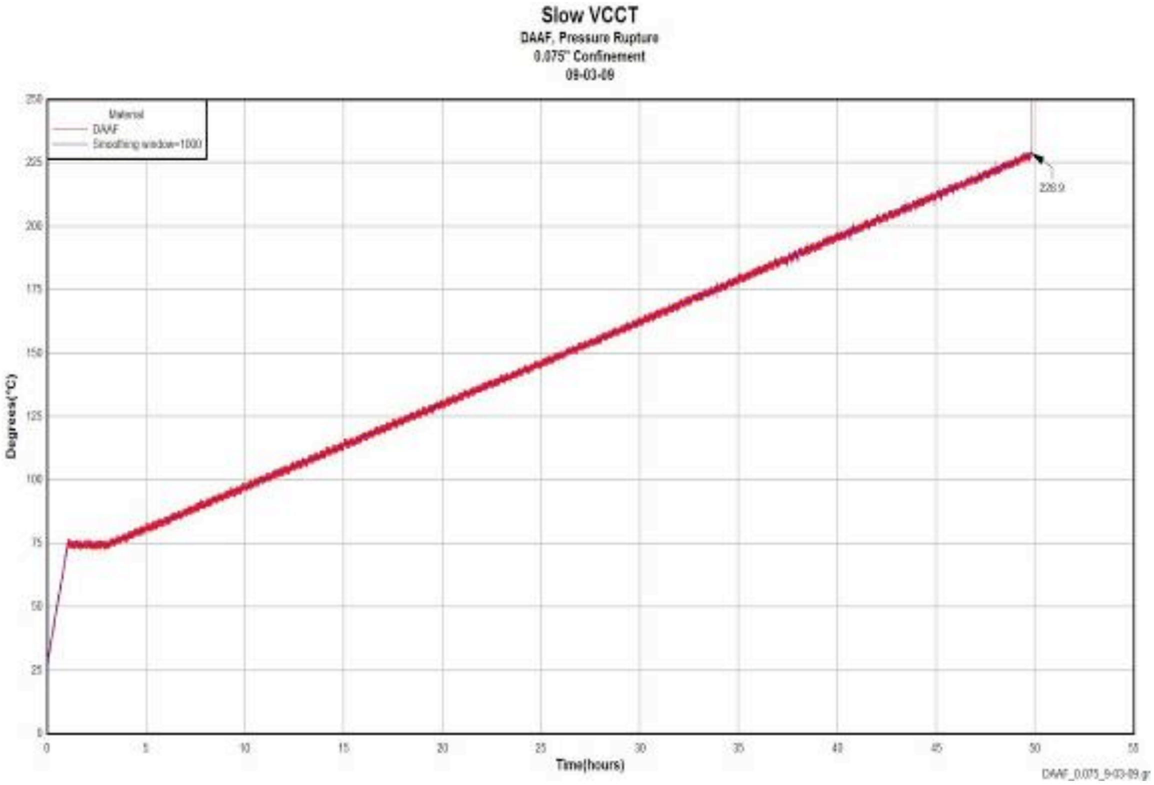
7. The last three pictures show the remains from the 3 test cycles (2 tests were run simultaneously in the same chamber). They are combined as we could not determine the difference between which pellet belonged to which individual test. There was only one test (.090" confinement) that completely consumed all of the material.

8. There were no significant endothermic or exothermic events witnessed from the thermal traces.

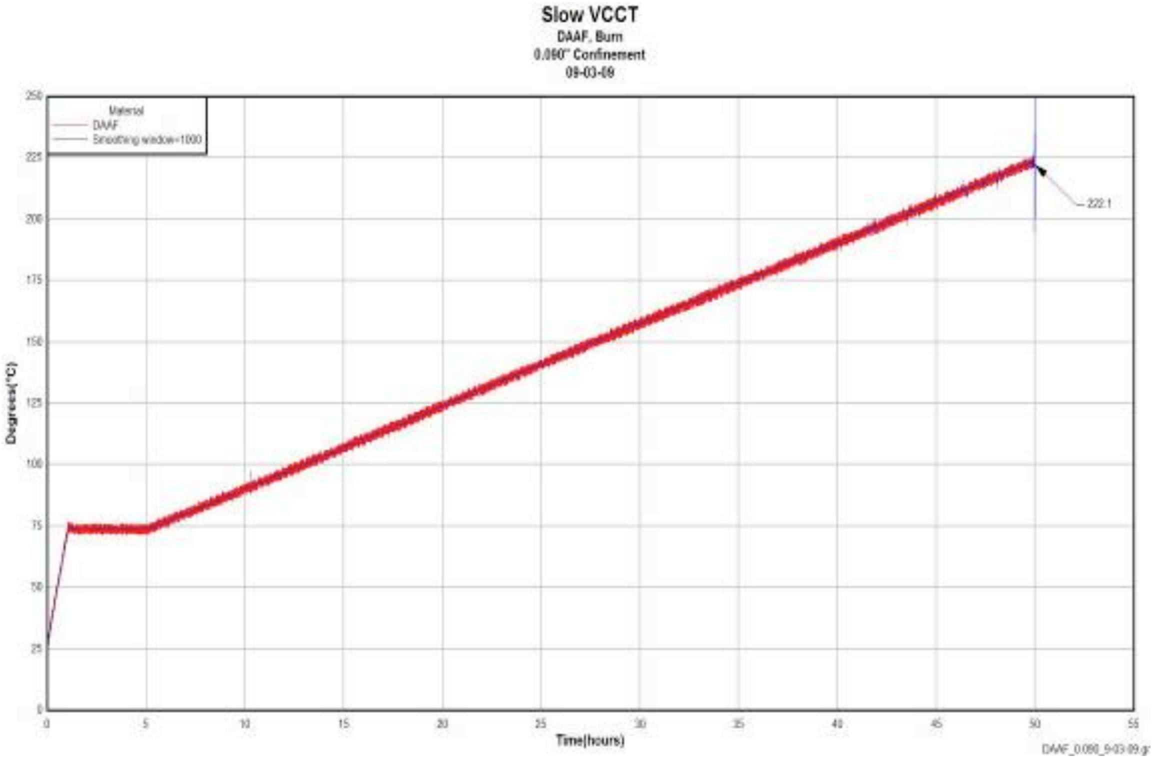
9. Pictures and graphs are included from the aforementioned tests. Please direct inquiries to Kevin Gibson, 301-744-1303, or Erin Marx, 301-744-1203.


Slow VCCT
DAAF, Burn
0.060 Confinement
9-15-09
Material
DAAF
Smoothing window=1000
225.9
Degrees(°C)
Time(hours)
0
25
50
75
100
125
150
175
200
225
250
5
10
15
20
25
30
35
40
45
50
55


21 SEPT 09 VCCT-SLOW
DAAF
0.060" BURN
DAAF


Slow VCCT
DAAF, Pressure Rupture
0.075" Confinement
09-03-09
Material
DAAF
Smoothing window=1000
228.9
Degrees(°C)
Time(hours)
DAAF_0.075_9-03-09.gr

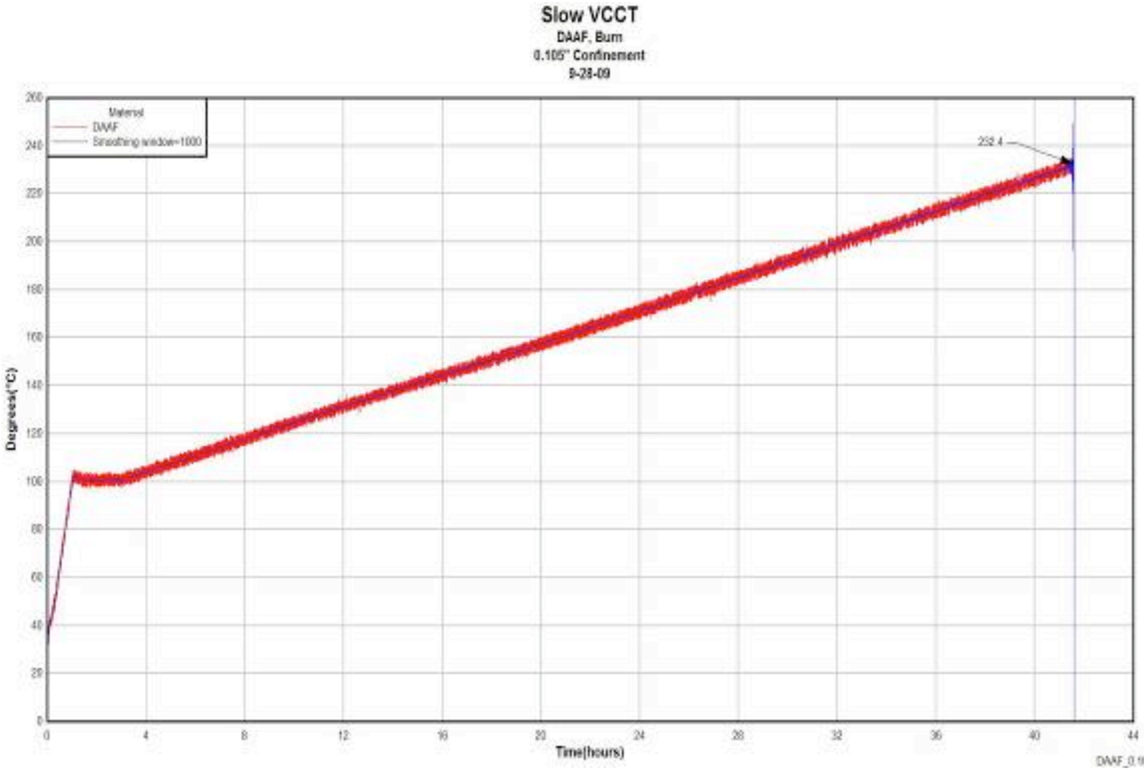

09 SEPT 09 VCCT-SLOW
DAAF
0.075" PRESSURE RUPTURE
DAAF
.075



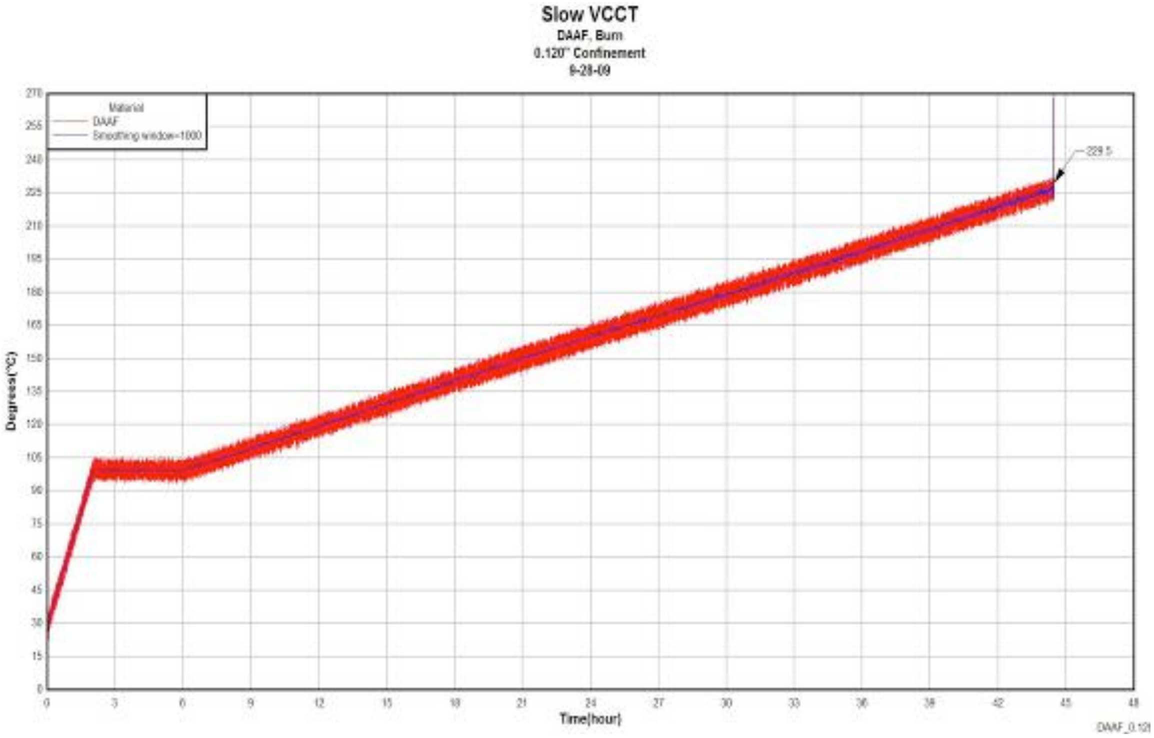
Slow VCCT
DAAF, Burn
0.090" Confinement
09-03-09
Material
DAAF
Smoothing window=1000
222.1
Degrees(°C)
Time(hours)
DAAF_0.090_9-03-09.gr

09 SEPT 09 VCCT-SLOW
DAAF
0.090" BURN


21 SEPT 09 VCCT-SLOW
DAAF
0.105" NO TEST
105


Slow VCCT
DAAF, Burn
0.105" Confinement
9-28-09
Material
DAAF
Smoothing window=1000
232.4
Degrees(°C)
Time(hours)
DAAF_0.105


30 SEPT 09 VCCT-SLOW
DAAF
0.105" BURN


Slow VCCT
DAAF, Burn
0.120" Confinement
9-28-09
Material
DAAF
Smoothing window=1000
229.5
Degrees(°C)
Time(hour)
DAAF_0.120


30 SEPT 09 VCCT-SLOW
DAAF
0.120" BURN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8 Appendix 2: VCCT on DAAF Formulations

DEPARTMENT OF THE NAVY
INDIAN HEAD DIVISION
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3767 STRAUSS AVENUE
SUITE 201
INDIAN HEAD, MD 20640-5150

3310
Ser R33/06
17 Sep 10

From: Commander, Indian Head Division, Naval Surface Warfare Center
To: Los Alamos National Laboratory, Elizabeth Francois

Subj: SLOW VCCT (VARIABLE CONFINEMENT COOK-OFF TEST) ON DAAF

Encl: (1) Test Report for Slow VCCT on DAAF-Nitramine Explosives

1. The attached enclosure (1) is the test memorandum for the Slow VCCT (Variable Confinement Cook-off Test). Each test in the series contained 3 pellets averaging 20g each. Testing was conducted at different confinement levels. The VCCT (Standard and Modified) that was conducted soaks the test hardware at 75°C for a minimum of 2 hours prior to a 3.3°C/hour increase for the duration of the test.

2. Test results summary:

   a. Testing was conducted on DAAF with HMX and DAAF with RDX.
   b. Test results varied, based on confinement level and material composition.
   c. Pictures and graphs are included within the memo.

3. For further information, please contact Erin Marx, Indian Head Division Naval Surface Warfare Center (IHD NSWC), Code R33EM, at 301-744-1203, email: erin.marx@navy.mil or Kevin Gibson, IHD NSWC, Code R33KG at 301-744-1303 or email: kevin.gibson@navy.mil.

R. E. KACZMAREK
By direction

Test Report for Slow VCCT (Variable Confinement Cook-off Test) on DAAF-Nitramine Explosives

23JUNE2010

E. Marx (R33EM)
K. Gibson (R33KG)

Background

1. Variable Confinement Cook-off Testing (VCCT) was performed on the DAAF-RDX and DAAF-HMX formulations at several confinement levels. Tests were conducted per the VCCT standard (Alexander, K., Gibson, K., Baudler, B., (1996). *Development of the Variable Confinement Cookoff Test* (NSWC-IHTR-1840)). Table-1 displays corresponding static burst pressure for a particular confinement level. The standard test soaks the test hardware at 75 °C for a minimum of 2 hours prior to a 3.3 °C/hour increase for the duration of the test. A burning reaction and a pressure rupture reaction are the only passing criteria in the VCCT (TYPE-V). Figure 1 and Figure 2 are photographs of the standard hardware/setup. The following lots were tested:

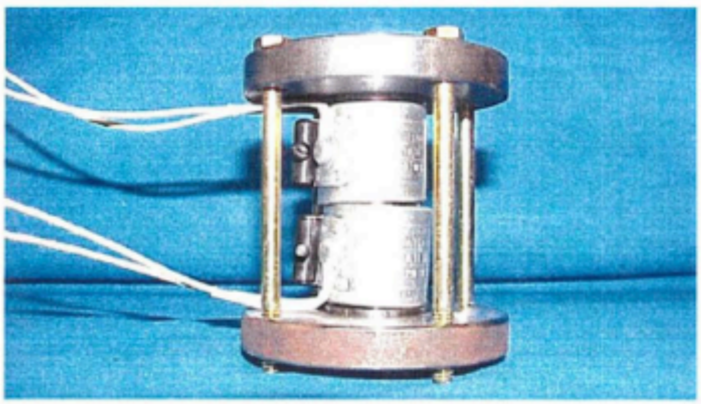
- DAAF-RDX:
  - LAX-117-4; 80% DAAF + 15% RDX + 5% Viton
  - LAX-117-6; 60% DAAF + 35% RDX + 5% Viton
- DAAF-HMX:
  - LAX-117-8; 80% DAAF + 15% HMX + 5% Viton
  - LAX-117-10; 60% DAAF + 35% HMX + 5% Viton

Table-1:

Confinement Sleeve Thickness (in)	Calculated Burst Pressure (psi)	Measured Burst Pressure (psi)
.015" steel	2507	2350
.030" steel	5150	5230
.045" steel	7795	7725
.060" steel	10270	10000
.075" steel	12999	12700
.090" steel	15305	---
.105" steel	17634	---
.120" steel	19963	---

Figure 1: Standard VCCT Hardware

Figure 2: Standard VCCT Assembled Hardware



2. For some of the testing, the standard VCCT hardware was modified to incorporate a pressure gauge and a center thermocouple. The pressure gauge was installed into the bottom witness plate, and a 0.060"diameter stainless steel sheathed thermocouple was inserted through the center of the top explosive pellet in contact with the middle pellet. See Figures 3 and 4.

Figure 3: Modified VCCT Hardware

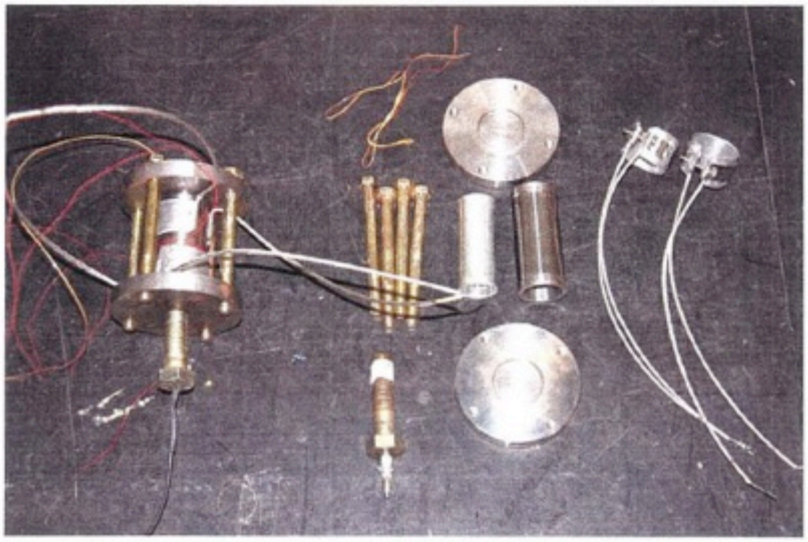
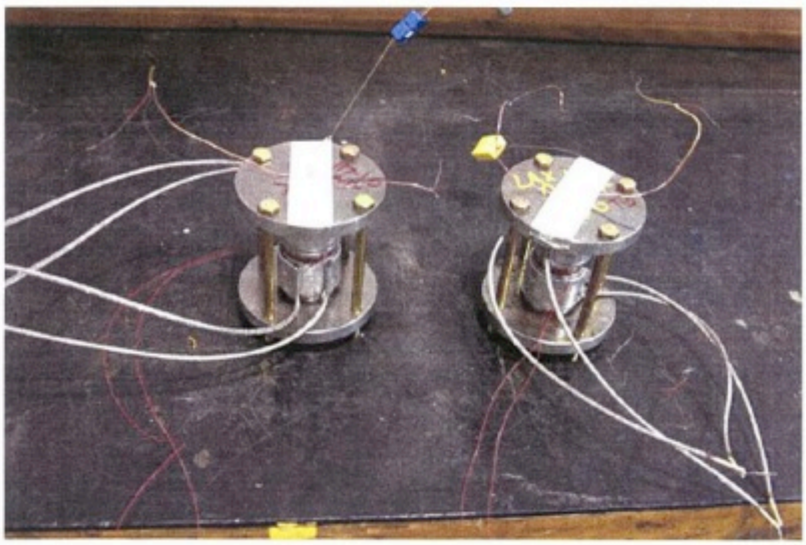


Figure 4: Modified VCCT



3. The accompanying link displays data collected for all testing due to the size of the files. DAAF LAX-117 Graphs (Please change link appropriately to match wherever

the file is saved.) Files are organized by lot and shot number, and include pictures, thermal traces, and pressure traces (when applicable). The following figures are examples of the data collected.

Figure 5: Example of a Thermocouple Trace

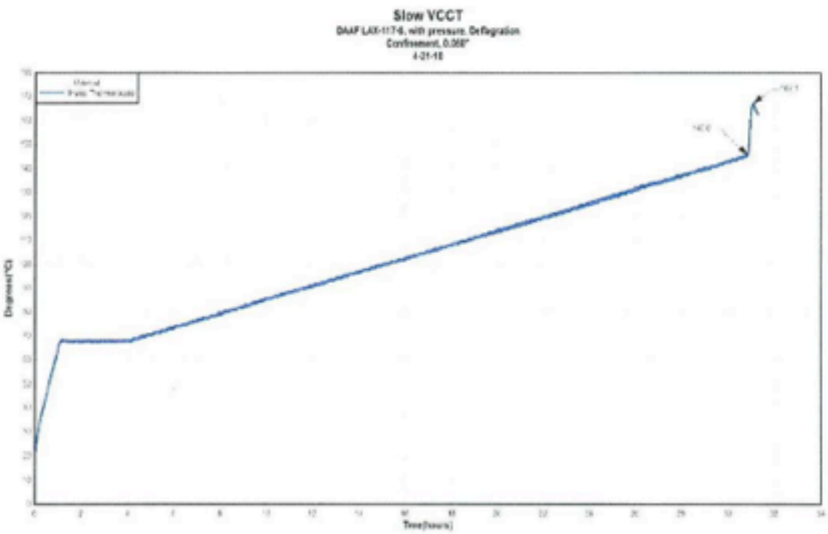


Figure 6: Example of a Pressure Trace

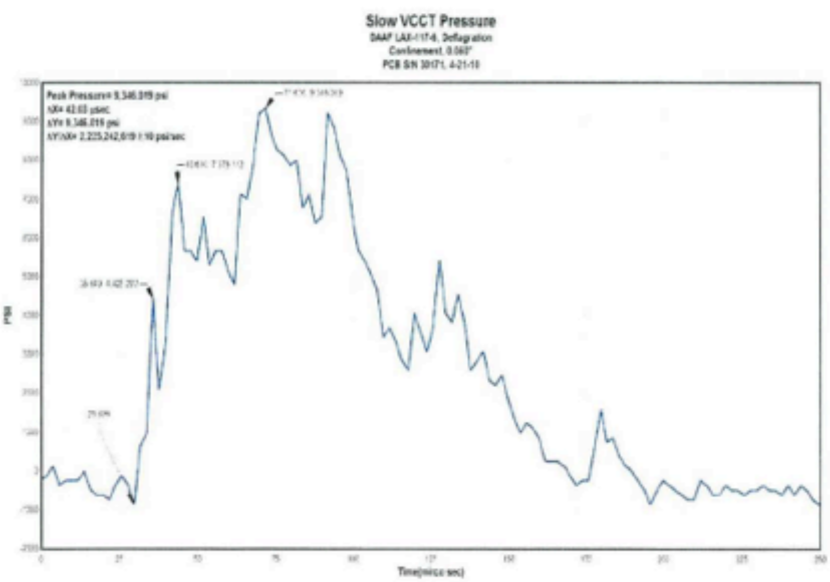


Figure 7: Example of a Post-Test Picture

Results

4. Lot LAX-117-4 was the worst performer. At 0.030" confinement a deflagration reaction occurred, at 0.060" and 0.090" explosions occurred, and at 0.105" a deflagration occurred. Curiously, two tests at the 0.120" confinement resulted in a pressure rupture and deflagration reaction. The pressure rupture at 0.120" was considered an anomaly due to the fact that all other tests were a deflagration or explosion reaction, even at lower confinement levels. Reaction temperatures as measured by the thermocouple on the aluminum sleeve ranged from a low of 160.7°C (pressure rupture-0.120") to a high of 187°C (deflagration-0.030"). Center thermocouples were used on LAX-117-4 (0.030", 0.060", 0.105", & 0.120"-deflagration). The closest agreement between thermocouples (aluminum and center) was the 0.030" test at 185.5°C for the center and 187°C for the aluminum. The largest disagreement between thermocouples (aluminum and center) was the 0.120" test at 217.1°C for the center and 184.3°C for the aluminum. The pressure results will be discussed in a separate section. The accompanying link displays photographs, thermal graphs and pressure graphs. DAAF-117 Graphs

5. Lot LAX-117-6 was the second worst performer. At 0.045" confinement a burning reaction occurred, at 0.060" and 0.075" deflagrations occurred. At 0.090" an explosion occurred. At the 0.120" confinement a deflagration reaction occurred. Reaction temperatures as measured by the thermocouple on the aluminum sleeve ranged from a low of 153.6°C (burn-0.045") to a high of 168.3°C (deflagration-0.120"). Center thermocouples were used on LAX-117-6 (0.045", 0.060", and 0.075"). The closest agreement between thermocouples (aluminum and center) was

the 0.060" test at 191.8°C for the center and 161.1°C for the aluminum. The largest disagreement between thermocouples (aluminum and center) was the 0.045" test at 188°C for the center and 153.6°C for the aluminum. The thermocouple on the aluminum sleeve for the 0.075" test malfunctioned at 146.3°C. An extrapolation from this point to the 'off-scale line' suggests a cook-off temperature of 148.4°C. This would make the difference between the aluminum and center of 27.2°C. The pressure results will be discussed in a separate section. The accompanying link displays photographs, thermal graphs and pressure graphs. DAAF-117 Graphs

6. Lot LAX-117-8 was the best performer. A burning reaction occurred at 0.090", 0.105" and 0.120" confinement. Reaction temperatures as measured by the thermocouple on the aluminum sleeve ranged from a low of 162.4°C (burn-0.105") to a high of 199.1°C (burn-0.120"). A center thermocouple was used on LAX-117-8 (0.105"). The agreement between thermocouples (aluminum and center) was 193°C for the center and 162.4°C for the aluminum. The pressure results will be discussed in a separate section. The accompanying link displays photographs, thermal graphs and pressure graphs. DAAF-117 Graphs

7. Lot LAX-117-10 was the second best performer. At 0.060" confinement a pressure rupture reaction occurred, at 0.075" burn occurred. At 0.090" and 0.105" a pressure rupture occurred. At the 0.120" confinement a burning reaction occurred. Reaction temperatures as measured by the thermocouple on the aluminum sleeve ranged from a low of 165.2°C (burn-0.075") to a high of 184.6°C (pressure rupture-0.105"). Center thermocouples were used on 117-6 (0.060", 0.075", 0.105", and 0.120"). The closest agreement between thermocouples (aluminum and center) was the 0.060" test at 188.6°C for the center and 184.1°C for the aluminum. The largest disagreement between thermocouples (aluminum and center) was the 0.120" test at 221.4°C for the center and 177.7°C for the aluminum. The pressure results will be discussed in a separate section. The accompanying link displays photographs, thermal graphs and pressure graphs. DAAF-117 Graphs

8. Dynamic pressure was measured on the following samples:

   LAX-117-4 (0.030", 0.060", 0.105", 0.120")
   LAX-117-6 (0.060", 0.075")
   LAX-117-10 (0.060", 0.105", 0.120")

   Equipment malfunction resulted in no data being collected for LAX-117-6 (0.045"), LAX-117-8 (0.105"), and LAX-117-10 (0.075").

   Through further testing on multiple formulations it is believed that pressure information can be used as a quantifiable indicator of cook-off violence. At present, the focus is on rise time (delta-t), peak pressure (delta-P), pressurization rate, and peak pressure versus calculated burst pressure. See Table-2 for pressure data.

Table-2:

Result	**Rise time**	**Peak Pressure** (Usec)	**Rate** **(PSI)**	**Peak/Burst** **(PSI/sec)**	**ID**
Burn	21.98-235.99	24651	Varied	1.23	117-10-120
Pressure Rupture	9.99	12788	1.28E+09	0.725	117-10-105
Pressure Rupture	26	8196	3.15E+08	0.8	117-10-060
Deflagration	No Data	26814	No Data	1.34	117-4-120
Deflagration	10.01	27213	2.72E+09	1.54	117-4-105
Deflagration	34.01	44648	1.31E+09	3.43	117-6-075
Deflagration	42.03	9346	2.22E+08	0.91	117-6-060
Deflagration	21.97	12604	5.74E+08	2.45	117-4-030
Explosion	21.96	45112	2.05E+09	4.39	117-4-060

9. Please direct inquiries to Erin Marx, 301-744-1203 or Kevin Gibson, 301-744-1303.