# Comparison of Shock Stimuli from Current Hazard Classification Testing and Potential Threats

Paul Braithwaite, Robert Hatch, Robert Wardle
Northrop Grumman, Innovation Systems; Brigham City, Utah, USA

## ABSTRACT

The process of determining hazard classification of energetic materials and articles containing energetic materials in the United States is described and governed in a Joint Technical Bulletin issued by the Army, Navy and Air Force titled "Department of Defense Ammunition and Explosives Hazard Classification Procedures." This document is often referred to simply as TB 700-2. Articles requiring hazard classification range from very small initiating devices with under a gram of energetic material to extremely large rockets containing over a million pounds of propellant. It is challenging to require a single protocol to properly address hazard classification for this broad range of items. This paper summarizes an ongoing effort to improve knowledge regarding the relationship between storage, handling and transportation related shock hazards larger solid rockets may experience and the tests used to determine their hazard classification. This paper presents the results of this study and recommends potential modifications to current protocols used in shock testing for hazard classification determination.

## BACKGROUND

Solid rocket propellants are energetic by nature and design. Transportation, storage and handling of these solid propellant rockets are carefully monitored and their specific hazard classification is governed by the Department of Defense Ammunition and Explosives Hazard Classification Procedure most commonly referred to as TB 700-2[1]. Solid rocket propellants are Class 1 Hazard Division materials and are commonly classified into either 1.1 (mass explosion) or 1.3 (mass fire, minor blast or fragment) categories. To determine if a specific formulation or article is a Class 1.1 or Class 1.3 composition, specific tests are performed beginning with basic handling tests (impact, friction, thermal stability and ignition without confinement). Once formulations have passed these tests, additional testing is required if a 1.3 hazard classification is desired. For propellants targeted for use in large rocket motors, two additional major tests are called out in TB 700-2, namely a shock test and a liquid fuel/external fire test.

This paper focuses on current shock testing described in TB 700-2 and complements and enhances an extensive body of work performed by other researchers in the late 1990s and early 2000s. Examples of references on this topic may be obtained by contacting the authors. The current TB 700-2 protocol offers three different options for shock testing as summarized below. To be considered for a 1.3 classification, the composition must pass one of these options.

- Option 1: Test and pass the super large-scale gap test (SLSGT) at zero cards
- Option 2: Determine the unconfined critical diameter of the subject formulation and then test the composition in a configuration representing motor confinement at 1.5 times the critical diameter with a shock input of 70 kbar
- Option 3: Test and pass a gap test at motor diameter with a shock input of 70 kbar

A top-level evaluation of these three shock testing options for solid rocket propellants planned for use in larger rocket motors (> 24 inches in diameter) leads to the following observations regarding Options 1 and 3. Option 1 is a very severe test (the SLSGT) that consists of testing propellant cast in a substantial steel tube and being subjected to the detonation of a large Composition B booster without any attenuation between the booster and acceptor. Experimental data generated for a wide range of compositions indicates that formulations containing even modest amounts of classical high explosives (e.g., cyclotetramethylene tetranitramine [HMX], cyclotrimethylenetrinitramine [RDX], and nitroglycerin) will not pass this test. Option 3 requires production of very large test articles that are costly to manufacture and test. For example, a 24-inch-diameter article must be 96 inches long, which will weigh more than 2,500 lbs. and require an explosive booster weighing more than a hundred pounds.

The challenges associated with Options 1 and 3 often drive researchers tasked with developing high performance hazard class 1.3 propellants for large rocket motors to the Option 2 test.

## UNDERSTANDING THE TB 700-2 OPTION 2 SHOCK TEST

Because Option 2 shock testing is the only viable route for many new formulations, it is important to understand the details of this test and how the impulse it delivers compares with potential threats a large solid rocket motor may experience during handling, storage and transportation.

### IMPULSE AND PRESSURE EFFECTS

Testing described in TB 700-2 specifies the propellant acceptor geometry and confinement, booster/initiator composition and geometry and attenuator type and geometry and requires that a 70 kbar shock be delivered to the propellant. The Option 2 article is not a fixed size but is based on the critical diameter of the propellant (or other energetic formulation) being tested. In evaluating this protocol, the first observation is that as the propellant's critical diameter increases, the Option 2 test article also grows.

A theoretical evaluation of Option 2 articles for three notional formulations was performed to gain insight into potential implications associated with changes in test article size and is summarized in Table 1. Formulation A had a notional critical diameter of 3.33 inches, Formulation B's critical diameter was 4.67 inches and Formulation C had a critical diameter of 8.0 inches. It was assumed that all propellants had the same density, all articles used a modified conical Comp B booster, all used lightweight cases, all used a poly(methyl methacrylate) (PMMA) attenuator and all articles used the TB 700-2 specified length-to-diameter ratio of four to one. Hydrocode analysis was used to predict the impulse which would be delivered during each test.

**Table 1. Theoretical Study Showing Option 2 Test Articles for Three Different Formulations**

| Parameter | Formulation A | Formulation B | Formulation C |
|---|---|---|---|
| Critical Diameter (in) | 3.33 | 4.67 | 8.0 |
| Option 2 Test Propellant Diameter (in) | 5.0 | 7.0 | 12.0 |
| Option 2 Test Article Length (in) | 15.0 | 28.0 | 48.0 |
| Option 2 Propellant Weight (lb) | 25.5 | 70.1 | 353.0 |
| Option 2 Booster Weight (lb.) | 4.7 | 10.3 | 44.2 |
| Impulse at 70 kbar Input (kbar-μsec) | 440 | 826 | 1122 |

**: Comp B booster weight is based on a full diameter (case plus propellant) booster with a 2-inch cylindrical section that transitions to a truncated cone with a 2-inch upper diameter*

Test articles described in Table 1 for Formulations A, B and C are compliant with Option 2 requirements; however, it is clear that there are substantial differences from article to article. For example, the weight of the acceptor article for Formulation C is nearly 14 times as much as the article for Formulation A. Further, the booster for Formulation C is nearly 10 times more massive than the corresponding booster for the Formulation A test. Hydrocode analysis shows that the increasingly large boosters associated with Formulations B and C generate substantially more impulse than the Formulation A booster despite the fact that the acceptor propellant in all tests receives the same level of pressure.

To better understand the potential role of impulse in shock sensitivity, we carefully reviewed data generated by Aerojet General in the 1960s under Project SOPHY[2,3]. Some of Project SOPHY involved determining the critical diameter of three solid propellants that used an inert binder system, ammonium perchlorate (AP), aluminum (Al) and varying levels of RDX. By changing the RDX level, the critical diameter (Dc) was varied. Next, the propellants were tested in increasingly larger samples to determine their go/no-go point as a function of test diameter/critical diameter. The go/no-go data (Figure 1) indicated that as the RDX level increased, the pressure required to cause a detonation also increased. This finding did not agree with more recent work, which indicates adding nitramines such as RDX increases a propellant's susceptibility to detonation.

To resolve the apparent conflict between Project SOPHY and more recent work, we used hydrocode analysis. The details of each gap test article in Project SOPHY were input into a current hydrocode to generate pressure time profiles. The hydrocode output was analyzed and used to determine go/no-go impulse for each formulation over the range of testing (Figure 2). The information shown in Figure 2 indicates that increasing the RDX content decreases the impulse required to produce a detonation. This observation is in agreement with more recent data and suggests that impulse should be considered when conducting gap tests of varying diameters, particularly for larger articles.

The hydrocode modeling suggests that the current shock testing protocol described in TB 700-2 favors more sensitive propellants.

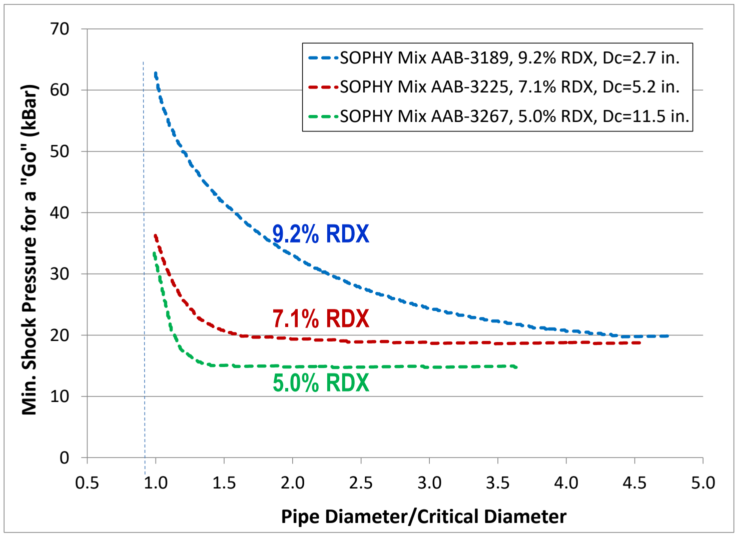


**Figure 1. Go/No-Go Pressures for Three Propellants with Different Levels of RDX Tested in Project SOPHY**

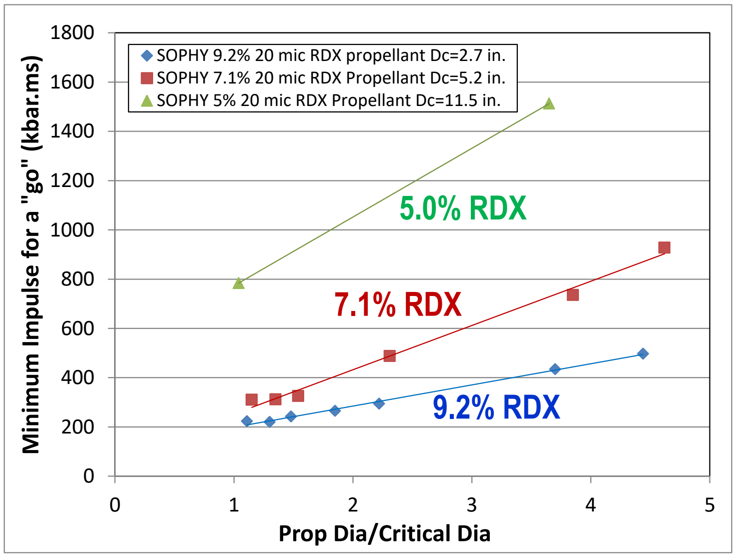


**Figure 2. Go/No Impulse for Three Propellants with Different Levels of RDX Tested in Project SOPHY**

## MODELING POTENTIAL ACCIDENT SCENARIOS

Another important aspect of the current study involved modeling the impulse delivered to a typical larger rocket motor during potential events. The scenarios chosen were:

- 0.50 caliber bullet impact
- 80-foot drop
- 100 and 150 mile per hour collisions

Pressure time curves were generated for each of these potential events. For bullet impact, the model assumed a bullet impacting the case at a 90-degree angle and the pressure time profile was determined at 0.2 cm from dead center. The 80-foot drop was evaluated for a rocket motor dropped on a concrete floor. The motor collisions assumed an end on impact between the rocket and a 24-inch-thick steel wall. The pressure and impulse delivered to the rocket motor were compared with pressure and impulse generated by a 5-inch gap test, which meets Option 2 requirements and three other common gap tests (Table 2).

**Table 2. Pressure and Impulse Values for a Rocket Motor Exposed to Accidents/Events and Common Gap Tests, Including a 5-inch-diameter Gap Test That Meets Option 2 Requirements**

| **Gap Tests** | | | | |
|---|---|---|---|---|
| **Parameter** | **5-inch Option 2** | **LSGT** | **ELSGT** | **SLSGT** |
| CJ Pressure at Zero Cards (kbar) | N/A | 206 | 206 | 275 |
| Impulse at Zero Cards (kbar - μ sec) | N/A | 585 | 1099 | 2236 |
| Impulse at 70 kbar (kbar - μ sec) | 439 | 246 | 456 | 753 |
| **Event** | | | | |
| **Parameter** | **100 mph Impact** | **150 mph Impact** | **80-ft drop** | **0.50 cal impact** |
| Peak Pressure (kbar) | 1.09 | 2.25 | 0.34 | 3.2 |
| Impulse (kbar - μ sec) | 61 | 99 | 31 | 31 |

Pressure time curves for the hypothetical event scenarios and the 5-inch- diameter gap test meeting TB 700-2 Option 2 requirements are

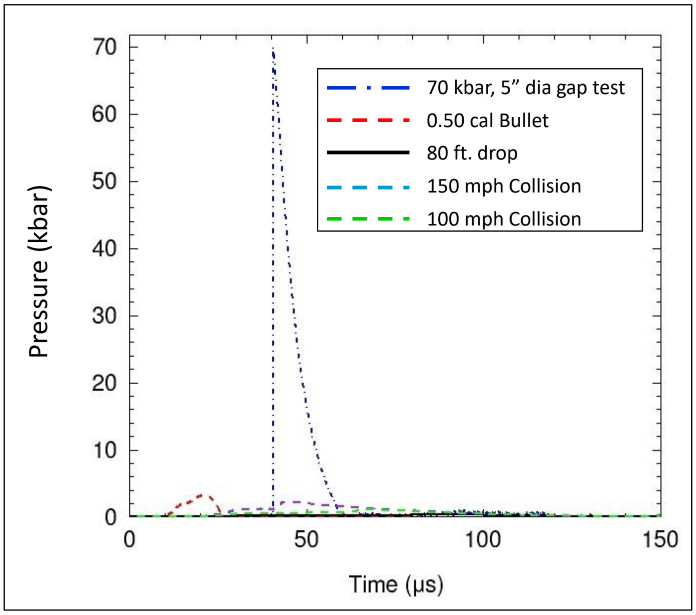
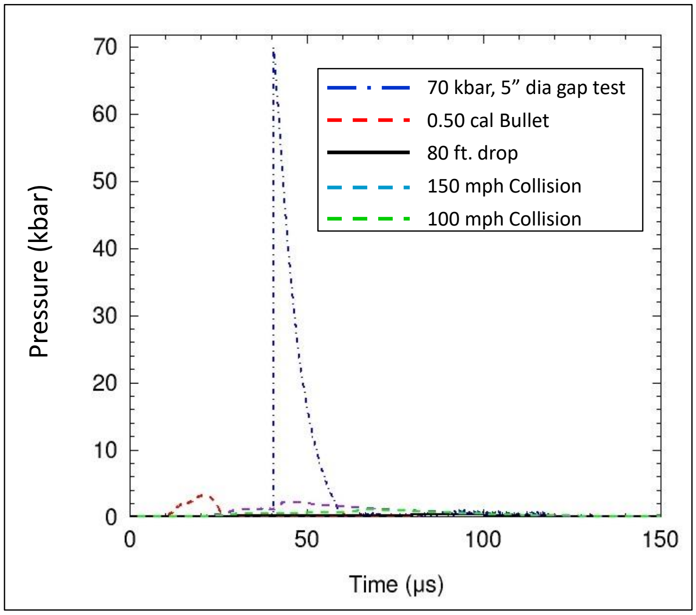


**Figure 3. Pressure Time Curves for a Rocket Motor Subjected to Hypothetical Events and a 5-inch-diameter Gap Test at 70 kbar**



presented visually in Figure 3. Evaluation of the tabulated data and the entire pressure time curves for these events leads to the conclusion that current gap testing produces an impulse far above any credible accident scenario. It is also interesting to note that the impulse delivered by the large-scale gap test (LSGT) at a pressure of 70 kbar generates more than double the impulse than even a 150 mph collision. (The LSGT 70 kbar criterion was used for several decades to determine if a formulation was a Class 1.1 or Class 1.3 material.) It is also important to realize that the low peak pressure generated during the events evaluated is insufficient to produce a detonation in even common Class 1.1 high explosives like Comp B.

## AN INITIAL EXPERIMENAL STUDY EVALUATING PRESSURE AND IMPULSE

To supplement modeling studies described above, a pathfinder experimental study was conducted using a modern propellant formulated to have a critical diameter less than 3 inches so it could be compared with the formulation developed for Project SOPHY that contained 9.2% RDX and had a critical diameter of 2.7 inches. One of the goals of this experimental work was to begin exploring the influence of changes in both pressure and impulse on detonability of solid propellant.

## BOOSTER SELECTION TO APPROACH CONSTANT IMPULSE TESTING

Hydrocode modeling was used to help devise a test matrix to assess the influence of changes in booster geometry on impulse at a fixed pressure, particularly as they relate to an Option 2 shock test. Table 3 shows an example of the calculations performed to determine the change in impulse with different booster geometries. The first row presents data for a notional propellant that has a 6-inch critical diameter and the remaining two entries show data for 9-inch-diameter articles (1.5 times the baseline diameter) with cylindrical Comp B boosters of varying height. These calculations indicate it is impossible to match the impulse of a baseline article with articles 1.5 times the baseline diameter when full diameter boosters of any reasonable height are used to provide shock stimuli.

**Table 3. Theoretical Calculations Showing the Change in Impulse as Booster Charge Weight is Reduced by Decreasing the Height of a Conical Comp B Booster**

| Propellant Acceptor O.D. (in.) | Comp B Booster | | Attenuator O.D. (in) | Pressure (kbar) | Impulse @ 70 kbar (kbar-μ sec) |
|---|---|---|---|---|---|
| | Height (in) | Wt (g) | | | |
| 6.0 | 6.25 | 2739 | 6.25 | 70 | 530 |
| 9.0 | 9.25 | 7553 | 9.25 | 70 | 788 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 9.0 | 2.00 | 1772 | 9.25 | 70 | 641 |

After evaluating a number of different alternate booster geometries, a series of calculations were run that fixed booster size at the booster that would have been used at the point of the critical diameter. This booster was then used in simulations of larger articles. These calculations are summarized in Table 4 for a notional formulation with a 5-inch critical diameter and show that after a small initial increase in impulse, there is no change in impulse despite significant increases in the acceptor diameter.

**Table 4. Theoretical Calculations Showing the Change in Impulse When a Fixed Booster Is Used with Increasingly Larger Acceptor Articles**

| Propellant Acceptor Diameter O.D. (in) | Comp B Booster |  | Attenuator O.D. (in) | Impulse (kbar - μ sec) |
|---|---|---|---|---|
|  | Height (in) | Wt (g) |  |  |
| 5.00 | 5.25 | 1807 | 5.25 | 439 |
| 6.00 | 5.25 | 1807 | 6.25 | 459 |
| 8.00 | 5.25 | 1807 | 8.25 | 459 |
| 12.00 | 5.25 | 1807 | 12.25 | 459 |

## CRITICAL DIAMETER DETERMINATION

The propellant for the experimental study was formulated using carefully controlled ingredients. This formulation incorporated lessons learned over several decades and had the goal of achieving minimum sensitivity while delivering maximum performance. An important formulation development goal was to make a propellant with a critical diameter of between two and three inches. A critical diameter in this range would allow us to economically evaluate the detonability characteristics of article diameter/critical diameter for ratios of two and higher for direct comparison with Project SOPHY data.

Propellant samples were cast into thin-walled cylinders and the length-to-diameter ratio of all test articles was fixed at 4. Following accepted gap testing methods, cylindrical Comp B boosters matching the outside diameter of the acceptor article with a length/diameter ratio of 1 were placed on top of the test articles and detonated. Results of this gap test series are shown in Table 5 and indicate that the new propellant has a critical diameter between 2 and 2.25 inches. Photographs of the 7/16-inch-thick by 6-inch by 6-inch witness plates for the tests just under and just over critical diameter are shown in Figure 4.

**Table 5. Critical Diameter Test Results for New Candidate Propellant**

| I.D. (in) | Length (in) | Test Result | Observations |
|---|---|---|---|
| 1.6 | 6.4 | No Go | Some damage to witness plate - no hole |
| 2.0 | 8.0 | No Go | Some damage to witness plate - no hole |
| 2.25 | 9.0 | Go | Clean hole in witness plate |
| 2.5 | 10.0 | Go | Clean hole in witness plate |

**Figure 4. Witness Plates From 2-inch-diameter (left) and 2.25-inch-diameter (right) Critical Diameter Tests**

## GO/NO-GO TESTING USING DIFFERENT BOOSTER GEOMETRIES

Approximately thirty different samples of the new propellant were cast into plastic tubes with inside diameters ranging from 2.5 inches to 5 inches. The length-to-diameter of all test articles was fixed at 4. Two different booster approaches were used to evaluate the detonability of these samples. For series 1 tests, booster sizing followed a traditional pattern, namely the Comp B booster diameter was matched to the outside diameter of the article and the length-to-diameter ratio was fixed at 1. This approach allowed the booster to grow in size as the test articles grew larger. The approach used in series 2 testing was to fix the booster size for all tests. The specific booster used for series 2 testing was 2.75 inches diameter by 2.75 inches tall. Data for the 5-inch-diameter test article for series 1 and series 2 tests are shown in Table 6 and Table 7, respectively. Similar data were generated at other diameters.

**Table 6. Go/No-Go Data From Series 1 Gap Testing Using a 5-inch-diameter by 20-inch-long Test Article using a Full Diameter Comp B Booster**

| Booster (O. D., in) | Pressure (kbar) | Impulse (kbar-μ sec) | Result | Comment |
|---|---|---|---|---|
| 5.25 | 79.8 | 566 | Go | Punched hole in witness plate, few firebrands |
| 5.25 | 74.7 | 508 | Go | Punched a hole in witness plate, no firebrands |
| 5.25 | 72.9 | 489 | No-Go | Undamaged witness plate, multiple firebrands |
| 5.25 | 70.0 | 469 | No-Go | Undamaged witness plate, multiple firebrands |

**Table 7. Go/No-Go Data From Series 2 Gap Testing for 5-inch-diameter by 20-inch-long Test Articles using a 2.75 inch in Diameter by 2.75 inch High Comp B Booster**

| Booster O.D., in) | Pressure (kbar) | Impulse (kbar-μ sec) | Result | Comment |
|---|---|---|---|---|
| 2.75 | 93.7 | 426 | Go | Punched hole in witness plate |
| 2.75 | 88.5 | 402 | Go | Punched a hole in witness plate |
| 2.75 | 83.9 | 384 | No-Go | Undamaged witness plate, multiple firebrands |
| 2.75 | 78.9 | 362 | No-Go | Undamaged witness plate, multiple firebrands |

Photographs of post-test witness plates for the 5-inch articles are shown in Error! Reference source not found.**.** It is interesting to observe that for both sets of 5-inch-diameter tests, two tests resulted in clear detonations with a clean hole punched in the witness plate and the other two tests caused little, if any damage to the witness plate. It is also important to note that the go/no-go pressures were above 70 kbar.

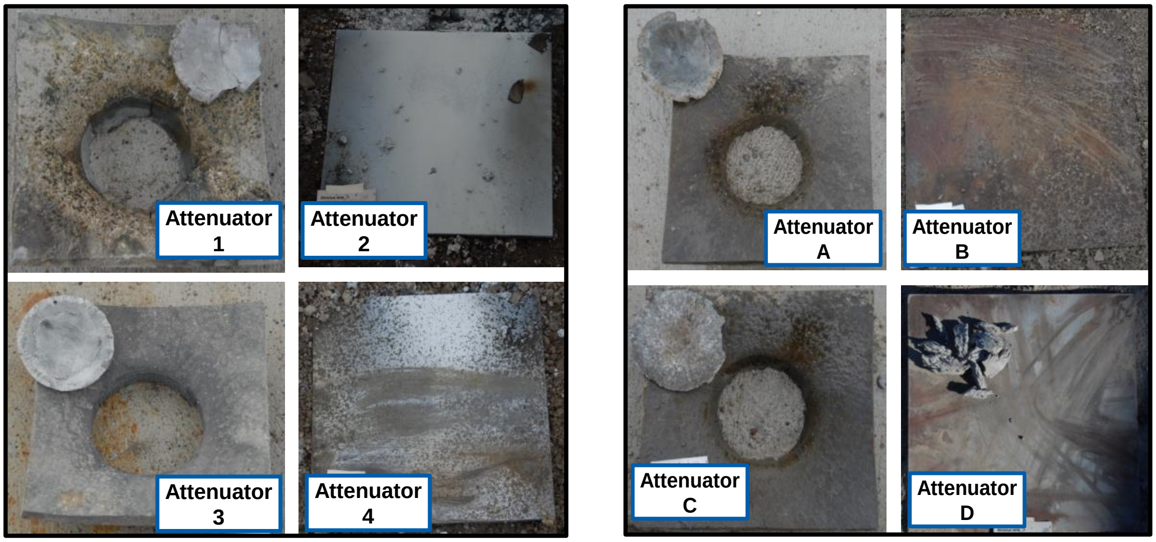


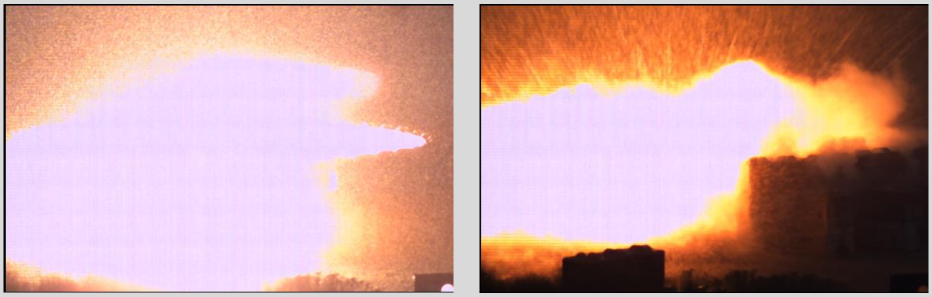
**Figure 5. Witness Plates from 5-inch-diameter Full Diameter Series 1 (left set of photographs) and Reduced Booster Series 2 (right set of photographs) Tests Showing Two Clear Go and Two Clear No-Go Reactions for Each Series**

Real-time (RTV) and high-speed (HSV) digital video were used to record each test conducted in this project. The RTV was particularly useful when evaluating tests that did not detonate. Often these nondetonation reactions would result in significant amounts of propellant that burned for an extended period of time. These lengthy reactions were readily captured on the RTV and provided additional evidence of a nondetonation response.

Frame-by-frame analysis of images from HSV also yielded a considerable amount of information. Figure 6 and Figure 7 show the visual differences observed in detonation and nondetonation reactions for two representative tests. Figure 6 documents the detonation response of a 5-inch-diameter test article using a small booster. The fireball produced during this test grew rapidly and had a relatively short duration. Figure 7 shows a non-detonation response of a 5-inch-diameter test article also using a small booster and only slightly thicker attenuator. The fireball in this test was much smaller than produced in the detonation response. On subsequent frames not shown in Figure 7 undetonated propellant chunks are seen driving into the ground and kicking up sand and dirt.

The test articles used in this project were not instrumented with velocity pins or other similar devices. The use of velocity pins adds cost and increases the time between tests but it also provides additional information. These pins could be included in future testing.

- First light
- + 50 frames (0.005 sec)



- + 10 frames (0.001 sec)
- + 500 frames (0.05 sec)

**Figure 6. Images from a 5-inch-diameter Test Using a Small Booster; Propellant in This Test Detonated; Light Rain During Testing Produced Interesting Visual Images on the Video**

- First light
- + 50 frames (0.005 sec)

- + 10 frames (0.001 sec)
- + 500 frames (0.05 sec)

**Figure 7. Images from a 5-inch-diameter Test Using a Small Booster; Propellant in This Test Did Not Detonate**

## COMPARISON OF NEW TEST RESULTS WITH PROJECT SOPHY DATA

Go/no-go pressure and impulse data for the new propellant were plotted on the same graphs as data from Project SOPHY in Figure 8 and Figure 9, respectively. Comparison of go/no-go pressures and impulses lead to the conclusion that the new propellant is less shock sensitive than propellant tested by Project SOPHY researchers despite having a smaller critical diameter. The new propellant also appears to show the same general trends observed in Project SOPHY including the trend of increasing go/no-go impulse for larger test articles.

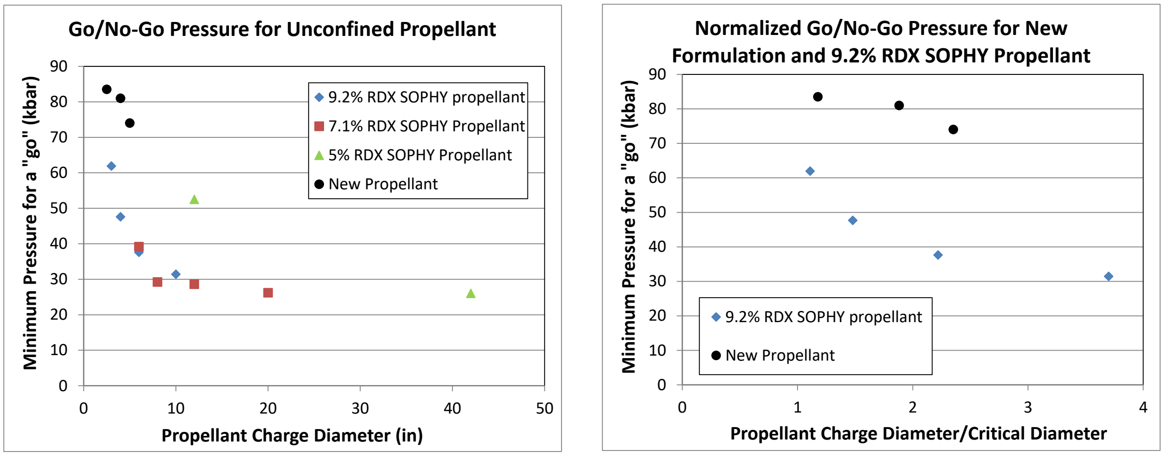


**Figure 8. Go/No-Go Pressures for Entire Set of Project SOPHY Propellants and a New Composition (L) and Comparison of Normalized Go/No-Go Pressures for Two Propellants with Critical Diameters Below 3 inches (R); All Tests Shown Used Full Diameter Boosters**

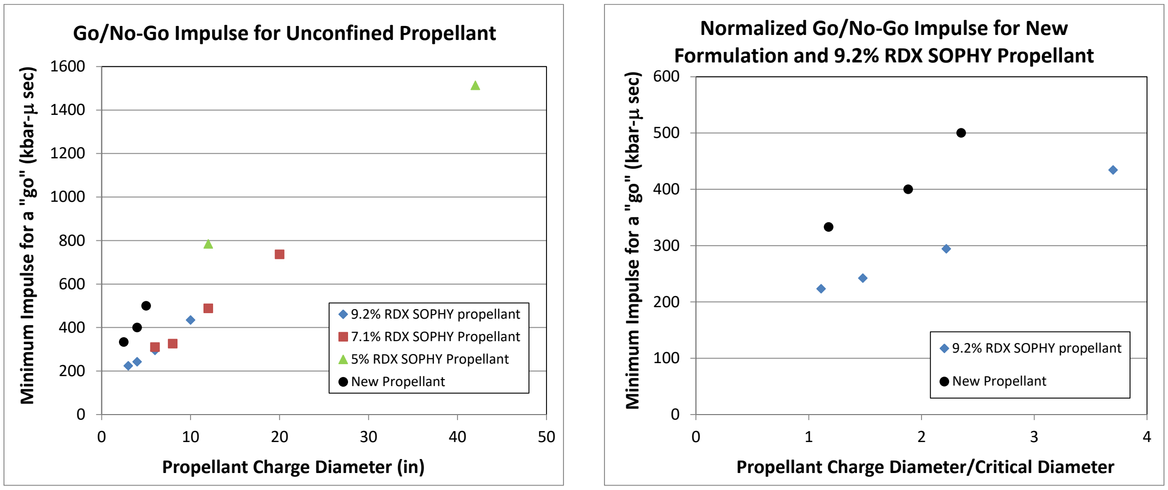


**Figure 9. Go/No-Go Impulse Values for Entire Set of Project SOPHY Propellants and a New Composition (L) and Comparison of Normalized Go/No-Go Impulses for Two Propellants with Critical Diameters Below 3 inches (R); All Tests Shown Used Full Diameter Boosters**

## GO/NO-GO DATA FOR DIFFERENT BOOSTER APPROACHES

Results of go/no-go testing using the increasing or full diameter booster (series 1 testing) and the fixed size or small diameter booster (series 2) are shown graphically in Figure 10.

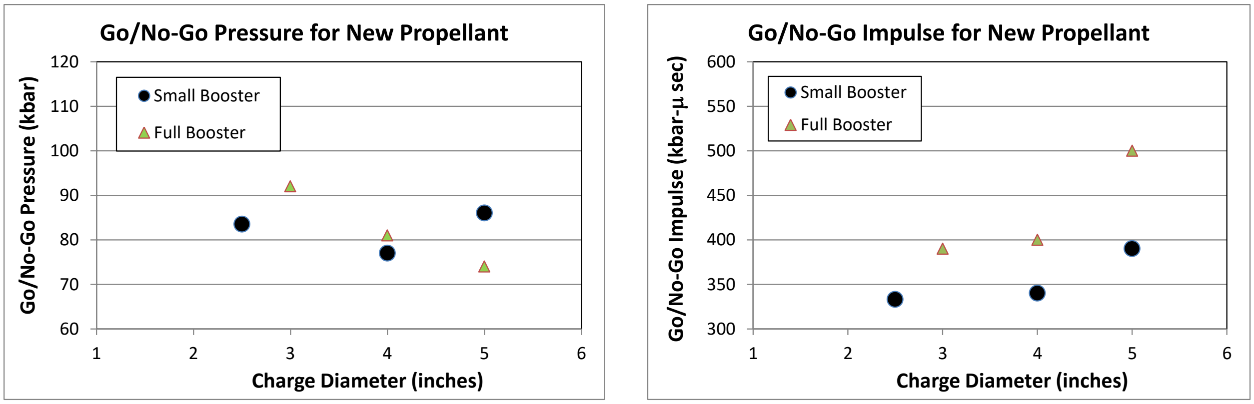


**Figure 10. Comparison of Go/No-Go Pressure (L) and Impulse (R) Values for Two Different Booster Approaches**

Data presented in the left hand graph depicting go/no-go pressure indicates that this propellant has a go/no-go point above 70 kbar and would therefore pass the Option 2 test protocol needed to obtain a 1.3 hazard classification. The increasing diameter booster data suggest a downward trend in go/no-go pressure as the test article increases in diameter. On the other hand, testing with the fixed size or small diameter booster does not show this trend.

Go/no-go impulse data in the right hand graph shows a trend of increasing impulse for both approaches. However, the rate of increase is considerably more pronounced for tests that use the full diameter booster. This finding supports the early analysis of Project SOPHY data that impulse is an important factor that must be considered when conducting gap tests.

## SUMMARY

Theoretical and experimental work has been performed to increase understanding of the relationship between storage, handling and transportation related shock hazards larger solid rockets may experience and shock testing used to determine hazard classification. Theoretical studies comparing shock testing required in TB 700-2 to obtain a 1.3 hazard classification with potential events a large rocket motor may see during its lifetime support the position that our current testing is overly conservative.

Theoretical analysis shows an unintended consequence associated with the current TB 700-2 Option 2 protocol. This unintended consequence favors formulations seeking a 1.3 hazard classification, which have relatively small critical diameters when compared with formulations that have larger critical diameters. Pathfinder experimental studies have generated data using a new propellant that illustrates and supports this position.

Go/no-go testing using different booster approaches has generated data that indicates both pressure and impulse should be considered when conducting gap tests, particularly for larger articles.

## RECOMMENDATIONS

It is recommended that hazard classification driven shock testing of new propellants planned for large rocket motors be based on experimental studies, theoretical analysis and threat hazard assessment. An approach that takes these factors into consideration is shown in Figure 11. This approach allows customization of test conditions based on motor specific storage, transportation and handling conditions.

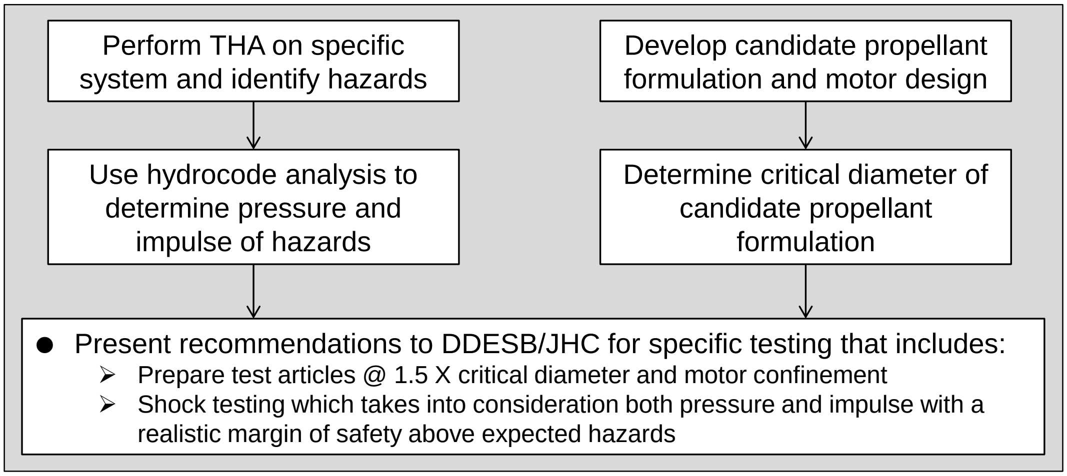


**Figure 11. Flow Diagram Outlining a Protocol Leading to Improved Shock Sensitivity Testing for Hazard Classification of New Solid Rocket Propellant and Rocket Motors**

A near-term recommendation is to conduct additional experimental work to better understand the relationship between go/no-go pressure and impulse for modern propellants. This testing should include duplication of experimental work described in this paper with multiple booster approaches for at least two additional propellants with larger critical diameters.

A long-term goal is to develop improved testing that more closely matches the level and rate of shock associated with potential accident and event scenarios.

## REFERENCES

1. Joint Technical Bulletin, “Department of Defense Ammunition and Explosives Hazard Classification Procedures,” TB 700-2, 30 July 2012.
2. Elwell, R.B., Irwin, O.R., Vail, R.W., “Solid Propellant Hazards Program,” Technical Documentary Report No. AFRPL-TR-66-25, Report Number 0977-01(03) QP, June 1966.
3. Elwell, R.B., Irwin, O.R., Vail, R.W., “Project Sophy – Solid Propellant Hazards Program,” Technical Report AFRPL-67-211 – Vol. 1, August 1967.