OVERVIEW OF PROPOSED JOINT AIR FORCE AND NAVY SUBSCALE FAST COOK-OFF PROGRAM

Daniel F. Schwartz
Air Force Research Laboratory Propulsion Directorate, Edwards AFB, CA

Alice I. Atwood, D. Tri Bui, Melody K. Rattanapote
Naval Air Warfare Center Weapons Division, China Lake, CA

A. Garn Butcher
Safety Management Services, West Jordan, UT

ABSTRACT

Department of Defense (DoD) and Department of Transportation (DOT) hazards classifiers as well as propulsion hazards personnel from the military and industry have long recognized the potential hazards of storage and transportation of solid rocket motors. DoD hazard classification guidelines in Technical Bulletin (TB) 700-2, NAVSEAINST 8020.8B, TO 11A-1-47, and DLAR 8220.1 (hereafter referred to as TB 700-2), and 49 CFR 100-180, UN Test Manual, and other related documents address the specifics of testing and classifying materials and articles containing explosives.

At the present time, the Department of Defense Explosive Safety Board (DDESB) and Joint Hazard Classifiers (JHC) require compliance with the United Nations (UN) Test Series 6 (c) external fire fast cook-off (FCO) test protocol (or pre-approved test plan) for any solid propellant system that is to be classified into Hazard Divisions 1.1, 1.2, 1.3 and 1.4. The protocol requires that full-scale articles in their shipping containers be subjected to a series of external fire FCO tests and meet the specific requirements as listed in TB700-2 to qualify for a Hazard Division (HD) 1.3 classification.

A project is described to identify the critical features needed for a subscale analytical and experimental alternative to the UN Test Series 6 (c) external fire FCO test protocol. The work would include a definition of fire scenarios and characteristics of the fire hazards associated with transportation and storage of large rocket motors. The response of an item to thermal threat would be obtained through the compilation of existing data, in combination with a synergistic analytical and experimental program. A hazards response protocol, which identifies the controlling parameters of fast cook-off, would be generated. Analytical tools would be used to perform a sensitivity analysis on the controlling parameters to identify their importance. Subscale testing would be performed to verify these parameters and to validate the analytical models.

INTRODUCTION

When the DoD revised its TB 700-2 hazard classification guidelines[1] in January 1998, it offered an alternate shock test protocol to the stack test, one of the tests required for hazards classification. Conducting the alternate protocol in lieu of the stack test protocol reduces the amount of full-scale test articles by nine. Originally for the propellant sample to pass the alternate test and obtain a HD 1.3 classification required a non-detonation (“no-go”) when subjected to a shock stimulus of >250 kbar (>3.5 Mpsi). In addition, there is no alternate protocol for the external fire test which still requires one full-scale test article for obtaining a final hazard classification (FHC).

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **MAY 2005**	2. REPORT TYPE	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Overview of Proposed Joint Air Force and Navy Subscale Fast Cook-off Program**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Daniel Schwartz; Alice Atwood; Tri Bui; Melody Rattanapote; A Butcher**	5d. PROJECT NUMBER **5026** 5e. TASK NUMBER **03BG** 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory (AFMC),AFRL/PRSB,4 Draco Drive,Edwards AFB,CA,93524-7160**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Department of Defense (DoD) and Department of Transportation (DOT) hazards classifiers as well as propulsion hazards personnel from the military and industry have long recognized the potential hazards of storage and transportation of solid rocket motors. DoD hazard classification guidelines in Technical Bulletin (TB) 700-2, NAVSEAINST 8020.8B, TO 11A-1-47, and DLAR 8220.1 (hereafter referred to as TB 700-2), and 49 CFR 100-180, UN Test Manual, and other related documents address the specifics of testing and classifying materials and articles containing explosives. At the present time, the Department of Defense Explosive Safety Board (DDESB) and Joint Hazard Classifiers (JHC) require compliance with the United Nations (UN) Test Series 6 (c) external fire fast cook-off (FCO) test protocol (or pre-approved test plan) for any solid propellant system that is to be classified into Hazard Divisions 1.1, 1.2, 1.3 and 1.4. The protocol requires that full-scale articles in their shipping containers be subjected to a series of external fire FCO tests and meet the specific requirements as listed in TB700-2 to qualify for a Hazard Division (HD) 1.3 classification. A project is described to identify the critical features needed for a subscale analytical and experimental alternative to the UN Test Series 6 (c) external fire FCO test protocol. The work would include a definition of fire scenarios and characteristics of the fire hazards associated with transportation and storage of large rocket motors. The response of an item to thermal threat would be obtained through the compilation of existing data, in combination with a synergistic analytical and experimental program. A hazards response protocol, which identifies the controlling parameters of fast cook-off, would be generated. Analytical tools would be used to perform a sensitivity analysis on the controlling parameters to identify their importance. Subscale testing would be performed to verify these parameters and to validate the analytical models.

15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**37**	

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

In January 2002, the TB 700-2 alternate test protocol for hazard classifying large rocket motors was revised as a result of deliberations involving the JHC, DDESB, Joint Army-Navy-NASA-Air Force (JANNAF) propulsion industry representatives, and the DOT. The 2002 guidelines lowered the dividing line between HD 1.1 and 1.3 propellants back down to the previous 70 kbar (>1,015,264.21 psi) shock stimulus for two of the three options (Options 2 and 3) but required shock sensitivity testing at either 150% of the unconfined critical diameter (D_c) (minimum of 5 inches), or motor diameter in "motor like" confinement. Option 1 of the revised alternate test protocol is a Super Large-Scale Gap Test (SLSGT), zero card shock sensitivity test at >250 kbar.

The 2002 revision of TB 700-2 with additional alternates to the test protocol for hazard classifying large rocket motors (that are transported individually) offers considerable flexibility with respect to the shock sensitivity test. The solid rocket community still has concerns with the protocol, specifically the cost prohibitive full-scale test article requirement for the external test and the assessment of fragment throw relative to large rocket motors. Current restrictions would categorize many large rocket motors into a HD 1.2 classification.

To address the current hazard classification concerns of the solid rocket community and to prevent possible hazard classification issues for future Intercontinental Ballistic Missile (ICBM) systems, a program has been sponsored by the Air Force. The goal of this program is to develop a subscale hazard classification protocol for large rocket motors. The protocol must address fragment throw restrictions relative to HD 1.2 and 1.3 with respect to large solid rocket motors.

This paper outlines a proposed effort to develop an acceptable alternate subscale test protocol to the external fire test currently used for hazard classification of large rocket motors to fulfill the intent of TB 700-2 and ultimately be considered by the DDESB and JHC for incorporation into future hazard classification guidelines.

BACKGROUND

UN Test Series 6 Protocol

UN Test Series 6 is mandatory for obtaining a final hazard classification in Hazard Divisions 1.1 (Mass explosion), 1.2 (Non-mass explosion, fragment producing), 1.3 (Mass fire, minor blast, or fragment) and 1.4 (Moderate fire, no blast, or fragment). The test series discriminates between these divisions and consists of three tests:

- Single package test — UN Test 6(a)
- Stack test. — UN Test 6(b)
- External fire (bonfire) test. — UN Test 6(c)

The **single package test** is designed to determine whether initiation or ignition in the package causes a burning or explosive reaction and how those effects could endanger the surroundings. In this test, a detonator of sufficient energy to ensure ignition of the material is set off in the middle of the package. If the result is explosion of the total contents as indicated by:

a. A crater at the test site,
b. Damage to the witness plate under the package,
c. Measurement of a blast, or
d. Disruption and scattering of most of the confining material (a minimum of 1- meter (3.28 ft) of sand on all sides),

then the product is given a HD 1.1 designation. The test is performed three times. For substances intended to function by deflagration, the first trial is initiated with a standard detonator and the last two with an igniter. If the test sample is an article that has its own means of ignition, that ignition source is used (this would be a static test if the article were a rocket motor). The proposed 2005 rewrite of TB 700-2 would not allow static tests for rocket motors. DDESB and the JHC are looking at other means of external ignition such as shape charge jets (SCJ) and donor charges.[2]

The **stack test** is used to determine whether burning or explosion in one package in the stack propagates to the other packages, and how the surroundings could be endangered by this event. At least three articles are required for this test. As with the single package test, a detonator or igniter is used in the stack test to initiate one article. The other packages/articles are situated in the configuration in which they are to be shipped. The criteria for classification for the stack test are similar to those for the single package test. The basic criterion for a HD 1.1 designation is the explosion of virtually the entire contents of the articles. This is evidenced by:

a. A crater at the test site appreciably larger than that given by a single package,
b. Damage to the witness plate beneath the stack which is appreciably greater than that from a single package,
c. Measurement of blast, which significantly exceeds that from a single package, or violent disruption and scattering of most of the confining material (once again, a minimum of 1-meter (3.28 ft) of sand on all sides).

The final test of the UN Series 6 protocol is the **external fire (bonfire) test** and is performed on a stack of packages as configured for transportation or storage. The procedure calls for a minimum of three packages to be supported on a frame and heated by wood or liquid fuel combustion at a rate consistent with what might result from a shipping accident. Three aluminum witness screens are set up 4 meters (13.12 ft) from the edge of the stack of articles. The outcome of this test allows materials to be classified as HD 1.1, 1.2, 1.3 or 1.4. If an explosion of the total contents of the package appears to occur instantaneously, the article is classified as HD 1.1.

The articles are classified as HD 1.2 if debris from the event perforates any of the three aluminum witness plates, or if more than 10 metallic projections, each with a mass exceeding 25 grams (0.05 lbm) are thrown more than 50 meters (164 ft), or if a metallic projectile with a mass exceeding 150 grams (0.33 lbm) is thrown more than 15 meters (49.21 ft) from the edge of the stack. There is a caveat in the fragment throw criteria that states that the fragments are thrown as the result of an 'explosion reaction[1].

Unfortunately, while the definition of 'explosion reaction' includes descriptive terms such as 'violent pressure rupturing', 'air shocks,' and 'blast pressures', it does not quantify these effects to accurately describe the criteria for an event to qualify as an 'explosion reaction'. The product is assigned to HD 1.3 if it cannot be classified as HD 1.1 or HD 1.2, but any of the following four events does occur:

a. A fireball, which extends beyond any of the three witness screens,
b. A jet of flame, which extends more than 3 meters (9.84 ft) from the flames of the fire,

[1] TB 700-2 defines 'explosion reaction' thus: "Ignition and rapid burning of the confined energetic material builds up high local pressures leading to violent pressure rupturing of the confining structure. Metal cases are fragmented (brittle fracture) into large pieces that are often thrown long distances. Unreacted and/or burning energetic material is also thrown about. Fire and smoke hazards will exist. Air shocks are produced that can cause damage to nearby structures. The blast and high velocity fragments can cause minor ground craters and damage (breakup, tearing, gouging) to adjacent metal plates. Blast pressures are lower than for a detonation reaction."

c. The irradiance of the burning product exceeds that of the fire by more than 4 kW/sq. m at a distance of 15 meters from the stack, or

d. Fiery projections emanating from the product are thrown more than 15 meters from the edge of the stack.

If none of the events occur that would place the article into HDs 1.1, 1.2 or 1.3, then the article is classified as HD 1.4, unless it is determined there is no explosive hazard at all, in which case the product is considered for exclusion from Class 1.

DISCUSSION

Concerns With TB 700-2 UN Test Series 6 Protocol

DDESB, JHC, DOT and members in the propulsion community involved with hazard classification have recognized that the current UN Test Series 6 (c) bonfire test protocol is not practical for large solid rocket motors (diameter greater than 12 inches). The test protocol is expensive for large motor development programs because according to the TB 700-2 guidelines, 13 to 15 full-scale rocket motors may be required with three full-scale test articles for the Single Package Test (3 replications), nine full-scale test articles for the Stack Test (3 articles per test with 3 replications) and three full-scale test articles (one test article for a large rocket motor transported singly) for the External Fire Test. There are alternate tests available for the single unit and stack test but not for the external fire which requires a full scale article in its shipping configuration.

There are procedural difficulties in the performance of the external fire test with large solid rocket motors with regard to the prevention of propulsive behavior that could result in the article leaving the facility and the amount of fuel (wood or petroleum based) necessary to heat the motor to reaction. Per the UN Test Series 6(c) Protocol requirements, articles must be heated to reaction and in the case of large rocket motors, this is estimated to be well in excess of 120,000 gallons of fuel. The liquid fuel/external fire test described in North Atlantic Treaty Organization (NATO) standardization agreement (STANAG) 4240 requires the article in its shipping and storage configuration be exposed to a liquid fuel fire. The fuel must extend a minimum of one meter beyond the edge of the item and be of sufficient volume to burn for 150 percent of the estimated time required to cause a reaction.[3] There is no credible storage and transportation scenario that would involve this quantity of fuel.

With large booster motors costing upward of $5 million or more apiece, even one test article is expensive. In addition to the high cost of each test article, there are the extra costs of conducting a large-scale test of this magnitude such as:

- The cost of building a test facility that could contain the amount of fuel needed to heat the motor to reaction and keep a large rocket motor from going propulsive.
- The cost of setup and conducting the test.

When the total costs are factored in, it is likely to escalate to several million dollars per test over the cost of the motor.

In addition to the concerns listed above, there is an additional concern regarding the fragment throw restrictions. The attempt by the DDESB to make TB 700-2 agree with UN regulations has resulted in fragment throw restrictions to less than 50.29 meters (165 feet). Under the latest version of TB 700-2 this would result in a hazard classification of HD 1.2. (if the fragment throw is the result of an explosion reaction) for a majority of the large solid rocket motors. HD 1.2 also contains large artillery shells that present lethal, 4π distribution, and metal fragment hazards out to 381 meters (1250 feet). No HD 1.3 rocket motor under case burst conditions would throw more than a few fragments half that distance.

Deliberations between DDESB/JHC and JANNAF Propulsion Systems Hazards Subcommittee (PSHS) and Propellant Development & Characterization Subcommittee (PDCS) members identified areas of concern with TB 700-2 and paved the way for efforts to address these issues and develop improved hazard classification guidelines. It was suggested that a reasonable subscale alternate test be developed that can be substituted for the current UN Test Series 6 (c).

A joint JANNAF/DDESB Workshop on Hazards Classification of Large Rocket Motors (held 4-8 June 2001) [4] addressed the area of thermal hazards relative to transportation and storage of large rocket motors. The need for improved thermal tests at the sub-scale level was again recognized. It was the conclusion of the workshop that a generic subscale/modeling approach for bonfire testing could not be recommended at that time due to the lack of sufficient technological maturity in the area FCO. It was also concluded, however, that a generic test/modeling approach would be very useful as an engineering tool to comparatively evaluate propellant, motor case and liner combinations with respect to the thermal threat.

Due to the complexity of the FCO hazard, a subscale test procedure for hazard classification would only be successful if it can be coupled with fully validated modeling techniques. Since the 2001 workshop, there have been advancements made in the areas of thermal hazards characterization and modeling under the Department of Energy (DOE) Accelerated Strategic Computing Initiative (ASCI), research performed at the University of Utah’s Center for the Simulation of Accidental Fire and Explosion (C-SAFE) and efforts between the DoD and the DOE National Laboratories through the DoD/DOE Technical Coordinating Groups (TCG). These efforts have reaffirmed the need to incorporate modeling and subscale assessment for thermal hazards characterization.

The purpose of the proposed effort is to develop a sufficiently detailed technology base with respect to the fire threat associated with transportation and storage of solid rocket motors so that a subscale alternate FCO test protocol may be recommended, developed and ultimately be considered by the DDESB and JHC for incorporation into a future revision to the TB 700-2 DoD hazard classification guidelines.

APPROACH

In order to develop an efficacious subscale test, it is necessary to understand the fire scenarios associated with transportation and storage of large-scale rocket motors. It is assumed that these threats are most akin to those currently associated with the hazard known as FCO. It then becomes important to first identify the driving mechanisms of FCO. Without knowing the mechanisms, the relevance of a test, which is less than full-scale, is questionable. The friability or shotgun test has been mentioned as a subscale test to evaluate the Deflagration-to-Detonation (DDT) potential of an energetic material. In this test, a cylindrical sample is fired at a steel plate and the resulting fragments are collected and fired in a closed bomb. If the change in pressure over time (dP/dt) is beyond a certain limit, then the material is defined as susceptible to DDT.

Distribution A: Approved for public release/ distribution unlimited.

Within the test is an assumption about the mechanism driving DDT, the grain is damaged and the resulting rapid burning of the fractured material creates a runaway transition to detonation. Without an understanding of the controlling mechanisms of FCO, development of a useful subscale test would be very difficult. The approach to this effort would include the following:

- Definition of the article's storage and transportation fire threat (hazard classifiers need to know the credible fire threats associated with transportation and storage).
- Characterization of the fire threat (type of fire, size, duration of burn, temperature, flux and heating rates).
- Determination of article response to the fire threat (burn, explosion or detonation).
- Compilation and review of existing FCO data (configuration and critical features of the article, i.e. fins versus no fins, how the test was run and type of fire stimulus).
- Determination of the technical drivers of the controlling reaction mechanisms.

Storage and Transportation Fire Threat Assessment

To gain a better understanding of the credible fire threats associated with the transportation and storage of energetic materials and to support the propulsion community's desire for a subscale FCO test protocol, DDESB and the JHC supported the following two studies/papers:

- "A Survey of Transportation and Storage Accidents Involved in Thermal Events." [5]
- "Development of a Subscale Bonfire Test Protocol." [6]

Survey of Transportation and Storage Accidents Involved in Thermal Events Study

The "A Survey of Transportation and Storage Accidents Involved in Thermal Events" work and paper conducted by NAWC, China Lake was the initial investigation into the description of the thermal stimulus, which might be associated from transportation and storage incidents involving energetic materials/articles.

DDESB maintains a database that contains reports with information regarding incidents within DoD. The database, known as the Explosives Safety Mishap Analysis Module (ESMAM), contains brief summaries of mishaps involving energetic ordnance. For the current study, over 6200 individual incidents that occurred between 1 January 1900 and 30 December 2003 were reviewed and 200 reports involving fire as a stimulus were identified. For this investigation all ordnance items were considered due to the very small number of transportation and storage accidents associated with large solid rocket motors. In examination of these reports, an organizational action was taken to better categorize the incidents. Overall, the incidents were first grouped as either storage or transportation. Within these two groups, the mishaps were organized according to the nature of the stimulus.

The mishaps related to storage were divided into those fires caused by lightning, surrounding vegetation, or other ignition sources. A total of 86 storage mishaps are summarized in Table 1.

Table 1. Storage-Related Incidents.

Subcategory	Total Quantity Assessed
General	59
Lightning-related fire	18
Vegetation fire	9
Total number of storage incidents	86

Transportation mishaps were first separated into those occurring on the railway or the roadway. The two transportation categories were further divided by initiation type: impact, mechanical failure, spontaneous ignition, or other. Thirty-five rail mishaps resulting in fire are summarized in Table 2 and 51 roadway mishaps are summarized in Table 3. These data are being used to determine the time/temperature relationships for a realistic thermal stimulus. Further details of this survey can be found in Reference 5.

The accident data will be used in the determination of the time/temperature/flux relationships, which describe a thermal stimulus relative to transportation and storage scenarios. These data will serve as input into an analytical evaluation of the worst-case thermal event.

Table 2. Railway Mishaps

Subcategory	Total Quantity Assessed
Impact/collision	4
Mechanical failure	20
Self-start	11
Total number of rail incidents	35

Table 3. Roadway Mishaps

Subcategory	Total Quantity Assessed
Impact/collision	20
Mechanical failure	19
Self-start	12
Total number of rail incidents	51

The accident scenario that appears to be most relevant to our program was "Scenario 5" that occurred in Charleston, SC on May 28, 1971. A trailer transporting a large solid rocket motor crashed into a fuel tank at a service station. The investigation concluded that the fuel, which was not gasoline, ignited the rocket motor. Fortunately, the reaction violence of the rocket motor (Class B explosives) was a low–order deflagration. Although firebrands (floating embers) were present, no propulsion occurred. The driver was the sole fatality in this instance, and it is thought he may have suffered a heart attack.[7]

To achieve more specific information that may be of use in developing a subscale FCO test protocol, future endeavors call for efforts to locate more information regarding energetic fill, fire and/or fuel type, the flux output, the duration of the reactions, as well as the violence of these reactions. In having data of this nature, there will be the ability to move forward in the investigation with a realistic description of the thermal stimulus required in a subscale FCO test protocol.

Development of a Subscale Bonfire Test Protocol Study

The "Development of a Subscale Bonfire Test Protocol" work and paper conducted by Safety Management Services, Inc., was a complementary effort to the "A Survey of Transportation and Storage Accidents Involved in Thermal Events" work mentioned above. This study addressed defining the parameters affecting the fire conditions and the parameters most likely to affect the propellant/motor response to that fire. The objectives of this study were to:

- Identify the critical features needed for the development of a subscale alternative to the UN Test Series 6(c) protocol.
  - Define the types of accidents most likely to occur and involve a propellant/motor in a fire.
  - Define parameters affecting fire conditions.
  - Define parameters affecting propellant/motor response.
- Perform risk assessment of the concept of an alternative test as a scaling tool to define hazard classification.

The study specifically addressed the risk assessment portion of the objectives. Two approaches were taken to initially describe the occurrence of events. The first approach started with an initiation of a fire and logically moved forward to an event involving a motor in that fire. Charts were developed that laid out the steps involved to ultimately excite some type of reaction from a propellant/motor in a fire. These charts are shown in Figures 1-4.

The responses chosen were:

- Burn
- Deflagration
- Explosion
- Detonation

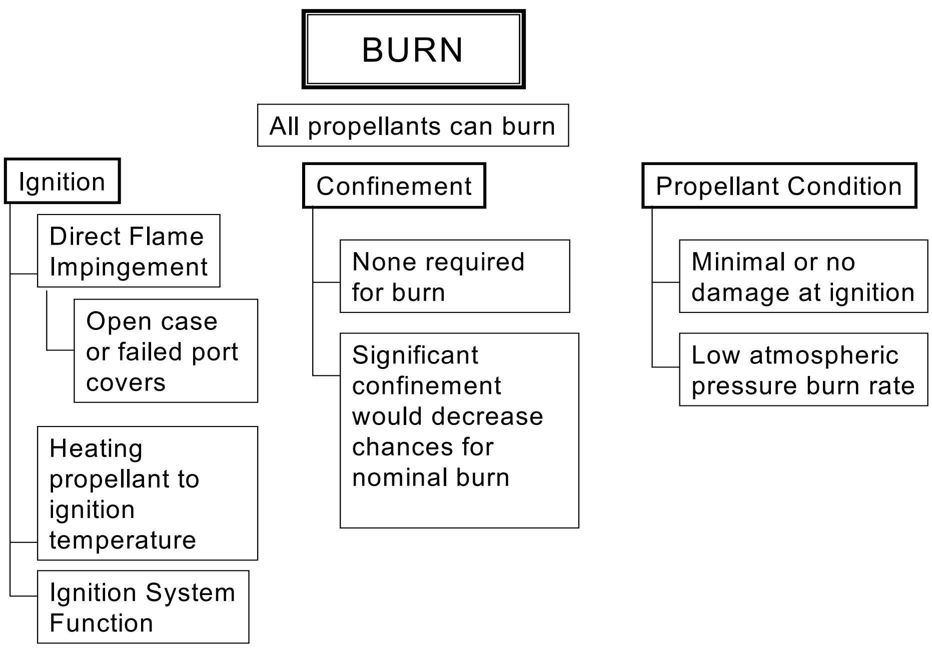


Figure 1. Flow Diagram Outlining Conditions Favoring a Burning Reaction in a Bonfire Test.

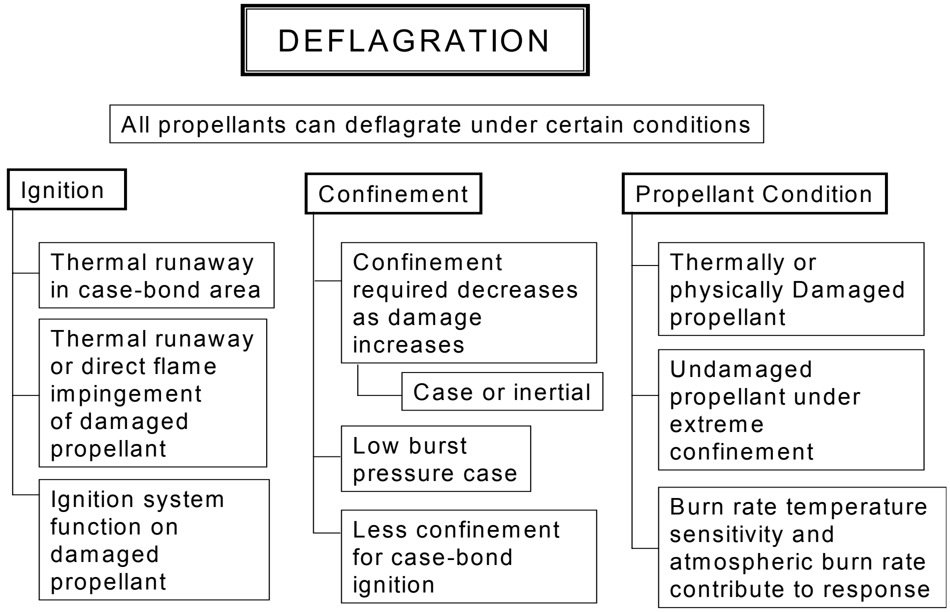


Figure 2. Deflagration Reaction Conditions for Ignition, Confinement and Propellant.

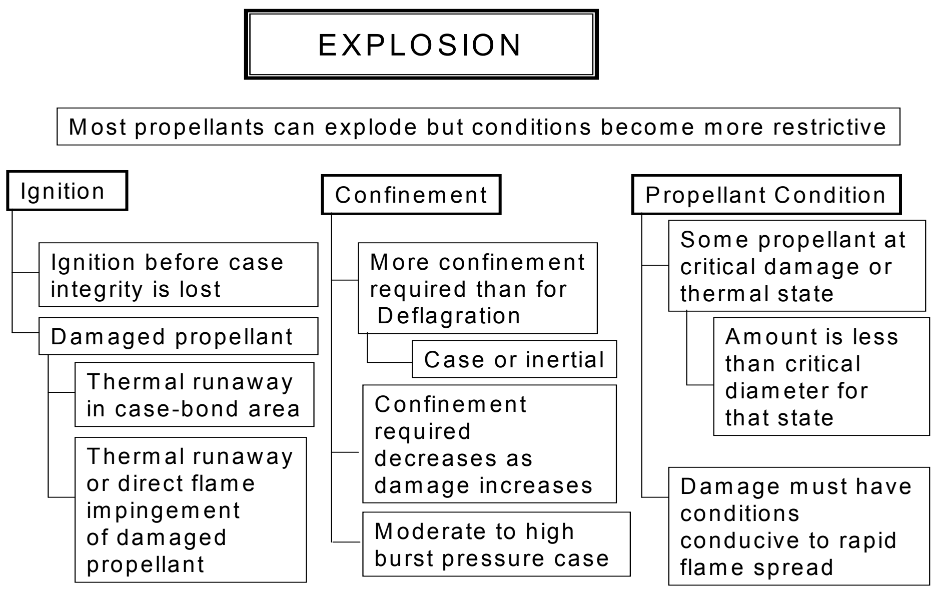


Figure 3. Conditions Required for an Explosive Reaction in a Bonfire.

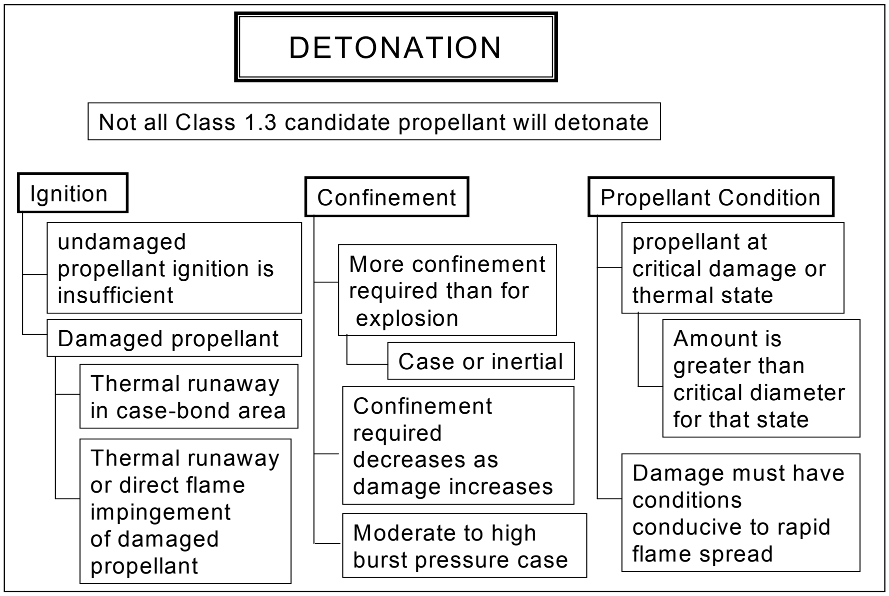


Figure 4. Conditions Required for a Detonation Reaction from a Bonfire.

The second approach was to start with each propellant/motor response and logically move backward to define the exact conditions needed to create that response from a fire using Fault Tree Analysis (FTA).

The risk assessment portion of this study generated the FTA diagrams that defined the paths to each of the four propellant/motor responses. An example FTA diagram is shown in Figure 5. These paths have been defined relative to propellant and case properties conducive to allowing a specific response to occur. The analysis showed that the parameters critical to these paths need to be quantified through test and/or analysis. Critical propellant parameters are:

- Change in critical diameter with temperature
- Change in critical diameter with thermal damage
- Change in physical state with temperature
- Change in chemical state with temperature
- Change in critical diameter with mechanical damage
- Degree of damage/fragmentation from pressure rupture of motor case

The quantification of these parameters is essential in determining the amount of propellant required to reach a critical state. A sufficient amount of propellant reaching critical state is required before transition to deflagration, explosion or detonation can occur.

As with the critical propellant parameters, the following parameters must be quantified for the rocket motor composite case and surrounding materials:

- Change in case integrity with temperature
- Change in case integrity with exposure to flame
- Heat transfer parameters of surrounding materials, including radiation parameters

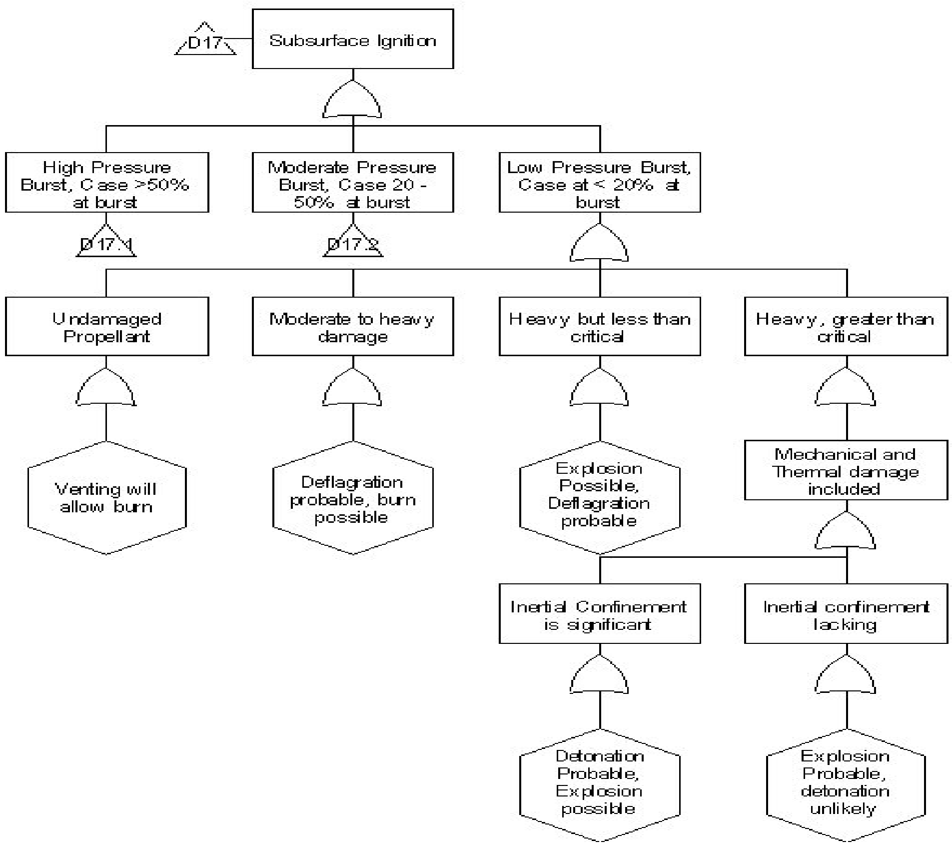


Figure 5. Example FTA Diagram.

Quantification of these parameters will allow modeling of the thermal environments imparted into the propellant and allow some determination of the amount of confinement remaining at the elevated temperatures. Assessing confinement is key in defining the amount of propellant that needs to be at a critical state for transition to deflagration, explosion or detonation to occur.

The final step in this process is to evaluate the temperature flux on the propellant/motor configuration and predict of how much propellant is in a critical state when it reaches ignition temperature. A comparison of the amount of propellant in a critical state to the amount required to alter the critical diameter would allow assessment of whether a propellant can transition to a deflagration, explosion or detonation that would change its classification from HD 1.3. The conclusions from this study are as follows.

A low risk approach to development of an alternate to the full-scale bonfire test can be developed by carefully assessing the changes a propellant undergoes during exposure to excessive heat. The development process would require basic knowledge of how the propellant changes and what constitutes reaching a critical state. The critical state can be characterized by subscale testing in standardized tests, such as cook-off, shock initiation of thermally damaged propellant, or other such tests. The amount of propellant in a critical state can be modeled given flux parameters from the fire and thermal properties of the surrounding materials such as case, transport containers, etc.

If the critical state of the propellant in the article can be determined and the amount of propellant in a critical state can be modeled, this could allow hazards classifiers one of two options:

1. Give the agency applying for the hazard classification the option of not performing the test and accepting an HD 1.1 classification, knowing that the conditions required to create a transition may readily be achieved, thus the propellant/motor configuration would fall out of HD 1.3 and into HD 1.1 or HD 1.2.

2. Define an alternate bonfire test that would provide sufficient information for classification of HD 1.2 and 1.3.

At this time, it appears that knowing the critical diameter and/or critical relative critical impact velocity of a propellant as affected by thermal and mechanical damage are important parameters in development of an alternate bonfire test protocol. This knowledge, combined with predictions of how much propellant is affected by a fire (which can be determined by modeling) may directly predict whether a propellant/motor configuration can achieve a critical state and make a transition to a reaction that would change its classification from HD 1.3. The proposed effort would validate these assumptions

Two parts of this model are yet to be finalized. The first is a series of tests to characterize the development of critical state resulting from exposure to the thermal environment. The second is to define parameters relative to the fire that are imposed on the motor required to predict the time of ignition, location of ignition and the thermal gradient in the propellant at the time of ignition. This involves primarily the heat flux. Heat flux is the driving force to cause the propellant to react. The case and other surrounding materials will modify the flux arriving at the propellant. Parameters that need to be identified for future quantification include the following:

- Fuel type
- Flux output
- Duration of the fire

The definition of the fuel type and duration of the fire would rest heavily upon the finding of the NAWC efforts on accident investigation. From this investigation, the primary sources of accident related fires can be defined. Experiment and modeling would be required to develop an understanding of the flux generated from these fires.

Subscale Testing

Subscale testing associated with FCO would only be successful with a combined analytical/experimental approach. When considering a subscale testing procedure, a number of issues and their interaction must be considered. The fire stimulus is not readily scalable, it is transient, and its behavior varies by fuel type. The boundary conditions between the fire and the test item must be well-defined for analysis, and the test item must also be well-defined and characterized with respect to the motor case, liner/insulator characteristics and propellant. The cook-off response of an ordnance item involves highly coupled phenomena between the energetic materials, inert components, stimulus and the external environment. Not all of the conditions between a full-scale and subscale can be matched and to understand both thermal and structural effects more that a single test would be required.

The fire stimulus should be as well-defined as possible. It should be of sufficient size to engulf the test item. The type of fire used may have a significant effect on the final response of the test item. Differences between a liquid fuel fire and viable non-fire stimuli would be investigated. Factors which contribute to the temperature and heat flux of the fire such as opacity, soot, irradiance and turbulence (from wind and self-generated) must be considered.

Of greater importance than accurate scaling of the boundary conditions is their proper understanding and description. Heat flux and temperature variations around the item as well as in the interfaces between motor case and insulation and motor case and propellant need to be measured. Once a reasonably accurate set of boundary conditions is known, they can be varied parametrically using analytical tools.

This study would begin with simple sample geometries. A series of small scale "pipe" experiments would be used to first evaluate the response of the energetic to high rate thermal stimuli. The analytical tools must first demonstrate success with the simple geometry before attempting to evaluate the complexities of large rocket motors and their canister and packaging that must be considered with a full-scale test. Larger items tend to produce more violent reactions but, the appropriate scaling of a subscale test motor is not clearly understood.

It is proposed that a subscale motor such as the Light Analog Motor (LAM) with geometry of approximately 0.3 meter (12 inch) outer diameter and a length of about 0.5 meter (18 inch) be utilized as an intermediate test article. To address scaling issues, at least one larger rocket motor representative of full-scale size (at least 2.5 times larger in diameter and length than for the subscale motors) would be tested. Minimum data collection goals for the test program are to determine air shock, fire brand and fragment ranges. Temperature gradients, internal case/liner/propellant behavior as well as propellant burn back are also required.

Composite motor cases offer the advantage of high strength without significant increase in overall system weight. The thermal/mechanical behavior of these devices is not simple and often othotropic. Quasi-static burst pressure data are not sufficient to understand the motor case failure mechanisms as the thermal contribution must be assessed. How the confinement changes as the epoxy melts and gasifies must be evaluated. The insulator/liner contribution to case failure is extremely important and may be the major source of confinement in the fiber wound system.

It is proposed that the initial tests and subscale motors be loaded with samples of a high performance HD 1.3 propellant. Properties such as thermal diffusivity, conductivity and thermal expansion, density and specific heat would be measured for the selected propellant as a function of initial temperature.

Initial tests would be performed on a composite system with a cylindrical geometry. Subscale, composite cased motors cast from the selected propellant type would be used to validate the small scale experiments. These motors would be tested using a liquid fuel fire. The fire sources must simulate the conditions which are associated with hazards relative to transportation and storage.

Propellant Sample/Parameters

The propellant(s) selected for this study would be representative of the next generation solid propellants being developed by the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program to raise rocket motor performance while maintaining a lower cost HD 1.3 hazard classification. These formulations pass the tests required to obtain an HD 1.3 Interim Hazard Classification (IHC):

- Test Series 3 protocol:
  - Bureau of Explosives impact machine (UN Test 3(a) (i)).
  - ABL friction test (UN Test 3(b) (iii)).
  - Thermal stability test at 75^{o}C (UN Test 3(c)).
  - Small-scale burning test (UN Test 3(d) (i)).
- NOL Gap Test 2(a) (iii)) at $\leq$ 69 cards.
- Cap Sensitivity Test 5(a).

In addition, this formulation passes the zero card (>250 kbar) kbar shock input test in the LSGT and option 2 of the revised TB 700-2 alternate test protocol (70 kbar, $\geq$ 12.7-cm (5-in) diameter or 150% of unconfined critical diameter in "motor like" confinement).

The propellant formulation used in this study would be sufficiently characterized to allow for the population of the various models that would be employed. These parameters include but are not limited to the following:

- Ignitability and burning rate as a function of initial temperature and pressure
- Thermal properties as a function of initial temperature and physical state, including diffusivity, conductivity, expansion.
- Mechanical properties as a function of temperature (shear and bulk modulus)
- Chemical reactions/decomposition kinetics
- Physical state of the energetic (thermal damage effects)
- Shock sensitivity as a function of temperature and physical state
- Contact resistance

Modeling

Previous modeling efforts have focused on the slow cook-off hazard threat, however, for transportation and storage issues, the focus should be in the area of FCO. Both engineering and detailed models based on first principles should be utilized for this effort. In cases where the need for data predicting the time to reaction is adequate a robust engineering model would be sufficient and cost effective. More detailed models would be required to evaluate reaction violence and the contribution of such geometric complexities as fins and storage containers. The models and experiments must be iterative and highly coupled in order to succeed.

Database

Considerable work has already been performed in the area of FCO. A review of the existing FCO and bonfire testing would be made, especially of the Navy Insensitive Munitions tests. Another suggested source is the National Insensitive Munitions Information System (NIMIS II) database, which is available on the web. From these data, a list of parameters responsible for the FCO event would be compiled. An analytical evaluation would be made in order to identify critical parameters relative to the response of the item to the thermal stimulus.

In addition to historical data, the new data generated under this program would be incorporated into a master database related to FCO and bonfire test results for use by the propulsion and hazards classification community. The kinds of data that would be included in the fast cook-off database are temperature measurements from the skin of the rocket motor, time to reaction and fragmentation data. In addition, their weight and travel distance would be included. The details of the test set up and environmental conditions under which the test was performed would also be included, as the cook-off hazard is a strongly coupled relationship between the energetic and its environment. Every effort would be made to maximize the quality of instrumentation used to record the data. In addition, NATO and Munitions Safety Information Analysis Center (MSAIC) recommendations would be followed.

Scaling Issues

It was concluded at the JANNAF/DDESB Hazards Classification of Large Rocket Motors (HCLRM) workshop, that due to the transient nature of a fire, it does not readily scale. The size of the fire should be sufficiently large to engulf the item and the height monitored. The type of fire is also important. The two most common types of experimental fires, fuel and propane, differ widely in their radiative and convective behavior. The opacity of a sooty fuel fire and the irradiance should be evaluated. The contribution of turbulence, generated by either the wind or self-generated must be considered. The effect of variations in the fuel to air ratio should be measured as should temperature as a function of distance and time.

Scaling of the boundary conditions is not as important as knowing the initial conditions very well. If the boundary conditions can be described in one experiment, then they can be varied parametrically using the available models. As a minimum, heat flux and temperature variations should be measured around the test item and at the interfaces between the motor case and the insulation/liner and between the insulation/liner and the propellant.

With regards to a generic test item, the response of different propellant families should be understood and well defined. The response of a traditional HD 1.3 propellant and a high performance HD 1.3 should be clearly contrasted with a known HD 1.1 propellant or explosive. It was noted that larger items tend to react with a higher level of violence than smaller items; however, we do not fully understand how to scale the size of a test fixture.

The physical/chemical/mechanical properties of the motor case, liner, and propellant should be measured as a function of initial temperature in order to analytically describe the test item subjected to a thermal stimulus. Kinetic parameters for the energetic material should be determined from thermochemical data such as One Dimensional Time to eXplosion (ODTX). If a generic subscale test is to be useful to hazards classification, the experimental and analytical protocol must clearly delineate not only the time to reaction but also give some measure of reaction violence by means of the fragment size, mass and velocity, blast and thermal response of the item to fire.

Confinement

The HCLRM workshop participants agreed that the quasi-static burst pressure of a rocket motor case was not sufficient to describe the failure mechanisms associated with the FCO response. The effect of elevated temperature on motor case failure should be evaluated. Large solid rocket motors tend to be manufactured with motor cases consisting of composite materials. It was noted that the fiber wound epoxy filled systems are complex and their behavior is orthotropic, and there is a minimum thickness that can be laid up. How the motor case material behavior changes as the polymeric components soften, melt and gasify should be measured.

The role of the insulator and/or liner of the composite cased rocket motor are of equal or even greater importance since it may provide significant confinement during a thermal event. The gasification of the liner, followed by a debond region between the liner and motor case in which reactive gases may accumulate has been identified as a critical feature in the fast cook-off response.[8]

Fragments and Firebrands

The HD 1.2 hazards classification is based on the fragments that are generated as a result of an "explosive reaction." In order to avoid the HD 1.2 classification, the experimentalist must demonstrate that no explosive reaction occurred during the test. In other words, the tests must include the appropriate instrumentation such as blast gages, thermal flux measurements and video coverage. The mass of the fragments as well as the distance they travel must be recorded.

The 20-Joule criterion for fragments is very conservative, for example, 20 Joule = 4.4 ft-lb and a "lethal" fragment is defined as 58 ft-lb. The 20-Joule criterion is an international standard. The HD 1.2 classification, as it is currently defined, may be too broad, encompassing items from 155-mm (6.10-in) shells to large solid rocket motors. Any alternate external fire test protocol must include a means to evaluate reaction violence.

CONCLUSIONS

The current UN Test Series 6 protocol with its full-scale test article requirement is cost prohibitive and impractical for large rocket motors and may put many motors into a 1.2 HD. An alternate test protocol for hazard classifying large rocket motors utilize shock tests in place of the single package and stack (sympathetic reaction) tests is available but for the external fire test one full-scale test article is still required as no alternate exists at this time. It is the goal of this proposed effort to develop such an alternative..

In order to develop an efficacious subscale test, it is necessary to understand the fire scenarios associated with transportation and storage of large-scale rocket motors. It then becomes important to first identify the driving mechanisms of FCO. Without knowing the mechanisms, the relevance of a test, which is less than full-scale, is questionable.

The "A Survey of Transportation and Storage Accidents Involved in Thermal Events" work and paper conducted by NAWC, China Lake was the initial investigation into the description of the thermal stimulus, which might be associated from transportation and storage incidents involving energetic materials/articles. The research yielded information regarding conditional details of ordnance subjected to fire for case studies that would be assessed for the development of a sub-scale bonfire test protocol.

The "Development of a Subscale Bonfire Test Protocol" work and paper conducted by Safety Management Services, Inc., addressed defining the parameters affecting the fire conditions and the parameters most likely to affect the propellant response to that fire. The conclusions from this study are that a low risk approach to the development of a subscale alternate to the full-scale bonfire test can be achieved by carefully assessing the changes a propellant undergoes during exposure to excessive heat.

The development process would require basic knowledge of how the propellant changes and what constitutes reaching a critical state. The critical state can be characterized by subscale testing in standardized tests, such as cook-off, shock initiation of thermally damaged propellant, or other such test. The amount of propellant in a critical state can be modeled given flux parameters from the fire and thermal properties of the surrounding materials such as case, transport containers, etc. If the critical state of the propellant in the article can be determined and the amount of propellant in a critical state can be modeled, this could allow hazards classifiers one of two options:

1. Give the agency applying for the hazard classification the option of not performing the test and accepting an HD 1.1 classification, knowing that the conditions required to create a transition may readily be achieved, thus the propellant/motor configuration would fall out of HD 1.3 and into HD 1.1 or HD 1.2.

2. Define an alternate bonfire test that would provide sufficient information for classification of HD 1.2 and 1.3.

Subscale testing associated with FCO would only be successful with a combined analytical/experimental approach. When considering a subscale testing procedure, a number of issues and their interaction must be considered. The fire stimulus is not readily scalable, it is transient, and its behavior varies by fuel type. The boundary conditions between the fire and the test item must be well defined for analysis, and the test item must also be well defined and characterized with respect to the motor case, liner/insulator characteristics and propellant.

The cook-off response of an ordnance item involves highly coupled phenomena between the energetic materials, inert components, stimulus and the external environment. Not all of the conditions between a full-scale and subscale can be matched and to understand both thermal and structural effects more that a single test would be required.

The fire stimulus should be as well defined as possible. It should be of sufficient size to engulf the test item. The type of fire used may have a significant effect on the final response of the test item. Differences between a liquid fuel fire and one using propane burners would be investigated. Factors which contribute to the temperature and heat flux of the fire such as opacity, soot, irradiance and turbulence (from wind and self generated) must be considered.

Of greater importance than accurate scaling of the boundary conditions is their proper understanding and description. Heat flux and temperature variations around the item as well as in the interfaces between motor case and insulation and motor case and propellant need to be measured. Once a reasonably accurate set of boundary conditions is known, they can be varied parametrically using analytical tools.

FUTURE WORK

The ongoing "Survey of Transportation and Storage Accidents Involved in Thermal Events" study by NAWC, China Lake would continue to locate more information regarding energetic fill, fire and/or fuel type, flux output, the duration of the reactions and violence of the reactions. This information would help give a realistic description of the thermal stimulus required in a subscale test protocol.

Continued efforts are planned to:

1. Develop a series of tests to characterize the development of critical state resulting from exposure to the thermal environment.
2. Define parameters relative to the fire that are imposed on the motor to predict time of ignition, location of ignition and the thermal gradient in the propellant at the time of ignition.

The second effort primarily involves the heat flux which is the driving force that causes the propellant to react. The case and surrounding materials would change the flux into the propellant. Parameters that need to be identified for future quantification include:

- Fuel type
- Flux output
- Duration of the fire

The definition of the fuel type and fire duration would come from the NAWC, China Lake accident investigation study.

NAWC, China Lake and AFRL, Edwards AFB are currently working on the design of a well defined thermal stimulus for conducting small scale experiments. The requirements are that the stimulus be controllable and achieve temperatures needed to provide the desired heat flux. In addition, they are currently working on the design of a subscale composite test articles. The starting point may be a cylinder with ~ 70mm ID (2.75 inch). The controlling parameters for the test article include: Ignitability at ambient pressure, damage effects and free space.

Preliminary fire and test article scaling and modeling studies have been proposed. Advanced modeling and simulation efforts for the program are planned to be conducted by the DOE National Laboratories at Lawrence Livermore (LLNL), Los Alamos LANL) and Sandia (SNL).

REFERENCES

1. Department of Defense (DoD) Ammunition and Explosives Hazard Classification Procedures Joint Technical Bulletin TB 700-2/NAVSEAINST 8020.8B/TO 11A-1-47/DLAR 8220.1; 5 January 1998.

2. Joint Hazard Classifier, private communication, May 2005.

3. North Atlantic Treaty Organization Standardization Agreement (NATO STANAG), Liquid Fuel/External Fire Test.

4. JANNAF/DDESB Propulsion Systems Hazards Subcommittee and Propellant Development & Characterization Subcommittee (2001) Hazards Classification of Large Rocket Motors Workshop Report, *JANNAF JSC CD-18,* Alexandria, Virginia, Jun 4-8, CPIA, Laurel, Maryland.

5. Rattanapote, M.K., Atwood, A.I., and Covino, J., (2004) "A Survey of Transportation and Storage Accidents Involved in Thermal Events," *Proc. of 31st United States Department of Defense Explosives Safety Seminar,* San Antonio, Texas, Aug 24-26, CPIA, Laurel, Maryland.

6. Butcher, A.G., (2004) "Development of a Subscale Bonfire Test Protocol," *Proc. of 31st United States Department of Defense Explosives Safety Seminar,* San Antonio, Texas, Aug 24-26, CPIA, Laurel, Maryland.

7. "Memorandum," ORD-043B/AF, Department of the Navy, ESMAM #1425.

8. Vetter, R.F., *Reduction of Fuel Fire Cook-off Hazard of Rocket Motors*, Naval Weapons Center, China Lake, CA, NWC TP 5921 (1977), U-A.

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the following individuals for their vision and cooperation in working with and supporting the propulsion community: Dr. Jerry Ward and Dr. Josephine Covino from Department of Defense Explosive Safety Board and Mr. Peter Huisveld from Air Force Research Laboratory, Edwards AFB .

Overview of Proposed Joint Air Force and Navy Subscale Fast Cook-Off Program

Daniel F. Schwartz
Air Force Research Laboratory Propulsion Directorate

Alice I. Atwood
D. Tri Bui
Melody K. Rattanapote
Naval Air Warfare Center Weapons Division China Lake

A. Garn Butcher
Safety Management Services Inc.

2005 JANNAF CS / APS / PSHS / MSS Joint Meeting
Charleston, SC

13-17 June 2005

Approved for public release; distribution is unlimited.

DoD Hazard Classification

- Determines reaction of ammunition & explosives (A&E) to initiating influences from tests
- Required for A&E entering a DoD system
  - Transport by DoD
  - Storage at DoD facilities
- Provides for assignment of appropriate hazard classification for transport & storage (HD 1.1 through HD 1.6)
- Approved by DoD Explosives Safety Board (DDESB)
  - Coordinated by Tri-Service Joint Hazards Classifiers (JHC)
- DoD Ammunition and Explosives Hazard Classification Procedures:
  - Army (TB 700-2), Navy (NAVSEAINST 8020.8B), Air Force (TO 11A-1-47), Defense Logistic Agency (DLAR 8220.1)
- 2 types of hazards classification
  - Final Hazard Classification (initiated prior to release for service use)
    - Full-scale testing on articles in shipping containers
  - Interim Hazard Classification (developmental configurations, test articles, released articles with FHC in process)
    - Subscale testing on articles and substances

Approved for public release; distribution is unlimited.

DoD Hazard Final Classification Tests

- UN Test Series 6 (mandatory for HD 1.1 through HD 1.4)
  - Single package test (UN Test 6(a))
    - Blasting cap (1 test)
    - Articles own means of ignition (2 tests)
      - Static test for a rocket motor (current TB 700-2)
      - TBD, may be SCJ (TB 700-2 rewrite)

    Note: If reaction effects are contained within the package, skip stack test
  - Stack test (UN Test 6(b)) *
    - 3-articles/test (3 tests)
  - External fire test (UN Test 6(c))
    - 3-articles/test
- Pre-approved alternate test plan
- Alternate test protocol (large rocket motors)
  - Shock tests (options 1, 2, or 3) + 1-article bonfire

Approved for public release; distribution is unlimited.

Concerns With UN Test Series 6 & Alternate Tests

- The full test protocol requires as many as 15 full-scale test articles in shipping containers
  - Cost prohibitive for large rocket motors (>$5M/test)
  - Difficulties in preventing large rocket motors from becoming propulsive and potentially leaving the test facility
  - Large amounts of fuel required (could be in excess of 120,000 gals)
- Alternate test protocol still requires at least 1 full-scale fire test
  - The attempt by the DDESB to make TB 700-2 agree with UN regulations has resulted in fragment throw restrictions to less than 50.29 meters (165 feet)
    - This will drive many motors to a HD 1.2 classification
  - Single test may be misleading

Approved for public release; distribution is unlimited.

Proposed Solution

- Identify the critical features needed for the development of a subscale alternate test protocol to UN Test Series 6
  - Define storage & transportation accidents most likely to involve a rocket motor in a FCO scenario
  - Define & model parameters affecting fire conditions
  - Define & model parameters affecting propellant/motor response
- Perform risk assessment of the concept of an subscale alternate test protocol for hazard classification
- If feasible, develop and validate a subscale alternate test protocol for consideration by DDESB and JHC for future TB 700-2 DoD revisions

Approved for public release; distribution is unlimited.

Storage and Transportation Fire Threat Assessment

- To understand the credible fire threats associated with the transportation & storage of energetic materials, DDESB/JHC supported the following study/paper:
  - "A Survey of Transportation and Storage Accidents Involved in Thermal Events"
    - Initial investigation into the description of thermal stimulus associated with storage & transportation
      - Fire type
      - Duration
      - Time to ignition
    - Examined DDESB accident database (Jan 1900-Dec 2003)
- To define parameters affecting fire conditions and propellant response in FCO, DDESB/JHC supported the following study/paper:
  - "Development of a Subscale Bonfire Test Protocol"

Approved for public release; distribution is unlimited.

Survey of Transportation and Storage Accidents Involved in Thermal Events

Storage-Related Incidents

Subcategory	Total Quantity Assessed
General	59
Lightning-related fire	18
Vegetation fire	9
Total number of storage incidents	86

Railway Mishaps

Subcategory	Total Quantity Assessed
Impact/collision	4
Mechanical failure	20
Self-start	11
Total number of rail incidents	35

Roadway Mishaps

Subcategory	Total Quantity Assessed
Impact/collision	20
Mechanical failure	19
Self-start	12
Total number of rail incidents	51

- Storage incidents larger in scale due to large quantities of ordnance, especially in locations such as depots and dumps
- Majority of fires by spontaneous combustion
- Regardless of the cause of the initial fire, sympathetic deflagrations & detonations tended to initiate surrounding articles

- Transportation incidents more readily lead to potential loss of life, due to locations near or through populated areas
- Fire in transportation falls into 2 main categories:
  - Initiation of fuel
  - Possible failures: equip & human

Approved for public release; distribution is unlimited.

Survey of Transportation and Storage Accidents Involved in Thermal Events (cont)

- **Accident scenario most relevant to our program was a transportation mishap involving a trailer transporting a large first stage solid rocket motor that drove into a large above ground fuel tank**
  - **Rocket motor ignited by burning fuel (not gasoline)**
    - **Reaction violence of the rocket motor (Class B explosive) was a low order deflagration with no propulsion**
    - **Firebrands were present**
    - **Driver was the sole fatality in this instance (from a suspected heart attack)**

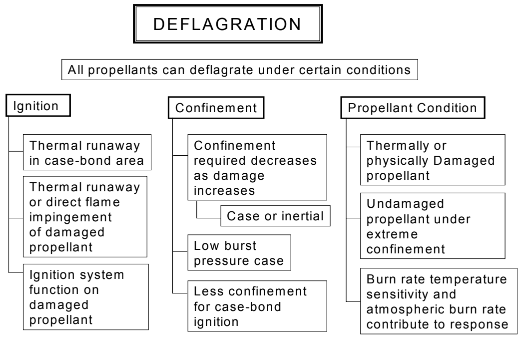
Approved for public release; distribution is unlimited.

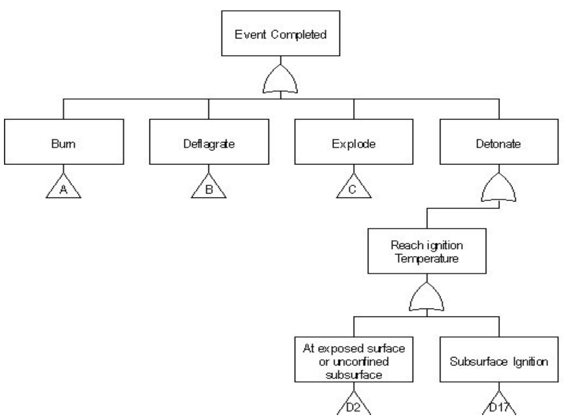
Development of a Subscale Bonfire Test Protocol Paper/Study (cont)

- The objectives of this study are to:
  - Identify the critical features needed for the development of a subscale alternative to the UN Test Series 6(c) protocol
    - Define the types of accidents most likely to occur and involve a motor in a fire (NAWC China Lake study)
    - Define & model parameters affecting fire conditions
    - Define & model parameters affecting motor response
  - Perform risk assessment of the concept of an alternative test as a scaling tool to define hazard classification
- Basic approach
  - Identify the parameters of the fire, motor and surroundings that will most affect the outcome of a bonfire test
  - Lay those findings on a logic diagram to evaluate cause and effect relationships

Approved for public release; distribution is unlimited.

FCO Parameters and cause and effect relationships





- The motor responses chosen were:
  - Burn,
  - Deflagration,
  - Explosion
  - Detonation
- Parameters affecting motor response
  - Change in critical diameter with temperature
  - Change in critical diameter with thermal damage
  - Change in physical state with temperature
  - Change in chemical state with temperature
  - Change in critical diameter with mechanical damage
  - Degree of damage/fragmentation from pressure rupture of motor case

Approved for public release; distribution is unlimited.

Development of a Subscale Bonfire Test Protocol Paper/Study Summary

- In all studies, detonation of all or part of the propellant in any motor requires that the D_C of the altered propellant is < the thickness of the altered propellant
- Unless this condition is met, Type I and Type II reactions cannot occur
- Therefore, test & modeling efforts would need to:
  - Evaluate the temperature flux on the propellant/motor configuration
  - Predict of how much propellant is in a critical state when it reaches ignition temperature
  - Concentrate on determining the magnitude of change in D_C as a function of propellant temp

Approved for public release; distribution is unlimited.

Development of a Subscale Bonfire Test Protocol Paper/Study Conclusions

- **If the magnitude of change in D_C as a function of propellant temp can be modeled, this could allow hazards classifiers one of two options:**
  - **Give the agency applying for the hazard classification the option of not performing the test**
    - **Accepting an HD 1.1 classification knowing that the conditions required to create a transition *may readily be achieved***
      - **The propellant/motor configuration would fall out of the HD 1.3 and into HD 1.1 or HD 1.2**
  - **Define an alternate bonfire test that will provide sufficient information for classification of HD 1.2 and 1.3.**

Approved for public release; distribution is unlimited.

Subscale Testing Considerations

- Combined analytical/experimental approach needed
  - Several issues and interactions must be considered:
    - Fire stimulus is not readily scalable
      - Transient, and its behavior varies by fuel type
    - Boundary conditions between the fire and test item must be well defined for analysis
    - Test article must also be well defined and characterized with respect to:
      - Motor case
      - Liner/insulator characteristics
      - Propellant
    - FCO response of an ordnance item involves highly coupled phenomena between:
      - Energetic materials
      - Inert components
      - Fire stimulus
      - External environment

Approved for public release; distribution is unlimited.

Subscale Testing Studies

- Study would begin with simple composite test articles
  - Small scale "pipe" experiments would be used to first evaluate & model response of the energetic to high rate thermal stimuli
  - Proposed intermediate scaling experiments would utilize a motor geometry of approx 0.3 meter (12 inch) OD and about 0.5 meter (18 inch) length
  - At least one larger rocket motor representative of full-scale (at least 2.5 times larger in diameter and length than for the subscale motors) would be used for test article and model verification and validation
- Data collection goals:
  - Air shock
  - Fire brand
  - Fragment ranges
  - Temperature gradients
  - Internal case/liner/propellant behavior
  - Propellant burn back

Approved for public release; distribution is unlimited.

Propellant Sample/Parameters

- IHPRPT propellant
  - Increased energy HD 1.3 formulation
    - Passes IHC tests for HD 1.3
    - Passes the zero card (>250 kbar) LSGT and
    - Passes Option 2 of the revised TB 700-2 alternate test protocol (70 kbar, $\geq$ 12.7-cm (5-in) diameter in "motor like" confinement)
  - Parameters to be characterized:
    - Ignitability and burn rate as a function of initial temperature and pressure
    - Thermal properties as a function of initial temperature and physical state, including diffusivity, conductivity, expansion.
    - Mechanical properties as a function of temperature (shear and bulk modulus)
    - Chemical reactions/decomposition kinetics
    - Physical state of the energetic (thermal damage effects)
    - Shock sensitivity as a function of temperature and physical state
    - Contact resistance

Approved for public release; distribution is unlimited.

Modeling

- Current modeling efforts have focused on the slow cook-off hazard threat
- For transportation & storage issues, the focus needs to be in the area of FCO
  - Both engineering and detailed models based on first principles should be utilized for this effort
    - For predicting the time to reaction, a robust engineering thermal model may be sufficient and cost effective
    - More detailed models would be required to evaluate:
      - Reaction violence
      - High performance motor design for constructing sub-scale test article & validation plan

Approved for public release; distribution is unlimited.

Future Activities

AF & Navy Development of a Subscale Bonfire Test Protocol

- AF plans to enlist the expertise of rocket community to:
  - Apply thermal model to modern high performance motor design in external FCO environment
  - Identify additional property needs for improved accuracy
  - Validate thermal approach with laboratory and subscale testing
  - Apply thermal model to small-scale pool fire and compare to test data
- AF & China Lake are currently working on the design of:
  - Well defined thermal model
  - Composite test article for conducting small scale experiments
    - Controllable
    - Achieve thermal environment for required heat flux
    - Starting size TBD based upon findings from thermal modeling community (possibility to use ~70mm ID cylinder/2.75 inch)
- China Lake plans to continue the Survey of Transportation and Storage Accidents work

Approved for public release; distribution is unlimited.

Future Activities (cont)

- Continued efforts are planned to:
  - Develop a series of tests to characterize the development of critical state resulting from exposure to the thermal environment
  - Define parameters relative to the fire that are imposed on the motor to predict:
    - Time of ignition,
    - Location of ignition
    - Thermal gradient in the propellant at the time of ignition
  - To conduct preliminary fire and test article scaling & modeling studies
- Advanced modeling and simulation efforts for the program will be conducted by the DOE National Laboratories (LLNL, LANL SNL)

Approved for public release; distribution is unlimited.