December 6, 1999

Brigadier General Thomas F. Gioconda
Acting Assistant Secretary for Defense Programs
Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585-0104

Dear General Gioconda:

The staff of the Defense Nuclear Facilities Safety Board (Board) has reviewed the handling of weapon subassemblies containing both insensitive high explosives (IHE) and conventional high explosives (CHE) at the Pantex Plant. In the enclosed report, *Safe Handling of Insensitive High Explosive Weapon Subassemblies at the Pantex Plant*, the Board's staff notes that the technical basis for performing operations on composite IHE and CHE weapon subassemblies does not fully support the assumptions used in establishing safety controls. As an example, the relaxation in safety controls on transportation (compared to all-CHE weapon subassemblies) does not seem justified or prudent.

The Board requests that the Department of Energy (DOE) reexamine its technical safety basis for handling composite IHE/CHE weapon subassemblies. Additional modeling, experimentation, and analysis would clearly strengthen DOE's understanding of the margin of safety in handling this class of subassemblies. There appears to be no reason to halt on-going operations while additional studies are being performed. However, DOE should determine whether additional engineered or administrative controls on composite IHE/CHE subassembly operations are needed in the interim. DOE should also evaluate any current or planned differences between the safety controls for this class of weapon subassemblies and the safety controls for all-CHE subassemblies to ensure that the differences are supported by the modeling, experimentation, and analysis completed to date.

Accordingly, pursuant to 42 U.S.C. § 2286b(d) the Board requests that DOE provide a report within 90 days of receipt of this letter, providing details on the path forward to resolve this issue. If you have any questions on this matter, please do not hesitate to call me.

Sincerely,

John T. Conway
Chairman

c: Mr. Mark B. Whitaker, Jr.
Enclosure

DNFSB/TECH-24

SAFE HANDLING OF INSENSITIVE HIGH EXPLOSIVE WEAPON SUBASSEMBLIES AT THE PANTEX PLANT

Defense Nuclear Facilities Safety Board

Technical Report

September 1999

SAFE HANDLING OF INSENSITIVE HIGH EXPLOSIVE WEAPON SUBASSEMBLIES AT THE PANTEX PLANT

This report was prepared for the Defense Nuclear Facilities Safety Board by the following staff members:

William Von Holle
Charles Martin

with the assistance of former staff member Josephine Covino

EXECUTIVE SUMMARY

Conventional high explosives (CHE) are characterized by a sensitivity to mechanical or thermal energy. Insensitive high explosives (IHE), on the other hand, require extraordinarily high stimuli before violent reaction occurs. Therefore, fewer constraints on handling IHE are required as compared with CHE.

Based on the measured differences in weapon subassemblies between explosives containing CHE and IHE, the two types of subassemblies are controlled differently in Pantex facilities. For example, IHE subassemblies, including those containing CHE, are allowed uncased in assembly bays, whereas uncased CHE subassemblies may be handled only in assembly cells.

Some weapon subassemblies containing IHE also contain CHE materials. In particular, boosters of many IHE subassemblies are made of CHE. For such configurations, the likelihood of violent reaction in abnormal environments at Pantex cannot be statistically defended on the basis of the small number of tests performed. In particular, the margin for a less-than-optimal stimulus of the CHE booster to detonate IHE is not well defined.

The staff of the Defense Nuclear Facilities Safety Board believes that additional evaluation of the technical basis for the use of separate controls for operations involving composite IHE/CHE subassemblies is warranted. Additional engineering or administrative controls on operations involving IHE/CHE subassemblies may be necessary to improve safety. Where significant uncertainties exist in the likelihood estimates for a violent reaction of IHE under credible abnormal environments, a vigorous program of additional tests and computer modeling may be required to improve confidence in the estimates.

TABLE OF CONTENTS

Section **Page**

1 INTRODUCTION 1-1

1.1 Purpose and Background 1-1
1.2 Scope 1-2
1.3 Organization of This Report 1-2

2 DISCUSSION OF PANTEX IHE OPERATIONS AND STORAGE IN TERMS OF PANTEX ENVIRONMENTS 2-1

2.1 Pantex Bay Handling Environments 2-1
2.2 Weapons in Transit 2-2
2.3 Operator-Attended Machining 2-2

3 ESTIMATED RELATIVE RISKS FOR OPERATIONS WITH IHE VERSUS CHE 3-1

3.1 Safety Analysis Report for Device Assembly Facility 3-1
3.2 Pantex W87 Hazard Analysis Report 3-2

4 CONCLUSIONS 4-1

APPENDIX A. CHARACTERIZATION OF IHE MATERIAL THROUGH SMALL-SCALE LABORATORY TESTS A-1

APPENDIX B. IHE SUBASSEMBLY AND OTHER LARGE-SCALE THERMAL AND MECHANICAL TESTING B-1

APPENDIX C. CHEMICAL AND PHYSICAL EXPLANATIONS FOR THE SAFETY OF TATB (IHE) C-1

REFERENCES R-1

GLOSSARY OF ACRONYMS GL-1

1. INTRODUCTION

1.1 PURPOSE AND BACKGROUND

The purpose of this report is to examine the justification for the insensitive high explosive (IHE) classification at Pantex, which allows special treatment for an explosive material, assembly, or weapon not allowed for a conventional high explosive (CHE). IHE is recognized for its uniqueness according to the following definition:

> Explosive substances which, although mass detonating, are so insensitive that there is a negligible probability of accidental initiation or transition from burning to detonation . . . (McGuire and Guarienti, August 1984).

If IHE materials are true to their definition, they require extraordinarily high stimulus before violent reaction would result; therefore, compared with CHE, fewer constraints on handling are necessary. Differences in treatment for IHE and CHE at Pantex are found in some operations and in the on-site transportation of nuclear explosives. For example, IHE is allowed uncased (bare) in assembly bays, but CHE is allowed uncased only in assembly cells, which afford the highest level of mitigation of the consequences of a high explosive detonation or deflagration (U.S. Department of Energy, March 1996). The staff of the Defense Nuclear Facilities Safety Board (Board) believes the Department of Energy (DOE) and the contractor must show that the different and relaxed handling of IHE is justified, at least when it is accompanied by a CHE booster.

The technical justification for the differences in handling and storage procedures for IHE is not explicitly defined in any one publication. Instead, Pantex has published the results of a series of tests on IHE materials and subassemblies (Mason & Hanger-Silas Mason Co., Inc., June 1986) required by the *DOE Explosive Safety Manual* (U.S. Department of Energy, March 1996). The only approved IHEs are triaminotrinitrobenzene (TATB) and TATB-Kel-F formulations. IHE-approved subassemblies are devices that contain mostly IHE materials and some CHE, and have been tested as prescribed in the *DOE Explosive Safety Manual*, which contains a list of approved IHE assemblies. In addition to these prescribed tests, the DOE weapon design laboratories have carried out large- and small-scale thermal and impact tests and computer modeling that serve to support the IHE special handling procedures.

The Board's staff conducted a review of the safety basis for IHE versus CHE operations at Pantex. Representatives from Mason and Hanger Corporation (MHC), the DOE Amarillo Area Office (DOE-AAO), and the two design laboratories were present during this review. The laboratory representatives agreed with the Board's staff that the assumption of negligible likelihood for violent reaction of IHE subassemblies rests on expert opinion and a limited number of tests. They maintained that a degree of safety margin exists, but more quantitative information is desirable, especially with regard to the amount of CHE materials required to initiate TATB to violent reaction in IHE subassemblies in credible abnormal environments (Von Holle, 1998).

1.2 SCOPE

Four generic types of energy are found at Pantex: thermal, electrical, chemical, and mechanical. Only threats from mechanical (e.g., shock, impact, puncture), and thermal (fast- and slow-heat fire scenarios) sources are considered in this report. Not all credible design basis accidents (DBAs) are considered, since within some environments, CHE and IHE alike will react to disperse plutonium in a DBA. Instead, this report treats only consequences resulting from the relaxation of preventive or mitigative measures for accidents with IHE weapons or subassemblies. Chemicals offer no credible threat to nuclear explosive safety at Pantex (U.S. Department of Energy, 1995). Electrical threats, especially lightning, are real and the subject of continued scrutiny at the present time. However, these threats, along with electrostatic discharge (ESD), are detonator threats, which are equivalent for IHE and CHE weapons and are beyond the scope of this report. It should be noted that so-called front-door vulnerabilities are equivalent except for differences in implementation of modern electrical detonation safety. TATB and its formulations have been the subject of numerous publications and reports. Two reviews contain hundreds of references to its superior safety in all abnormal and combinations of abnormal environments (Rice and Simpson, 1990; Dobratz, August 1995). Because the invulnerability of TATB in all types of accident scenarios is covered in these references, this report focuses on the results of tests prescribed by the *DOE Explosive Safety Manual*, which include IHE subassemblies containing CHE components.

1.3 ORGANIZATION OF THIS REPORT

Section 2 reviews IHE operations and storage at Pantex in terms of credible abnormal environments at the site. Section 3 describes how other DOE hazard evaluations have treated CHE versus IHE. Section 4 summarizes concerns and conclusions of the Board's staff with regard to the adequacy of IHE controls at Pantex. Appendices A and B provide the results of DOE-prescribed tests designed to qualify materials and subassemblies as IHE and several other tests exhibiting IHE's insensitivity. Appendix C provides a simple theoretical explanation of TATB's fundamental stability.

2. DISCUSSION OF PANTEX IHE OPERATIONS AND STORAGE IN TERMS OF PANTEX ENVIRONMENTS

The discussion in this section focuses on the two areas in which IHE weapons or subassemblies are allowed special treatment: Pantex bays and weapons in transit (for small-arms fire).

2.1 PANTEX BAY HANDLING ENVIRONMENTS

DOE limits the conduct of explosive operations in the Pantex bays to Class II (moderate accident potential) and lower hazard classes (U.S. Department of Energy, March 1996). IHE is allowed uncased in the bays; uncased CHE operations are not allowed. The bays are not designed to contain an explosion from a high explosive (HE), but rather to release the explosion products through the cantilevered roof so as not to endanger personnel in adjacent bays. Thus to reduce the likelihood of a plutonium dispersal accident, only IHE is allowed uncased. The assumption is that uncased IHE, in contrast to CHE, will not react violently to disperse plutonium in any credible handling accident or environment. For mechanical impact, relevant IHE tests are Spigot, Skid, and the relatively new rounded projectile impact test called the Steven Test (described in Appendix B). Any credible drop from the maximum height in any bay, 30 ft, is well below the 120 ft height of the Spigot test, in which the TATB main-charge explosive did not even burn (see Appendix B).

The goal of proving a negligible likelihood of IHE weapon or subassembly detonation cannot be accomplished based on the results of a few trials of a single test, even if it is an extreme overtest. The drops were performed at heights greatly exceeding those of the bays in a manner most likely to cause a reaction from the booster, and the bullets were fired into the booster (see Appendix B). In spite of the negative results of safety tests with actual size CHE boosters in IHE subassemblies, the threshold booster size for propagation of reaction from the sensitive booster (LX-10 or LX-07) to cause violent reaction in the main-charge IHE is unknown. At some size or confinement condition, the booster explosive will transit to detonation, as it does in tests of LX-10 and LX-07 large billets in the Skid, Spigot, and bullet tests (Dobratz and Crawford, January 31, 1985). This threshold size should be determined experimentally to identify the margin of safety that exists in potential accidents with IHE subassemblies containing sensitive boosters. Alternatively, appropriately instrumented safety tests with the booster CHE materials could yield the same information. Accurate computer models for predicting the violence of the reactions of IHE subassemblies would be very useful to bolster the scientific arguments, as would data on damaged IHE subassemblies subject to the environments of the bays. The tests that have been done reveal no reason to believe that the margin of safety is not adequate for IHE weapons or subassemblies with CHE boosters. However, since an adequate statistical validation of the likelihood of a violent reaction with an IHE subassembly is impractical, the negligible likelihood of a violent reaction cannot be demonstrated; therefore, the staff believes additional experimental safety data or preventive measures are necessary.

The Pantex Bay Safety Analysis Report (SAR) (U.S. Department of Energy, March 28, 1996) indicates that heating of the CHE or IHE in a fire scenario is an incredible, beyond-design-basis accident as the result of safety-class structures, systems, and components (SSCs) in place. However, according to the principle of defense in depth, thermal tests with IHE subassemblies and CHE boosters are necessary to estimate the safety margins for thermal explosions (violent reactions), since the CHE could react violently in a fire if present in large enough quantities. Appendix B describes full-scale slow-heating thermal tests that resulted in violent booster reactions, but no detonation in the main-charge IHE. Lawrence Livermore National Laboratory (LLNL) currently has an experimental/modeling program under way to predict the nature of a thermal explosion in CHE. This long-term study is relevant to the CHE booster margin of safety, but the outlook for a useful model is not clear at this time (Simpson, October 27, 1998).

2.2 WEAPONS IN TRANSIT

CHE weapons must have Kevlar blankets while being transported in certain areas since bullets are a credible threat at Pantex, but IHE subassemblies need not have such protection (U.S. Department of Energy, September 1995). The bullet impact tests described above were performed as an overtest by firing directly into the booster and allowing the bullets to come to rest in the explosive. In this case, as in the other mechanical tests, the minimum booster size or stimulus (e.g., velocity or caliber) that would result in a propagating reaction in the booster has not been reported. The staff believes such information is desirable to know the margin of safety, although in practice an accident in which an IHE subassembly would be subject to the conditions of the worst-case tests would be unlikely.

2.3 OPERATOR-ATTENDED MACHINING

Operator-attended machining is allowed on IHE materials, and not on CHE. Facilities in which this activity occurs are not allowed to contain fissile material. The staff has not examined this issue. The IHE insensitivity to reaction from shear and friction noted in this report and a number of the cited references supports this allowance, and is not analyzed further here.

3. ESTIMATED RELATIVE RISKS FOR OPERATIONS WITH IHE VERSUS CHE

Two recent attempts to estimate the probability of occurrence for accidents involving IHE are particularly insightful: the SAR for the Device Assembly Facility (DAF) at the Nevada Test Site (NTS) (U.S. Department of Energy, March 1995), and the Hazard Analysis Report (HAR) for the W87 disassembly and inspection (D&I) and assembly process at the Pantex Plant (Mason & Hanger Corporation, December 18, 1998).

3.1 SAFETY ANALYSIS REPORT FOR DEVICE ASSEMBLY FACILITY

The DAF SAR recognizes the uncertainty inherent in assessing the risks of nuclear explosive operations as follows: “Because of the lack of data, conservative engineering judgment is used to estimate basic event failure rates. These estimates do not provide an accurate probability of occurrence. Instead, an approximate probability of occurrence resulting from a systematic analytical process is sufficient to confirm the probability binning performed in the hazard analysis and to provide insight into the relative likelihood of each accident.” The analysis included fault trees that were populated using an expert elicitation process to estimate the probabilities of occurrence for the individual events. The key difference between bare CHE and bare IHE is that an explosion of IHE from a drop onto the DAF resilient flooring is judged to be incredible based on the flooring qualification program.

Several scenarios were analyzed that could lead to detonation of the IHE. First, the IHE could fall from a gurney onto an object on the floor having characteristics that could lead to detonation of the explosive. Second, as a result of a manual lift, the IHE could fall onto an object with characteristics that could cause an explosion. Third, a tool or fixture with the characteristics and velocity needed to cause an explosion could fall onto the IHE. Finally, a seismic event could initiate any of these scenarios.

The difference in total annual likelihood for these scenarios can be attributed to two point estimates. For the likelihood that an impacting object will have the characteristics and velocity to cause an explosion, the estimate for IHE or cased CHE is 1.0E-6 per year versus 5.0E-2 per year for bare CHE. In the case of an explosive falling onto an object, the estimate for the likelihood of an explosion for IHE or cased CHE is 1.0E-6 per year and for bare CHE is 1.0E-3 per year. An explosion due simply to dropping bare IHE on a resilient material floor in a bay was ruled out by these experts. For an object to cause detonation of bare CHE, it must have a certain shape and characteristics, and the impact must occur at an oblique angle at a velocity of more than 3 m/sec. For cased CHE, an object must be traveling at more than 30 m/sec to cause a detonation. The probability for the top event in the two fault trees is 1.0E-9 per year for IHE or cased CHE and 1.6E-6 per year for bare CHE. The point of this discussion is not the absolute estimates, but the relative reduction in assessed risk in the case of IHE or cased CHE.

3.2 PANTEX W87 HAZARD ANALYSIS REPORT

The W87 HAR considers several credible scenarios leading to HE detonation or deflagration. The scenario of greatest concern is perhaps a unit colliding with a forklift carrying combustibles, causing a fire of sufficient duration to ignite the IHE. This scenario is assessed to have an uncontrolled likelihood of 10^{-2} to 10^{-4} per year. For this scenario, the control proposed is the site-wide administrative program of qualification and training of workers, the conduct of operations program, and the protection afforded by the transport vehicle. Also addressed are several other scenarios assessed as being beyond extremely unlikely. These scenarios include aircraft crash during ramp transport, tornado-generated missile impact, lightning strikes, seismic events, external explosions caused by a two-way radio, fire in a bay, small-arms discharge, low- or high-voltage source from equipment in the bay, and explosion in the bay. All but three of these scenarios are considered to fall within the envelope determined through approved master studies or other existing facility safety studies and documented in SARs or Bases for Interim Operations (BIOs). Three fire/explosion scenarios are considered to require additional controls to reduce the likelihood to beyond extremely unlikely. For fires, additional controls include minimization of combustible loading, prohibition of unanalyzed energy sources, separation of IHE and combustible materials, and the site-wide fire protection program. The explosion scenarios postulate electrical energy reaching the detonators, resulting in detonation of the IHE. In these cases, the control relied upon is verification that the electrical pathways to the detonators are open circuits, thus preventing electrical signals from initiating the detonators.

It is interesting to note that even in the case of the all-IHE W87 weapon, additional controls are required beyond the insensitivity of the IHE itself. These controls are required to reduce the likelihood of detonation or deflagration to a level such that operations may proceed in a bay where there is no mitigation for off-site consequences.

4. CONCLUSIONS

Weapons experts assert there is a negligible likelihood that bare all-IHE assemblies would react violently during operations in a Pantex bay. The Board's staff believes this is a technically justified conclusion based on expert judgment, backed up by numerous test and experimental data, references to which are included in this report. However, the data are scattered and poorly documented, and are not readily available. Additional data to address weak areas, such as code predictions of IHE explosiveness (violence or damage) and the effect of predamage, would be welcome additions to the data on IHE responses under credible abnormal circumstances.

On the other hand, IHE weapons and subassemblies with CHE booster materials are a different technical issue. The only all-IHE weapons are the W87 and W84. The B83, for example, has LX-10 boosters that should have an impact on the likelihood of detonation in accidents. In addition, the B61-4/7/10/11 weapons contain some LX-07 explosive. The premise implicit in permitting IHE and cased CHE operations in a bay at either Pantex or the DAF is that these scenarios are beyond extremely unlikely. This assumption appears to be based on highly qualitative assessments of likelihood that may not be defensible given the state of the database for populating such assessments. In the analysis for the B61, for example, the estimated uncertainty spans two orders of magnitude for nearly all scenarios assessed. The large uncertainty in the estimates is based on the paucity of data from which the estimates are derived. The small number and stochastic nature of full-scale accident simulations fail to demonstrate negligible probability of violent HE reaction for these subassemblies in most credible abnormal environments.

The uncertainty in the estimates of violent reaction for these IHE/CHE systems leads to a lack of confidence in the safety margin. For most credible abnormal environments, the size of the CHE booster or the level of stimulus that would cause the booster to react with enough power (brisance) to initiate the IHE main charge to a violent reaction is unknown. Thus, the margin of safety is also unknown.

The staff believes that the following actions would improve the safety of IHE subassembly handling at Pantex, especially for subassemblies containing CHE:

- A reassessment of the likelihood of detonation or violent reaction of IHE subassemblies. This assessment should employ quantitative and semiquantitative data where appropriate, carefully examining the technical basis for each value.

- Strengthening of the technical basis for the point of likelihood estimates for violent reaction by performing further testing and computer modeling.

- An assessment of the need for developing additional engineering and administrative controls not now in force on IHE subassembly operations in order to further reduce the likelihood of an initiating event. Alternatively, only cased IHE subassemblies should be allowed in bays.

- Justification of any relaxation of controls for subassemblies with IHE and CHE by a complete hazards analysis.

APPENDIX A

CHARACTERIZATION OF IHE MATERIAL THROUGH SMALL-SCALE LABORATORY TESTS

Conventional high explosives are made up of HMX ($C_4H_8N_8O_8$-octahydro-1,3,5,7,-tetranitro-1,3,5,7-tetrazocine, octogen) and inert binders. IHEs consist of TATB ($C_6H_6N_6O_6$-1,3,5,-trinitrobenzene) and binder. The chemical and physical properties of the two types of explosives are quite different because the two organic molecules are derived from different families. HMX is a simple cyclic nitroamine, while TATB is a nitrobenzene derivative. TATB is the last of a series of nitrobenzene homologs, and within this family it is the most stable. In general, TATB is less reactive than HMX, more chemically stable, and more difficult to decompose (Rice and Simpson, July 1990).

The sensitivity of an energetic material is defined relative to a particular test. The test may be designed to give information about a particular hazard situation or to provide more general information on how the energetic material will behave over a wide range of conditions. There are small-scale tests to measure the explosive's response to energy input from shock, impact, thermal, friction, mechanical, and electrostatic discharge sources.

This appendix reviews some of the small-scale sensitivity tests prescribed by the *DOE Explosive Safety Manual* to qualify an IHE material. These tests are listed in Table A-1, along with the criteria and results (U.S. Department of Energy, March 1996). Two additional small-scale sensitivity tests—the Susan and wedge tests—are discussed.

Table A-1. DOE Small-Scale Qualification Tests for IHE and Results for TATB-based Explosives

Test	Criteria	TATB Results
Drop-Weight Impact Test	Comparable to or less sensitive than explosive D (ammonium picrate); minimum of 20 drops per test series	Pure TATB less sensitive than ammonium picrate
Friction Test	No reaction on Pantex friction machine (10 trials)	Ten trials; no reaction
Spark Test	No reaction at minimum of 0.25 joule (10 trials)	Ten trials; no reaction
Ignition and Unconfined Burning Test (small-scale burn)	TB 770-2 test procedures, any shape, minimum thermal path of 25 mm, no explosion	No explosion; however, fast-burning reactions measured
Card Gap Test	No reaction at explosive D 50% gap thickness (or less) using a Pantex modified Naval Ordnance Laboratory (NOL) card gap test (six trials); test diameter must be greater than unconfined failure (critical) diameter of candidate IHE	All reactions obtained were below explosive D 50% gap thickness

Table A-1. DOE Small-Scale Qualification Tests for IHE and Results for TATB-based Explosives (Concluded)

Test	**Criteria**	**TATB Results**
Detonation (cap) Test	TB 700-2 test procedures; no detonation (five trials)	No reaction
Cook-off	One-dimensional time to exposition (ODTX); no reaction more than pressure release	Burning reaction
Spigot Test	No reaction for 120 ft drop in LANL test (three trials)	Test height up to 150 ft; no reaction
Skid Test	No reaction (or sample failure) up to 20 ft drop at 14–15 deg test angle using standard-size billets (three trials at worst-case condition)	Impact angle 14 deg; test height 20 ft; samples failed; no test because object broke apart

A.1 DESCRIPTION OF SOME TESTS PRESCRIBED BY *DOE EXPLOSIVE SAFETY MANUAL*

A.1.1 Drop Weight Impact Test

Drop-weight impact testing is a relatively simple screening test for impact stability and uses a small amount of material. Basically, a weight is dropped from a variable height onto an anvil containing the sample material. A positive test for an unknown explosive is a certain level of “explosion” recorded on sound equipment. Since a positive test is somewhat subjective, the apparatus must be calibrated frequently against standard explosives. A summary of Los Alamos National Laboratory (LANL) impact tests on a variety of materials can be found in the *LLNL Explosives Handbook* (Dobratz and Crawford, January 31, 1985). The test is calibrated with respect to the explosive ammonium picrate. It consists of 20 drops per test series. Pure TATB and HMX are both more insensitive than ammonium picrate in this test. The test is not applicable to compacted explosives such as PBX-9502 or LX-17.

A.1.2 Friction Test

The friction test determines the relative friction sensitivity of an explosive by subjecting it to forces normal to the surface of the explosive sample while simultaneously applying a shearing, frictional action across the surface of the sample. The Pantex friction test machine consists of a 155.7 kg weight dropped at heights varying from 25.4 to 81.3 cm as the normal force varies from 50 to 5000 lb. The sample used is a pressed explosive sample disc 2.5 cm in diameter by 0.3 cm thick. TATB-based explosives are not friction sensitive, while HMX explosives are.

A.1.3 Card Gap Test

The gap test arrangement (see Figure A-1) consists of an explosive donor, an attenuating material, and acceptor energetic material. The attenuator, usually polymethyl-methacrylate (PMMA), is adjusted in thickness to change the shock level to the acceptor (Dobrantz and Crawford, January 31, 1985). The donor is pentolite (50 percent trinitrotoluene [TNT], 50 percent Pentaerthritoltetrianitrate [PETN]). The acceptor, 1.44 in. (~3.66 cm) in diameter, is confined in a steel sleeve. A mild steel witness plate, approximately 3/8 in. (~1 cm) thick and standing off about 1/16 in. (~1.6 mm) from the acceptor, is used to determine whether a detonation (a clean hole punched through the witness plate) has occurred. The data for the two materials are summarized below (Gibbs and Popolato, 1980):

- HMX (density 1.9 g/cc) small-scale gap test: G_{50} (mm) = 4.04
- TATB (density 1.9 g/cc) small-scale gap test: G_{50} (mm) = 0.127

G_{50} is the attenuator gap thickness that results in a detonation of the acceptor in 50 percent of the trials. The HMX receptor will detonate at a much more attenuated shock pressure than is required by the TATB. Thus, HMX is more sensitive than TATB.

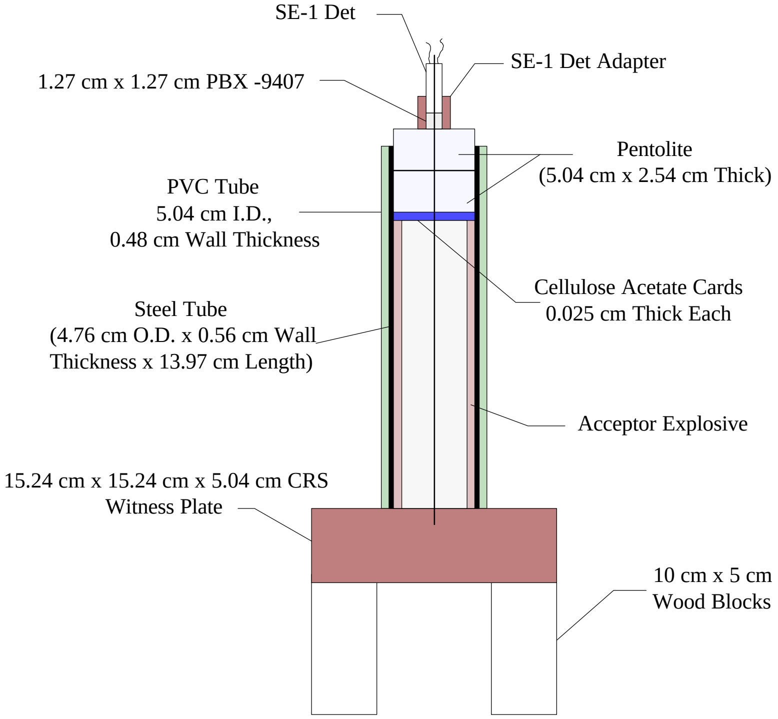


Figure A-1. Pantex Modified NOL Card Gap Test

Source: Mason & Hanger-Silas Mason Co., Inc., June 1984.

A.1.4 Cook-off Tests

Small-scale thermal data exist on both TATB- and HMX-based explosives. These data consist of differential thermal analysis (DTA), pyrolysis, differential scanning calorimeter (DSC), and one-dimensional time to explosion (ODTX) data. The DTA and pyrolysis data for HMX and TATB illustrate that HMX decomposes at a lower temperature than TATB (Dobratz, August 1995).

The ODTX experiment designed at LLNL (Catalano et al., 1976) is a small-scale time to explosion experiment. It uses a 1.27 cm diameter (~2.2 g of explosive) sphere. The cell is electrically heated, with the temperature controlled to within ± 0.2 K. The data from this test are presented as a time-to-explosion for various temperatures. The data suggest that HMX-based explosives thermally react at lower temperatures than TATB-based explosives. Recent ODTX results indicate that TATB explosions below 274^{o}C are “pressure bursts,” and above 274^{o} are true thermal runaway explosions (Tarver et al., 1996). ODTX results are used primarily to verify reaction mechanisms for use in thermal codes to predict the results of larger-scale experiments. They cannot be used to distinguish between IHE and CHE thermal responses in weapon assembly accidents.

A larger-scale cook-off test consists of an explosive totally confined in a close-fitting aluminum tube 1.3 cm in diameter. The tube is submerged in a bath of hot fluid until a reaction takes place. The violence of the reaction is judged and reported for the specific bath temperature and time of exposure in the hot environment. Four pellets 1.3 cm thick are stacked into each aluminum tube. Six tests were conducted with TATB. The tests resulted in sheared end plugs, followed by pressure release.

A.1.5 Conclusions and Modeling Limitations

The energetic material community has developed computational/predictive models to better predict how a weapon will respond when subjected to a complex accident environment. These models use fundamental data gathered in small-scale experiments for predicting the results of large-scale limited experiments. Single-event shock and impact results can be modeled very well. However, in the thermomechanical area, the models do not predict the weapons’ response. Specifically, in thermal scenarios, the models predict time to ignition of a system but cannot begin to evaluate the overall damage of the reaction. The Department of Defense (DoD) and DOE community, fully aware of this deficiency in the modeling and small-scale testing, have embarked on a coupled experimental/modeling program to eliminate such deficiencies. The program is making some progress in the development of computational tools. Small-scale experiments will not validate such models, but the data from these experiments can be used to improve the chemical kinetics and physical constants of the models.

A.2 ADDITIONAL SENSITIVITY TESTS

The following tests are not prescribed for IHE qualification, but they are traditionally used to characterize explosives for handling and shock sensitivity.

A.2.1 Susan Test

The Susan test is a projectile impact test designed to assess the relative sensitivity of an explosive under field conditions of crushing impact. An explosive test sample 5.1 cm in diameter x 10.2 cm long and weighing about 0.4 kg (0.9 lb) is loaded into a Mod 1 Susan projectile and gun fired at the desired velocity at an armor-plated target. A minimum of three tests are required for IHE qualification, and the results must indicate that the explosive output is less than or equal to 7 percent of TNT output at a given projectile velocity of 333 m/sec. Comparing this explosive energy, HMX-based LX-04 explosives measure above 40 percent of TNT output (Dobratz, August 1995), and TATB is barely distinguishable from mock at these impact velocities. Thus HMX-based explosives are more sensitive than TATB-based explosives in the Susan test. The Susan test has been supplemented by the Steven or Spigot Gun test described in Appendix B.

A.2.2 Wedge Test

The wedge test is a typical shock initiation test. The test data are in the form of run distance to detonation for variable input pressures; data on explosive performance and hazard response are provided. The wedge test is not a screening test for IHE at Pantex, but provides quantitative data on the differences in shock sensitivity among explosives.

In the wedge test, a planar shock wave is introduced into the explosive to be tested. As the shock progresses through the explosive, it generates hot spots that build up to a detonation. The objective of the wedge test is to determine the run-to-detonation point at which the detonation wave overtakes the shock wave. This point is characterized by a unique time and distance to detonation for a specific set of input conditions. A streak camera is used to record the wedge test event. The surface of the wedge is mirrored to reflect light into the camera. When either the shock wave or detonation wave reaches the surface, the surface distorts so that the light is no longer reflected into the camera. As the detonation wave overtakes the shock wave, the slope of the reflected light trace on the film changes. Thus, the run-to-detonation point can be determined from the film record. Schematics of the wedge test set-up and wedge test streak camera record are shown in Figure A-2.

The traditional method for plotting the wedge test data is known as the Pop-plot, after Alfonso Popolato. Popolato found that over a range of input pressures, log-log plots of run to detonation (x^*) or time to detonation (t^*) versus pressure (P) are linear. The equation for the Pop-plot over the linear range, in run-to-detonation versus pressure form, is then (Gibbs and Popolato, 1980):

$$\log x^* = A + B \log P$$

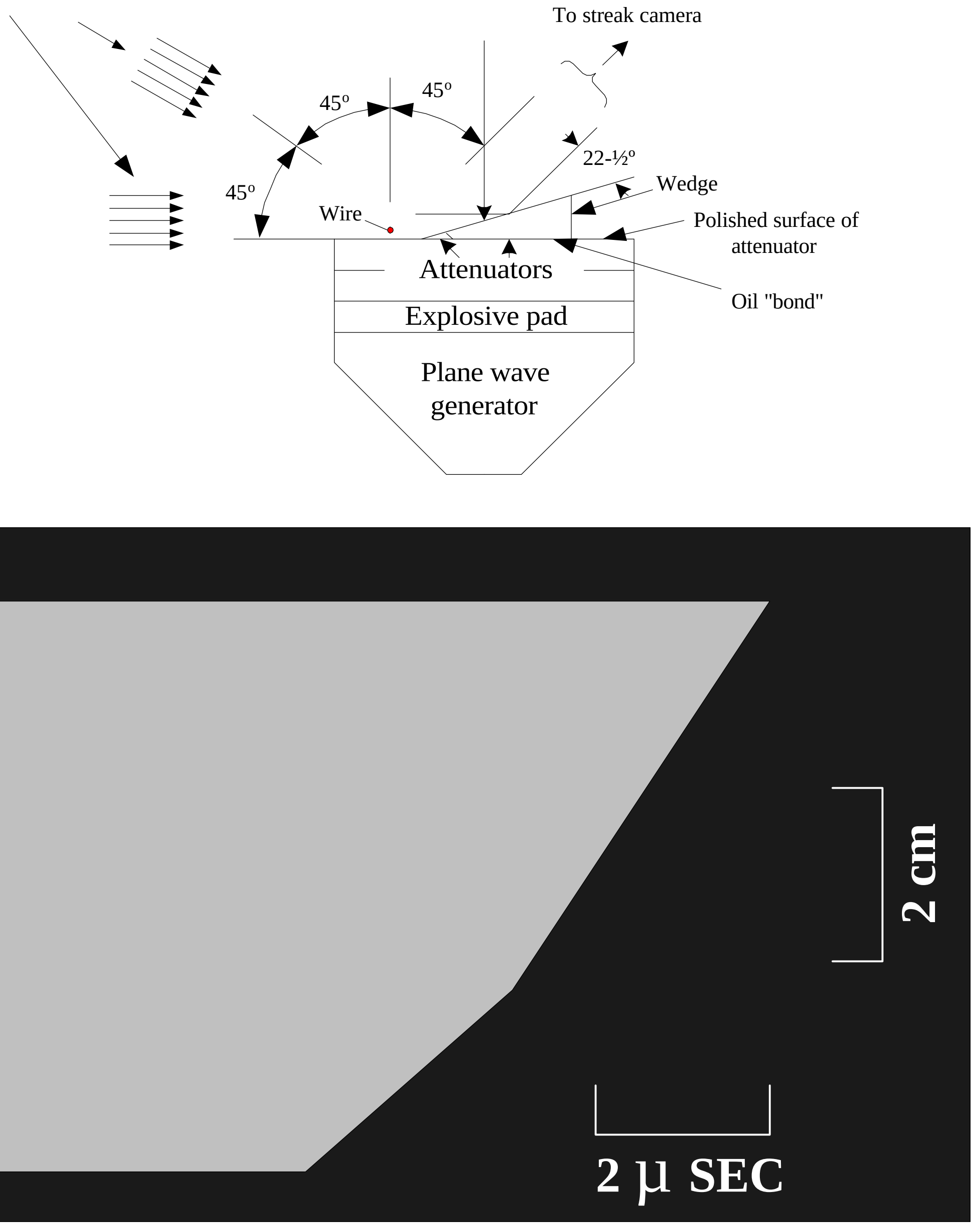


Figure A-2. Smear Camera Record of a Typical Explosive Wedge

In this form, P is in Gigapascals, x* is in millimeters, and A and B are determined from a least-squares fit in the log-log plane. Similarly, time to detonation versus pressure takes on the same form with different constants.

The Pop-plot data for HMX and TATB can be represented in by the following two equations:

HMX (density 1.9)

$$\log P = 1.18 - 0.59 \log x^* \text{ for the range: } 4.4 < P < 9.6 \text{ Gpa}$$

TATB (density 1.9)

$$\log P = 1.42 - 0.40 \log x^* \text{ for the range: } 11 < P < 16 \text{ Gpa}$$

Plots of these equations reveal the difference in shock initiation sensitivity. For a given run distance, the pressure required to initiate detonation in TATB is considerably larger, especially at longer run distances. The fact that the curves have been derived experimentally over two significantly different input pressure ranges indicates that TATB-based explosives are less sensitive than HMX-based explosives.

APPENDIX B

IHE SUBASSEMBLY AND OTHER LARGE-SCALE THERMAL AND MECHANICAL TESTING

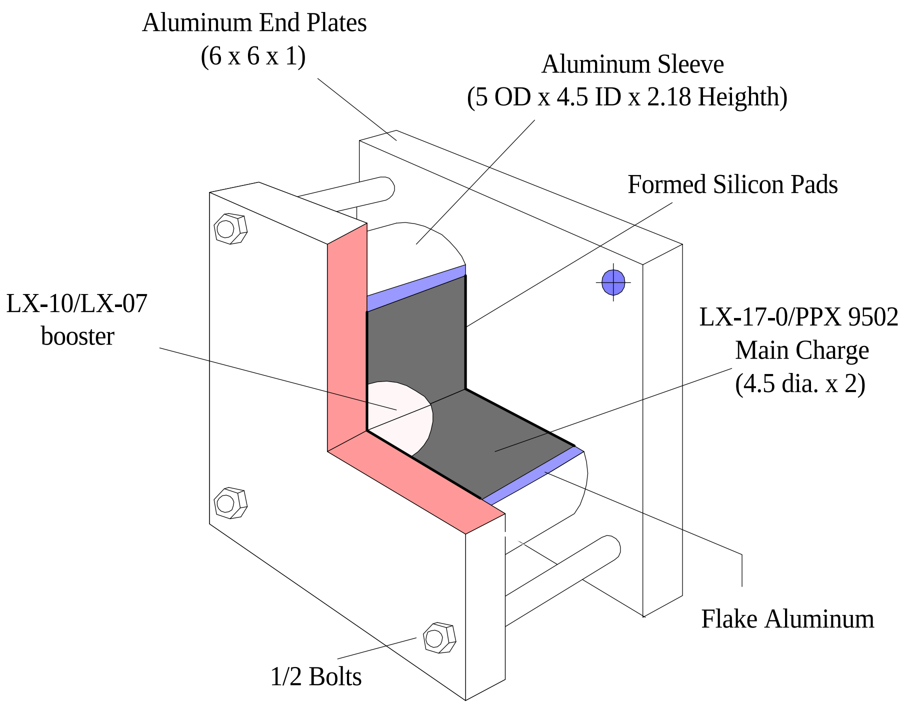
This appendix reviews the results of IHE subassembly and other large-scale testing and modeling. The *DOE Explosive Safety Manual* (U.S. Department of Energy, March 1996) requires that a suite of tests be performed to qualify an IHE subassembly for use in an IHE weapon. The following mechanical and thermal tests and associated success criteria are required at a minimum:

- Spigot test: No burning or violent reaction of main charge for 120 ft drop on booster in LANL test (three trials).
- Bonfire test: No detonation or violent reaction of main charge when engulfed in a fire (three trials).
- Slow cook-off test: No detonation or violent reaction of main charge when slowly heated to a reaction (three trials).
- Bullet impact test: No detonation or violent reaction of main charge with a three-round burst of 7.62 mm projectile impacts on booster (six trials).
- Skid test: No burning or violent reaction of main charge for up to 20 ft drop at 14–15 deg test angle (or sample failure) using subassembly configuration modified for impact on the booster (three trials at worst-case condition).

If conventional explosives are used in a subassembly, the entire subassembly must be qualified by the prescribed tests. Additional thermal testing and modeling have been performed by LANL and LLNL to demonstrate fundamental differences in the properties of IHE. The tests prescribed by the *DOE Explosive Safety Manual* and some of the additional tests designed and used to demonstrate the insensitivity of IHE weapons under environmental extremes are described in the following sections.

B.1 LARGE-SCALE FAST HEATING OR “BONFIRE” TESTS

IHE subassembly simulations of the LLNL and LANL systems were conducted using the test assembly shown in Figure B-1. Since the B83 and B61 bombs have the greatest confinement and represent the worst case for thermal safety, only these mockups were used in the thermal simulations. Two B83 (LX-17 main charge, LX-10 booster) and two B61 (PBX-9501 main charge, LX07 booster) simulations were carried out by immersion in a jet fuel fire, which resulted in no detonations or violent reactions of the main charges (Mason & Hanger-Silas



Note: All dimensions in inches.

Figure B-1. Thermal Test Assembly

Source: Mason & Hanger-Silas Mason Co., Inc., August 1985.

Mason Co., Inc., June 1986). The high explosive (HE) either burned completely or was thrown from the fire after the bolts holding the subassembly together broke. The subassemblies thus passed the criterion of no detonation or violent reaction that could disperse nuclear materials.

Data from weapon configuration bonfire tests were also obtained during weapon development for the B83 and B61 at LLNL and LANL, respectively (Mason & Hanger-Silas Mason Co., Inc., June 1986). One full-up B83 assembly with all live HE but without the nuclear material was tested in a JP-4 fuel fire. The subassembly broke apart as a result of a pressure buildup from thermal decomposition, with no detonation. The LANL test on the B61-like assembly resulted in controlled burning and no detonation in two trials. The test used PBX-9404 in the booster charge, which is less thermally stable than the LX-07 in the B61, and thus was a more conservative test.

The following additional mock IHE weapon fire tests were done by the national laboratories (Streit, January 27, 1992) to demonstrate thermal insensitivity (no violent reactions) in various rapid-heating environments:

- Mock W84 Fuel Fire, July 1985 (U)

- Mock W87 Fuel Fire, April 1986 (U)

- Mock W87 Solid Propellant Fire, June 1986 (U)

- Mock W85 Solid Propellant Fire, 1984 (U)

The IHE burned in all of these tests, but there was no violent destruction of the mock pit (Streit, January 27, 1992; Moen, 1992).

B.2 SLOW COOK-OFF TESTS

B.2.1 Tests Required by *DOE Explosive Safety Manual*

Slow heating is the worst-case heating scenario because the entire explosive charge is allowed to reach a runaway reaction condition nearly simultaneously. This case results in a larger energy release and more violence than fast heating, in which only a smaller layer of HE reacts because of limited thermal conduction, and the overpressure bursts the vessel, relieving the confinement and quenching the reaction.

The slow-heating test simulations were conducted using the same configurations as bonfire simulations for both the B83 and the B61 (see Figure B-1). Heater tape was wrapped around the aluminum cylindrical sleeve section of the devices, which were heated at a rate of 2°C/min. Two tests were performed in the fully cased configuration and three uncased (the end plate opposite the booster removed) for each weapon system. The bolts were broken in one B83 simulation. In all the remaining tests, the subassembly was deformed or partially melted. Imbedded thermocouples measured initial reaction temperatures from 324°C to 362°C and excursions peaking up to 600°C at various times in several tests as the explosive burned. The slow cook-off test resulted in the most damage to the explosive, as expected. Part of the main-charge explosive was recovered in only two of the ten tests; however, the main charge did not detonate in any of the tests.

B.2.2 Additional Full-Scale Slow Cook-off Tests on Nuclear Explosive-Like Subassemblies

Full-scale weapon-like simulations of the B83 with all live HE, including the boosters and detonators but without the live pits, were conducted. The subassemblies were heated with radiant heat at the rate of 0.15°C/min and instrumented with thermocouples. The B83-like device rapidly disassembled at 200°C but did not detonate, and fragments of the main-charge LX-17 were recovered. The booster reaction was violent, but it was “well below the level of a booster detonation” and could not have initiated the main charge (Mason & Hanger-Silas Mason Co., Inc., June 1986, p. 19). No evidence for the above statement is provided in the cited Pantex report. The report also states that the live detonators were rendered inoperable by the sublimation of the PETN at 138°C.

A similar slow cook-off test of the simulation of the B61 3/4 center case with all live HE had similar results. Heater tape was used to heat the assembly, surrounded by vermiculite insulation; reaction occurred at 260ºC after 5 hours. Some PBX-9502 burned, but "no violent reaction of the main charge occurred " (Mason & Hanger-Silas Mason Co., Inc., June 1986). Also, in this case, the PETN in the detonators had probably disappeared by sublimation long before the main charge or booster reaction took place.

B.2.3 Additional Large-Scale Simulations and Modeling at LLNL: Hollow Cylinder Experiment and Modeling

LLNL performed several large-scale heating experiments on LX-17 in a confined cylindrical geometry; the results of these experiments were published along with those of the same experiments on several conventional explosives (Chidester et al., 1997). Approximately 6.6 kg of LX-17 in the shape of a confined hollow cylinder was subjected to thermal soaking at temperatures near the critical temperatures for thermal explosion for 4–8 hours; the temperature was increased at 3.3 °C/hour to reaction. The reaction burst the vessel confinement, but the vessel did not violently explode, as indicated by the lack of measurable velocity of the inner and outer confining shells, recorded by adjacent velocity pins. Three trials were performed at various confinements; the heaviest confinement was provided by steel 2 cm thick; the lightest was provided by aluminum 5 mm thick. In the same experiments, LX-10, a conventional explosive, resulted in violent explosions and measurable velocities of the metal confining vessel walls. These highly instrumented, slow cook-off rate experiments indicated that LX-17 will not react violently in a heavily confined vessel or in a weapon, which is less heavily confined. The hollow-cylinder experiments provide measurements of temperatures, times, and quantitative energetics of the thermal reactions, all of which support the conclusions of the earlier weapon configuration tests. It appears that the TATB decomposes at the thermal "explosion" time and pressurizes the container until the pressure is relieved by rupture of the container.

B.2.4 Thermal Modeling of TATB

The hollow-cylinder heating experiments were modeled with the Chemical TOPAZ code (Chidester et al., 1997) with a three-step model involving two solid intermediate chemical reactions that was successfully applied to small-scale ODTX experiments (Tarver et al., 1996). The Chemical TOPAZ code calculates the time of runaway chemical reaction (time of vessel rupture), the temperatures, and the geometric positions of the onset of reaction. The calculations predict these measured times and temperatures for the LX-17 experiments well. This agreement indicates that the chemical kinetics of TATB decomposition are well enough understood, although the violence of the pressure burst cannot be calculated with this code. The fact that this instrumented, large-scale experiment was predicted with a model containing measured TATB properties, and that the results were similar to those of full-scale, weapon-like configurations, provides credibility that the weapon-like experiments are indicative and representative of IHE behavior in this most severe and demanding accident scenario.

B.2.5 Additional LANL Thermal Tests on Powdered TATB

LANL carried out burning experiments on powdered TATB to measure the violence of pressurized reactions in heavy confinement (Assay and McAfee, July 1993). Powdered TATB at three bulk densities (1.18, 1.23, and 1.30 g/cm^3) with no binder was ignited in very strong steel cylinders by means of pyrofuse. The TATB burned vigorously until the pressure burst the end caps of the vessel; then the TATB ceased to burn. The conclusions resulting from these experiments are that TATB will not undergo a self-sustaining deflagration at pressures less than 1500 psi, and it will not transition from burning to detonation, even in a heavily confined condition. The results also indicate that divided or damaged TATB presents no additional thermal hazard. The results of these experiments are consistent with those of the tests described above in which heavy confinement resulted in only a deflagration. However, small-scale experiments at Sandia National Laboratories have recently indicated the possibility of a TATB detonation as the result of heating under very heavy confinement (Renlund et al., 1998).

B.2.6 Reaction of TATB with Molten Metal.

In a related set of experiments, molten neodymium/iron (75/50 w/w) was dropped onto bare TATB. The TATB burned but did not detonate, and the reaction did not significantly add to the energy release rate (Maienschein et al., 1995). The burn rate of the TATB measured during this experiment was an order of magnitude less than that of conventional explosives.

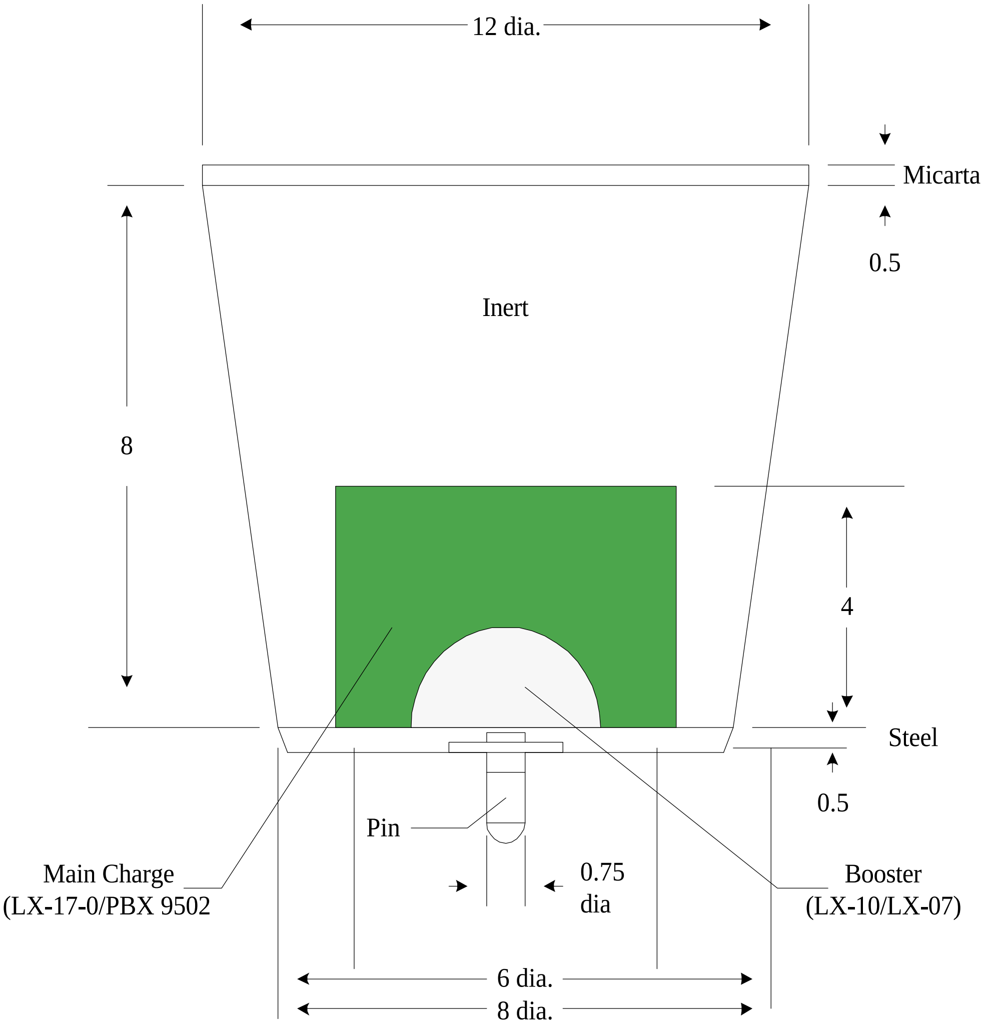
B.3 LARGE-SCALE MECHANICAL TESTING OF IHE SUBASSEMBLIES

B.3.1 Spigot (Drop) Test

The spigot test is designed to simulate the worst-case IHE weapon-dropping accident, in which the explosive is subjected to impact and shear at the worst position, i.e., in the more sensitive booster explosive. The test consists of dropping the spigot test subassembly from a 120 ft tower at LANL. The test assembly is depicted in Figure B-2. The explosive boosters are positioned in the explosive charge under the impact point of the “pin.” All 10 drops with B83 and LANL simulants listed in the figure were successful. There were some reactions detected from the boosters, but more than 95 percent of the main-charge explosive was recovered in each case. The subassemblies were completely destroyed, and explosive fragments were scattered about the impact area (Mason & Hanger-Silas Mason Co., Inc., June 1986).

B.3.2 Bullet Impact Tests

Bullet impact tests were conducted on test configurations depicted in Figure B-3. The gun used was an M-14 M1A with an average bullet velocity of 2834 ft/s (864 m/s). Three-round bursts of 30-caliber (7.62 mm) bullets were aimed at the center of the fixture at the location of the sensitive booster explosive, and the 0.25-inch-thick front plate allowed entry of the bullets and brought them to rest in the explosive. This was thought to be the worst-case scenario, where the hot bullet maximizes its contact with the explosive. Three trials each for subassemblies representative of the B83 and the LANL designs were conducted. The boosters reacted to varying degrees upon impact of the bullets, but the reaction did not consume the main-charge explosive in any trials, and most of the main charge was recovered.



Proposed Spigot Tests

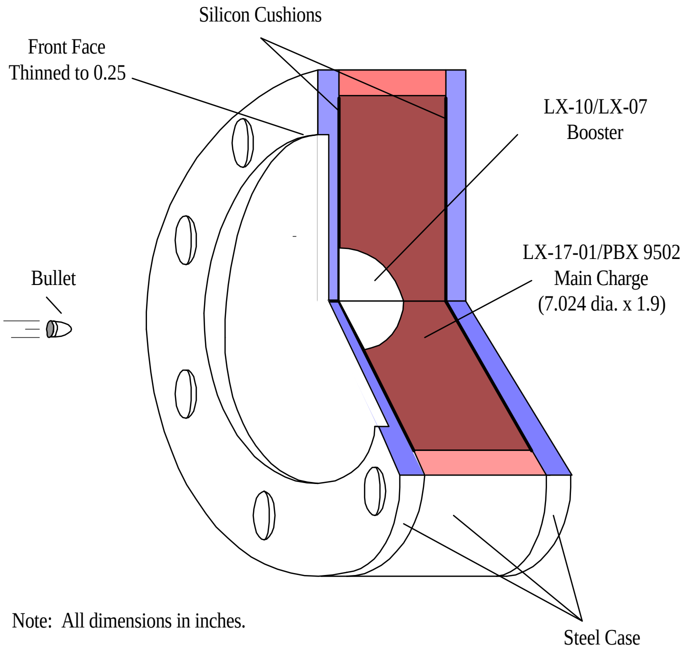
System	Booster/Main Charge	Minimum Number of Tests
B83	LX-10/LX-17-0	3
LANL	LX-07/PBX 9502	3

Figure B-2. LANL Spigot Test Assembly

Source: Mason & Hanger-Silas Mason Co., Inc., June 1984.

Proposed 7.62 mm Bullet Impact Tests

System	Booster/Main Charge	Rounds/Test	Minimum No. of Tests
B83	L-10/LX-17-0	3	6
LANL	LX-07/PBX 9502	3	6



Note: All dimensions in inches.

Figure B-3. Bullet Impact Test Assembly

Source: Mason & Hanger-Silas Mason Co., Inc., August 1985.

Additional bullet tests were done on LLNL assembly mockups. Test involving 30-caliber projectile impacts were performed on LX-17 and pressed TATB. One series was done on LX-17 at elevated temperatures up to 250°C with no detonations, but there was a light explosion, described as a level 3 reaction, with 0 equal to no reaction and 5 a detonation (Honodel, 1984). LANL performed additional bullet tests on IHE weapon cross sections containing CHE boosters and in some trials detonators, using M-16 and 50-caliber bullets. IHE burning resulted, but no violent reactions (Dobratz, August 1995).

B.3.3 TATB (LX-17) Detonation Threshold Parameters for Projectile Impact

TATB will detonate with a projectile-induced reaction of high enough velocity, as one might expect. The threshold for projectile initiation in two-stage light gas gun experiments was found to be 5.67 km/s (5,670 m/s) with a steel rod 6 mm in diameter by 19 mm long, and 6.53 km/s with a tantalum plate 24.2 mm in diameter (Dilestraty and Brandt, 1982).

B.3.4 New Low-Velocity Heavy Projectile Impact Test: Steven or Spigot Gun Test

Chidester and Green (July 1993) impacted explosives with heavy, round-nose projectiles to obtain thresholds for low-velocity initiation of violent reaction in cased charges. In this Steven test, termed the spigot gun test by LANL, the metal projectile is accelerated by a gas gun into an explosive charge 11 cm in diameter by 1.28 cm thick confined by steel. The test is similar to the Susan test described in Appendix A, except that this test uses less explosive, produces larger overpressures for the same impact velocity, and yields more reproducible results. LX-17 heated to 260°C did not react with a 120 kg steel projectile at the velocity limit of the gun used—141m/s (Chidester and Green, July 1993). However, no experiments were done on IHE subassemblies or weapon mockups.

B.3.5 Skid Test

The skid test is a drop/friction test designed to simulate drops of large charges at low angles, which adds the hazard of frictional heating to the drop scenario. In the test, a hemispherical charge attached to a tether is dropped from a distance, so the charge follows a circular arc, striking a planar roughened steel pad at an angle. Three drops each from 20 ft for the LLNL and LANL explosive main-charge billets at an angle of 14 deg onto the booster resulted in some reaction of the booster explosives, but no violent reaction or burning of the main charges. By comparison, a large billet of LX-10 (the LLNL CHE booster material) detonates at a height of approximately 38 cm under similar conditions (Dobratz and Crawford, January 31,1985). The LX-10 has a low threshold for reaction (1 cal/cm^2) for frictional heating in such a test (Chidester and Green, July 1993); however, in the IHE subassemblies, there apparently is an insufficient amount of LX-10 in the small booster to develop a reaction before the confinement is relieved.

APPENDIX C

CHEMICAL AND PHYSICAL EXPLANATIONS FOR THE SAFETY OF TATB (IHE)

Two extensive reviews and hundreds of references address the insensitivity of TATB and its formulations (Rice and Simpson, 1990; Dobratz, August 1995). Laboratory mechanical impact tests (drop weight, run distance to detonation, and gap tests) measure the shock and impact (crush) responses of TATB compared with those of HMX. Thermal tests (DTA, ODTX, Henkin critical temperature) measure the response to heating of small samples. Large-scale tests conducted on samples close to the size used in weapons are more relevant for safety, and in some cases they verify the results of the small-scale laboratory tests. Thermal tests were performed on cased and uncased large charges in jet fuel fires, and heated slowly with heating tape or radiant heat. Skid tests, assembly drops from a tower, and spigot (puncture) tests are large-scale impact tests conducted for some accident scenarios.

Studies of shock initiation and thermal decomposition of explosives have indicated that the mechanical (shock) and thermal insensitivity of TATB are related. Hot spots, which are microscopic points of high temperature resulting from a concentration of mechanical energy, have been postulated to explain explosive shock initiation. Hot spot theory, the leading theory for the shock initiation of explosives, has been developed and expanded for years since first being introduced. The formation and history of hot spots in explosive materials have been shown through calculations to support the observations of shock and impact experiments. An investigation of the kinetics of the thermal decomposition reactions of TATB and its intermediate compounds to form final products provides the basis for the thermal and impact responses of TATB at a macroscopic level. These results go a long way toward explaining the pronounced differences between TATB and other explosives, such as HMX. As one might expect, hot spot behavior depends on the thermal properties of explosives.

The thermal decomposition kinetics models for TATB and HMX (used for all DOE CHE explosives) are presented and compared by Tarver et al. (1996) to explain the thermal behavior of TATB and HMX explosives in the ODTX experiments. The TATB and HMX chemical reaction pathways are summarized as indicated in the following chemical reaction sequences for each:

$$\text{TATB} \rightarrow \text{solid fragments} + H_2O \rightarrow \text{solid fragments} + H_2O \rightarrow \text{final products}$$

$$\text{HMX} \rightarrow \text{solid fragments} \rightarrow \text{intermediate gases} \rightarrow \text{final products}$$

TATB's first two reactions are endothermic, yielding solid intermediates, and the last is exothermic. HMX also has two sets of intermediates and three reactions, but the second and third reactions are exothermic, yielding gases. Moreover, water, which does not enter into further reactions, is produced by TATB in all three reactions, whereas HMX produces water only in the final products. The endothermicity of the initial TATB decomposition steps explains qualitatively the thermal stability of TATB. The ODTX results are quantitatively modeled by the Chemical TOPAZ heat flow code using the postulated chemical kinetics. In addition to the fire safety of TATB assemblies, the differences between the thermal properties of TATB and HMX can be used to explain the fundamental reasons for the shock iniation insensitivity of TATB through hot spot theory (Tarver et al., 1996).

The hot spot model is used to explain qualitatively how mechanical impact causes shock iniation in explosives. The following is a simplified explanation meant to show the coupling between shock and thermal properties. The ease or difficulty of initiation depends on how well the hot spots can form initially, expand (burn), and coalesce to form a detonation wave in the explosive. Each step is strongly influenced by the explosive's chemical and physical properties. The initial formation of hot spots has never been completely understood, although numerous theories have been advanced to explain the phenomenon. In any case, some mechanism concentrates the available mechanical energy into chemical energy at discrete sites, which leads to chemical bond breaking. This could occur by the physical interaction of the shock wave with crystal boundaries, voids and other imperfections in the solid, or phonon (crystalline translational) energy to vibron (molecular vibrational) energy coupling in the crystalline material. The hot spot then begins to react (burn) at these discrete positions to either grow or extinguish, depending on the heat release rate and the thermal conductivity. If the rate of heat release exceeds the heat lost by conduction, the hot spots will grow and coalesce to a shock and a detonation if the dimensions of the material allow it. Otherwise, the hot spots will begin to cool, and they will not grow and coalesce to form a detonation. This generic hot spot mechanism explains why TATB is less sensitive to shock than HMX. Hot spots in TATB are cooler than those in HMX for the same stimuli because of the thermodynamics and kinetics of the reactions of TATB described above, and once they have been created, the higher thermal conductivity of TATB cools them more rapidly than hot spots in HMX. Thus the hot spot model for shock initiation can be used to explain qualitatively the difference between TATB and HMX in fundamental physical chemical terms.

Fundamental solid-state crystal properties and energy transfer mechanisms have been used to explain impact/shock initiation (Coffey, 1993). Coffey ascribes the mechanism of hot spot formation to shear during plastic flow. He describes how quantum processes of energy localization in regions of dislocation concentration originate from moving dislocations in the lattice. The method can be used to predict trends in drop height and shock initiation sensitivity, which represent two distinctly different phenomena, using the same theory. The unique TATB response to impact relative to CHEs can thus be predicted to some degree of accuracy on the basis of fundamental molecular and lattice properties.

REFERENCES

Assay, B. W. and J. M. McAfee, July 1993, “Temperature Effects on Failure Thickness and the Deflagration-to-Detonation Transition in PBX-9502,” *Proceedings of the Tenth International Detonation Symposium*, Office of Naval Research, ONR 33395-12, Arlington, VA, p. 485.

Boyer W., June 1, 1986, *Final Test Report, WLM-7903 Propellant Burn Test* (U), COMW-86-0283, Lawrence Livermore National Laboratory, Livermore, CA.

Boyer W., April 22, 1986, *Final Test Report, W87 LTU-4 Fuel Fire Test* (U), COMW-86-0209, Lawrence Livermore National Laboratory, Livermore, CA.

Boyer W., October 17, 1986, *Final Test Report*, *LTU-7 Propellant Burn Test* (U), COMW-86-0614, Lawrence Livermore National Laboratory, Livermore CA.

Catalano E., R. McGuire, E. Lee, E. Wrenn, D. Ornellas, and J. Watson, 1976, “The Thermal Decomposition and Reaction of Confined Explosives,” *Proceedings of the Sixth International Symposium on Detonation*, p. 214.

Chidester, S. K. and L. G. Green, July 1993, *Proceedings of the 10th International Detonation Symposium*, ONR 33395-12, Boston, MA, p. 786.

Chidester, S. K., C. M. Tarver, L. G. Green, and P. A. Urtiew, 1997, “On the Violence of Thermal Explosions in Solid Explosives,” *Combustion and Flame*, 110:264-280.

Coffey, C. S., 1993, *The Initiation of Explosive Crystals by Shock or Impact*, Proceedings of the 10th International Symposium on Detonation, Boston, MA.

Delistraty, J. and H. Brandt, 1982, “Detonation Properties of 1,3,5-triamino 2,4,6-trinitrobenzene When Impacted by Hypervelocity Projectiles,” *Propellants, Explosives, and Pyrotechnics 7* (113).

Dietel, G. E. and D. F. Cruff, September 25, 1997, *W87 Weapon Safety Specification* (U), Sandia National Laboratories, SS458804, Albuquerque, NM.

Dobratz, B. M., August 1995, *The Insensitive High Explosive Triaminotrinitrobenzene (TATB): Development and Characterization—1888 to 1994*, Los Alamos National Laboratory, LA-13014-H, Los Alamos, NM.

Dobratz, B. M., and P. C. Crawford, January 1985, *LLNL Explosives Handbook*, UCRL-52997, Lawrence Livermore National Laboratory, Livermore, CA.

Gibbs T. R. and A. Popolato, 1980, *LASL Explosive Property Data*, University of California Press, Berkeley, CA.

Honodel, C. A., July 1981, *Explosive Reaction of Cased Charges by Impacts of .30 Calibre Bullets*, Lawrence Livermore Laboratory report UCRL-86480, Livermore, CA.

Maienschein, J. L., A. L. Nichols III, and J. F. Wardell, 1995, “Reactions of TATB–Based Explosive with Molten Metal” *Propellants, Explosives, and Pyrotechnics,* Vol. 20 p. 287.

Mason & Hanger-Silas Mason Co., Inc., June 1984, *IHE Material Qualification Tests Description and Criteria*, MHSMP-84-22, Pantex Plant, Amarillo, TX.

Mason & Hanger-Silas Mason Co., Inc., August 1985, *Revised IHE Subassemblies Test Plan for the B83, B61 3/4/6/7/8, W80, W81, and W85,* MHSMP-85-40, Pantex Plant, Amarillo, TX.

Mason & Hanger-Silas Mason Co., Inc., June 1986, *IHE Subassembly Test Results for the B83, B61 3/4/6/7/8, W80, W81 and W85*, MHSMP-86-1, Pantex Plant, Amarillo, TX.

Mason and Hanger Corporation, December 18, 1998, *Interim Fire Hazards Evaluation of the W87 Process*, Amarillo, TX.

McGuire, R. R. and R. P. Guarienti, August 1984, *DOE Hazard Classification for Insensitive High Explosives (IHE)*, UCRL-91420, Lawrence Livermore National Laboratory, Livermore, CA.

Moen, W., 1992, *W-87 Test Matrix in Support of the MMIII/W87/W78 Weapon System Safety Analysis* (U), Lawrence Livermore National Laboratory, Livermore, CA.

Renlund, A., W. M. Trott, K. L. Erickson, M. L. Hobbs, and M. R. Baer, 1998, *Characterization of Thermally Degraded Energetic Materials*, Proceedings of the 11th International Detonation Symposium, Snowmass, CO.

Rice, S. F. and R. L. Simpson, 1990, *The Unusual Stability of TATB: A Review of the Scientific Literature*, UCRL-LR-103683, Lawrence Livermore National Laboratory, Livermore, CA.

Scruggs, C. A., June 23, 1998, *Nuclear Explosives Operations in Bays and Cells with Bonded and Unbonded Penetrations of the Faraday Cage*, E.I. No. ED98-029D, Pantex Plant, Amarillo TX, p. 2.

Simpson, R. R., October 27, 1998, Presentation to the staff of the Defense Nuclear Facilities Safety Board at Pantex.

Streit R., January 27, 1992, *DNA/LLNL Warhead Replacement Phase 1 Study: Estimated Thermal and Impact Conditions of Candidate Warheads (U),* Lawrence Livermore National Laboratory, Livermore, CA.

Tarver, C. M., S. K. Chidester, and A. L. Nichols, 1996, “Critical Conditions for Impact- and Shock-Induced Hot Spots in Solid Explosives,” *J. Phys. Chem.*, 100, 5794.

U.S. Department of Energy, February 1993, *Nuclear Explosive Abnormal Environments at the USDOE Pantex Plant*, Albuquerque Field Office, Amarillo, TX.

U.S. Department of Energy, March 1995, *Safety Analysis Report for the Device Assembly Facility at the Nevada Test Site*, Las Vegas, NV, DAF SAR-001-193-5394C.

U.S. Department of Energy, March 28, 1996, *Pantex Plant Safety Analysis Report (SAR), Nuclear Explosive Bays Module*, Draft D, Amarillo, TX.

U.S. Department of Energy, March 1996, *DOE Explosive Safety Manual*, DOE M440.1-1.

U.S. Department of Energy, January 16, 1997, *Revalidation Report of the Nuclear Explosive Safety Study of W87 Disassembly and Reassembly Operations at the USDOE Pantex Plant* (U), DOE Nuclear Explosive Safety Study Group, pp. 19–20.

Von Holle, W. G., October 30, 1998, Memorandum for G. W. Cunningham, Subject: Pantex IHE Safety Review, Defense Nuclear Facilities Safety Board, Washington, D.C.

GLOSSARY OF ACRONYMS

Abbreviation	Definition
BIO	Basis for Interim Operations
Board	Defense Nuclear Facilities Safety Board
CHE	conventional high explosive
D&I	disassembly and inspection
DAF	Device Assembly Facility
DBA	design basis accident
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOE-AAO	DOE Amarillo Area Office
DSC	differential scanning calorimeter
DTA	differential thermal analysis
ESD	electrostatic discharge
HAR	Hazard Analysis Report
HE	high explosive
HMX	($C_4H_8N_8O_8$-octahydro-1,3,5,7,-tetranitro-1,3,5,7-tetrazocine; octogen)
IHE	insensitive high explosive
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
MHC	Mason and Hanger Corporation
NOL	Naval Ordnance Laboratory
NTS	Nevada Test Site
ODTX	one-dimensional time to explosion
PMMA	polymethyl-methacrylate
PETN	pentaerthritoltetrianitrate
SAR	Safety Analysis Report
SSCs	systems, structures, and components
TATB	triaminotrinitrobenzene
TNT	trinitrotoluene