Super Large-Scale Gap Tests on Energetic Formulations

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Abstract

Over the years, Aerojet has performed a number of super large-scale gap tests (SLSGT) on various energetic formulations. Results will be presented for the earlier single-length (16") test; the current double-length test; and tests with attenuators between the booster charge and the acceptor.

Introduction

Propellant and explosives formulators have for years used the NOL Large-Scale Gap Test (LSGT) to provide information for hazard classification. This test provides a shock input through an attenuation system of Plexiglas or acrylic "cards", each 0.01-inches in thickness, to deliver a shock of known pressure and duration into a 1.44-inch diameter x 5.5-inch long energetic sample confined in a steel sleeve of 1.875 inches outer diameter. In the past, if the material under test detonated with more than 69 cards in the attenuator, the energetic was considered hazard class 1.1 (mass explosion); and if less than or equal to 69 cards, it was rated as hazard class 1.3 (mass fire, minor blast or fragment hazard).

Many rocket propellants and some plastic-bonded explosives have a critical diameter for sustained detonation that is much larger than the diameter of the LSGT. For many formulations, a value of zero cards was obtained in the LSGT. This yielded the false impression that these materials were only "non-detonable" fire hazards. However, almost all energetic formulations are detonable at some diameter, leading to a stable shock wave propagating through the energetic, with energy feeding into the shock wave from the high-pressure, high temperature reactions in the reaction zone at a rate that overcomes the loss processes of rarefaction and case fragmentation.

In recent years, there has been a change in the hazard classification methodology for shock sensitivity – from simply performing the LSGT, to the much larger scale, alternate tests (three variations) collectively called the "Super Large-Scale Gap Test" (SLSGT).[i] The Single Package and Sympathetic Reaction tests are typically not appropriate for large solid propellant rocket motors. For these large motors, either an alternate test plan must be submitted to the DDESB, or one of the three propellant shock sensitivity test options listed below must be conducted. Note that input stimuli, sample diameter, and confinement are different for each of the three tests.

Alternate Solid Propellant Rocket Motor Hazard Division Assignment Tests

Shock Sensitivity Test, Option 1.

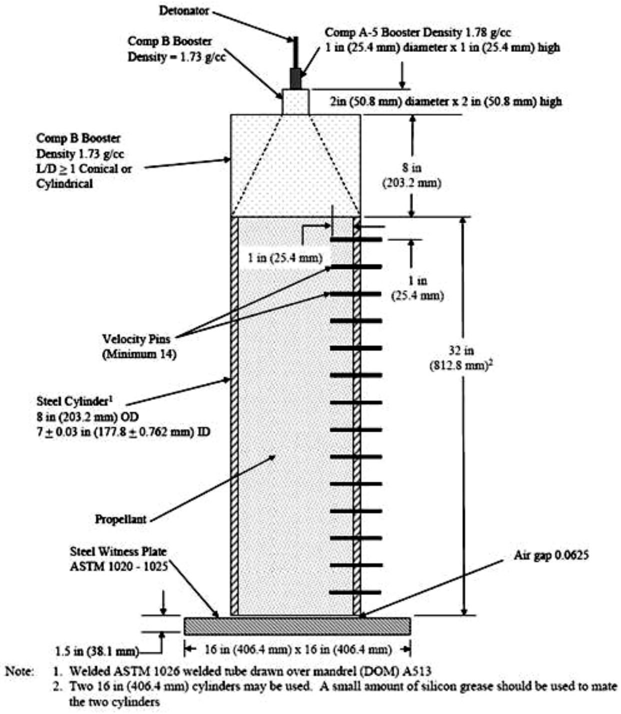
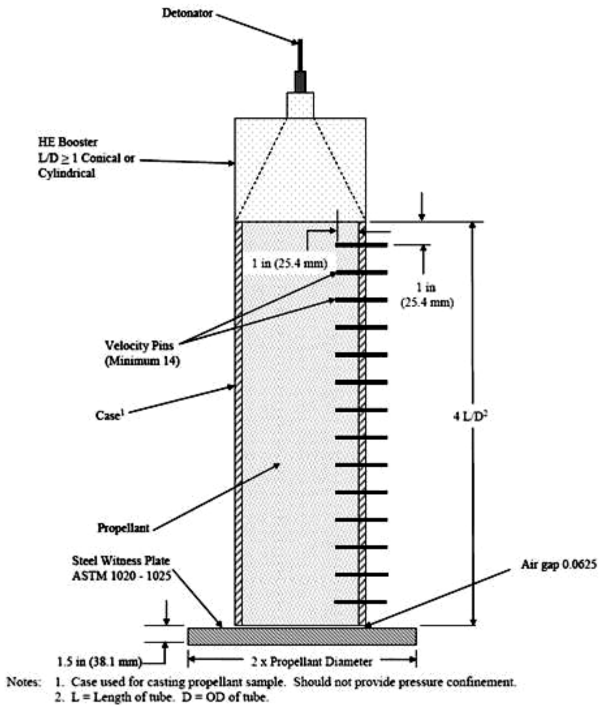


Figure 1. Super Large-Scale Gap Test Fixture

Super Large-Scale Gap Test (SLSGT). One test must be conducted at a zero gap (i.e., no buffer material) – see Figure 1. This provides an input shock of approximately 280 kbar. Propellant sample diameter is 7-inches confined by ½-inch thick steel case. Propellants that maintain a stable detonation as evidenced by velocity pins and the witness plate are classified as HD 1.1. No further testing is required if the projection hazard assessment determination for the rocket motor does not exceed the default value of 1250 ft (381 m). To be classified HD 1.3, the propellant must exhibit a decaying reaction approaching the velocity of sound in the propellant and meet the requirements of the Liquid Fuel/External Fire test.

Shock Sensitivity Test, Option 2.



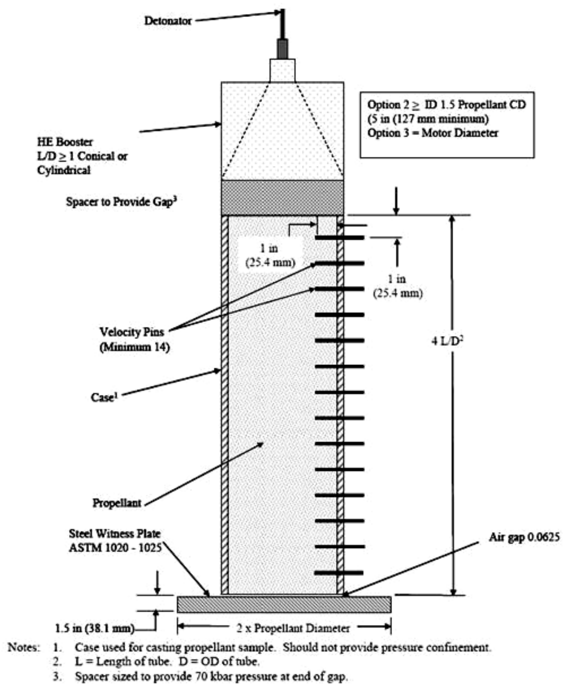


Figure 2. Unconfined Critical Diameter Test Fixture

Figure 3. 70 Kilobar Motor Confinement Gap Test Fixture

This option requires a propellant Critical Diameter (CD) be determined and a sample at least 1.5 times that size be subjected to a 70 kbar shock.

(1) **Unconfined Critical Diameter Test.** (Figure 2). This test provides data that will determine the diameter for the subsequent Gap Test. Preparation of the propellant sample must be such that the motor propellant is accurately represented. One test must be conducted.

(2) **Gap Test.** (Figure 3) The propellant sample diameter must be at least 5-inches or at least 1.5 times the CD of the propellant, whichever is greater. Preparation of the sample must be such that motor propellant is accurately represented. The sample must be contained in a case that affords confinement equivalent to that of the rocket motor case. One test must be conducted at 70 kbar shock pressure at the output end of the gap material (i.e., input to the propellant sample under test).

Shock Sensitivity Test, Option 3.

Gap Test. (Figure 3) Sample diameter must be equal to the motor diameter. Preparation of the sample must be such that motor propellant is accurately represented. The sample must be contained in a case that affords confinement equivalent to that of the rocket motor case. One test must be conducted at 70 kbar shock pressure at the output end of the gap material (i.e., input to the propellant sample under test).

Historical Information on SLSGT Development for Hazard Classification

In the 1980's Foster, ***et. al*** created an instrumented eight-inch diameter "super gap test" in order to gauge the sympathetic reactions of heavily confined explosives stored in close quarters such as general purpose bombs.[ii] The test method used a 7.15-inch diameter by 8-inch long Composition B booster confined in a 0.35-inch thick steel case with half-inch thick steel endplates to apply a stable pressure wave to a 7.15-inch diameter by 16-inch long acceptor charge which was also confined in a 0.35-inch thick steel case with half-inch thick steel endplates (Figure 4). The acceptor charge was instrumented with eight piezoelectric pins, spaced two-inches apart in order to measure the change in velocity of the shock front through the explosive. Tests were conducted with the fixture placed horizontally, lying on a witness plate, both with and without the aforementioned half-inch thick steel endplates on the booster and acceptor charge. In each test series, the shock from the booster was attenuated by placing various numbers of polymethyl methacrylate (PMMA) "cards" between the booster and acceptor.

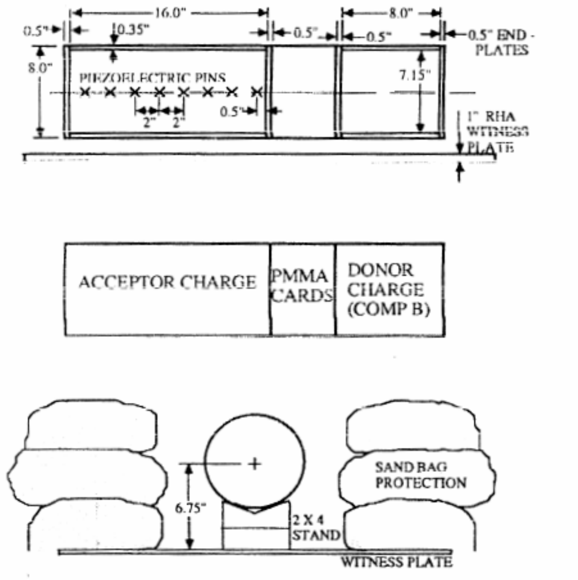


Figure 4. Test Set-up for the 8-inch "super gap test"

Through the course of examining several explosives, Foster noted that a much lower input pressure was required to shock initiate explosives when the shock was delivered by the heavily-confined larger 8" Composition B booster than that required in the NOL LSGT. The donor charge produced a long-duration pressure event which reduced the required input pressure to 60% of that required in the LSGT in order to transition to detonation.

Further investigation of the super gap test was undertaken in the early 1990's by Aubert ***et. al.***[iii] Numerical modeling studies showed that the heavy confinement of the Composition B donor resulted in complex rarefaction waves that confounded the input pressure and may have lead to erroneous assessment of shock sensitivity. This modeling study suggested that an unconfined donor charge would produce more easily discernable and controllable single peak pressure entering the acceptor charge through the PMMA attenuator. Aubert ***et. al*** went on to create and demonstrate a "super large-scale gap test" which consisted of an unconfined 8-inch diameter by 8-inch long Composition B donor and a similar acceptor charge as the super gap test. Unlike Foster's super gap test, the "super large-scale gap test" was run vertically, as in Figure 5, with the donor initiated by an explosive train consisting of an RP-83 detonator, a 1-inch diameter by 1-inch long Composition A-5 pellet, and a 2-inch diameter by 2-inch long Composition B charge. The shock output of the donor charge was attenuated through stacks of 8-inch diameter PMMA of various thicknesses, which were placed in direct contact with the acceptor charge, which was altered to have a diameter of 7.0-inches within a half-inch thick casing with no endplates. The relationship of shock input to the acceptor charge as a function of attenuator thickness was compiled by Glenn[iv] to aid in assessing shock sensitivity, and is provided in Figure 6 along with the relationships for the 1.44-inch diameter LSGT and the 2.88-inch diameter Extremely Insensitive Detonating Substance (EIDS) Gap Test. The reaction of the acceptor charges was assessed through the combination of piezoelectric pin data and the post-test appearance of a 1½-inch thick mild steel witness plate.

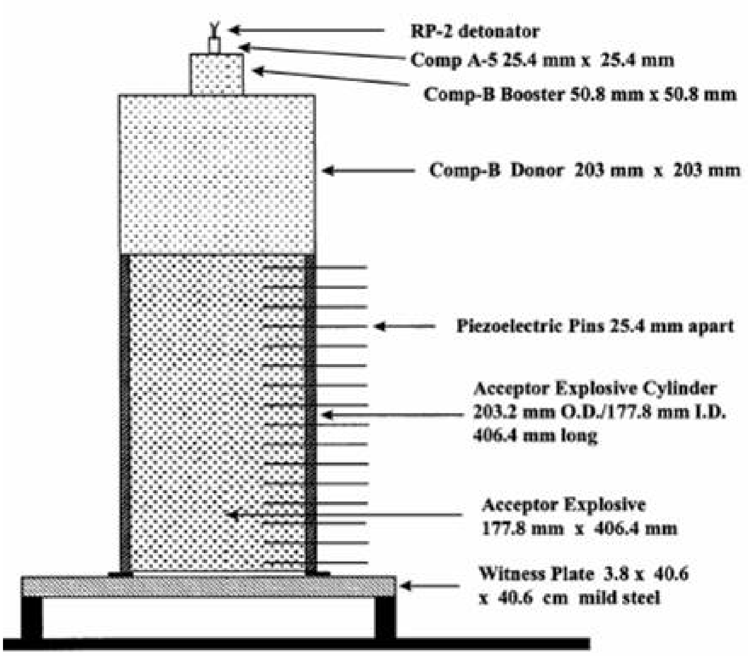


Figure 5. Test Set-up, Super Large-Scale Gap Test (circa 1999)

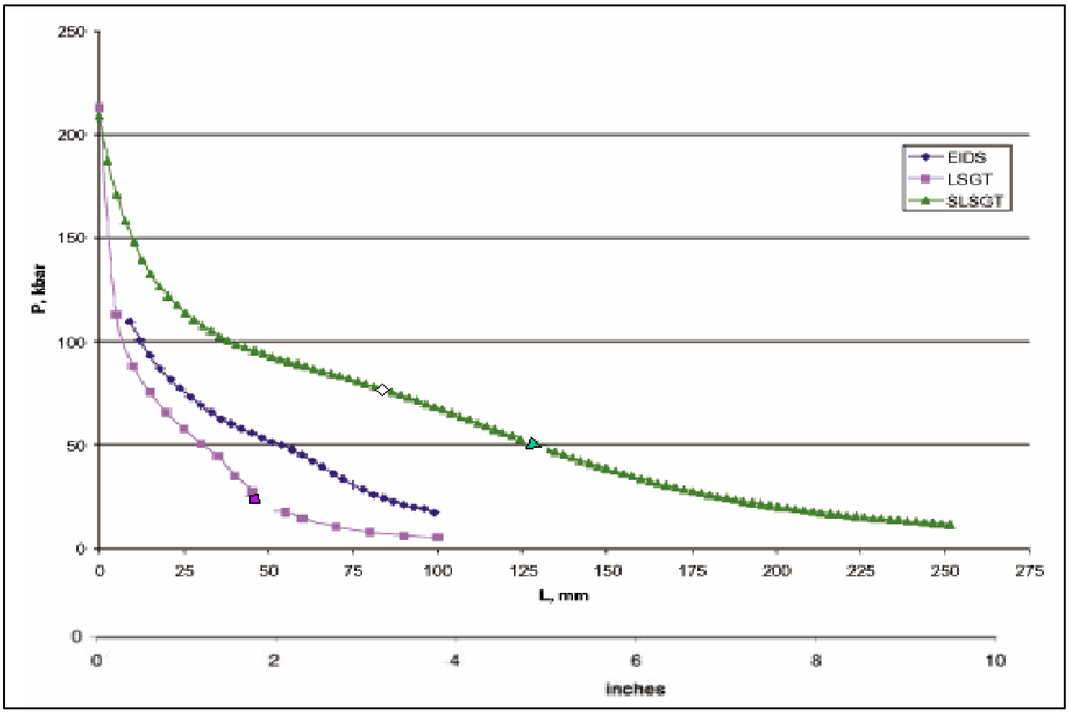


Figure 6. Input Shock into the Acceptor vs. Attenuator Thickness for Three Gap Tests

In January of 1998, the Joint Technical Bulletin TB 700-2 Department of Defense Ammunition and Explosive Hazard Classification Procedures officially adopted the zero gap 16-inch long Super Large-Scale Gap Test as a requirement for consideration for a Hazard Class 1.3 designation for propellants that would not maintain stable detonation in the NOL LGST or the EIDS gap test.[v]

Further investigation by the community[vi] in testing, analysis, and numerical modeling studies yielded controversy over the effectiveness of the test. Miller[vii] showed through use of DYNA2D modeling that the acceptor was both too short and too heavily confined to effectively gauge the shock sensitivity of the propellant. Matheson[viii] went on to use the CTH code to demonstrate that the high-impedance of the steel acceptor casing could cause detonations to occur at the outer radius of propellants that would have otherwise showed decay in the shock front, and that the initial shock front coming off of the booster is too curved and too strong to yield meaningful test results. Others noted that the input pressure of the Super Large-Scale Gap test was approximately 280 kilobars, orders of magnitude higher than the realistic shocks a rocket motor might be exposed to during its lifetime. As a direct result of these analyses, the DDESB issued a memorandum on 8 January 2002[ix] which altered the procedure of the SLSGT and added the two alternate tests described previously in this paper. The SLSGT was also altered to include double-length acceptor charge and to allow the use of a conical booster charge.

SLSGT Testing by Aerojet

Aerojet personnel have been testing SLSGT and its variants since the early 1990's. Through the course of the historical test configuration changes, Aerojet personnel conducted several Super-Large Scale Gap Tests, with both the single-length and the current double-length acceptor charges, accumulating shock sensitivity data on numerous propellants and propellant types. Results have been compiled below.

Initial testing[x] was performed at the Explosives Test Facility (EXTEF) in Camden, Arkansas, using the 16" long acceptor configuration, as specified in the 1998 version of TB 700-2, on two ammonium perchlorate (AP) and aluminum (Al) propellants with the hydroxyl-terminated polybutadiene (HTPB)-based binder system, propellant A and propellant B, respectively. For each of four tests, an explosive booster train consisting of a Number 8 blasting cap centered on a one-inch diameter by one-inch Composition A-5 cylinder, which was centered on two stacked two-inch diameter by one-inch tall Pentolite pellets, which were centered on an eight-inch diameter by eight inch tall, unconfined charge of Composition B explosive. The Composition B was detonated in direct contact with the steel-cased propellant cylinders to determine if the propellant would transition from shock to detonation in these conditions. For each test, the Composition B explosive weight was approximately 25 pounds. Each acceptor casing was outfitted with four holes, precisely located 5.0, 9.0, 13.0 and 15.0-inches from the donor-acceptor interface (Figure 7). Each test also utilized a 16-inch by 16-inch by 1½-inch thick witness plate, placed 1/16-inch below the acceptor charge to aid in the assessment of whether or not the propellant detonated during the test.

For each of two propellants, one test was conducted using piezoelectric pins and one test was conducted using fiberoptic probes to measure the shock velocity through the acceptor. Both measurement techniques showed a rapidly decreasing velocity for both propellants. After each test, the witness plate was bowed, but not punched or fragmented, demonstrating that the propellant did not detonate. Velocity data from these tests are given in Figure 8.

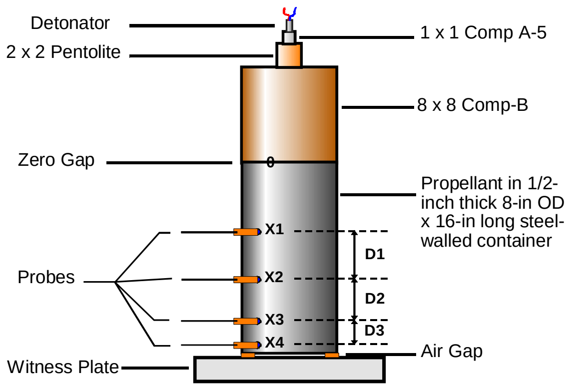


Figure 7. EXTEF 16-inch Length Acceptor, Super Large-Scale Gap Test

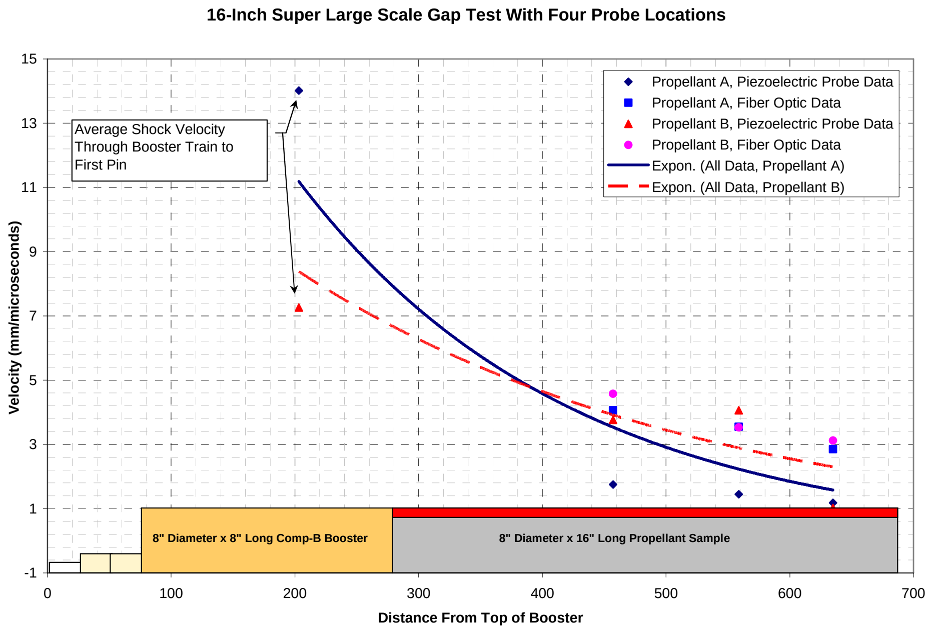


Figure 8. Shock Velocity Data for the 16-Inch Super Large-Scale Gap Test with Four Probe Locations

Confirmation testing was performed at the Eglin Air Force Base using acceptor cylinders which were equipped for diagnostics every two inches. Two tests were performed for each propellant using a 16-inch acceptor, and two tests were performed using two, stacked, 16-inch acceptor cylinders. In all tests the booster train was similar to that used at EXTEF, with and Exploding Bridgewire Detonator used in place of the Number 8 blasting cap, with typical setups given in Figure 9. The propellant failed to detonate in all Eglin tests of Propellant A and Propellant B. The distance vs. time relationship for Propellant B is given in Figure 10 and the velocity vs. distance relationship is given in Figure 11.

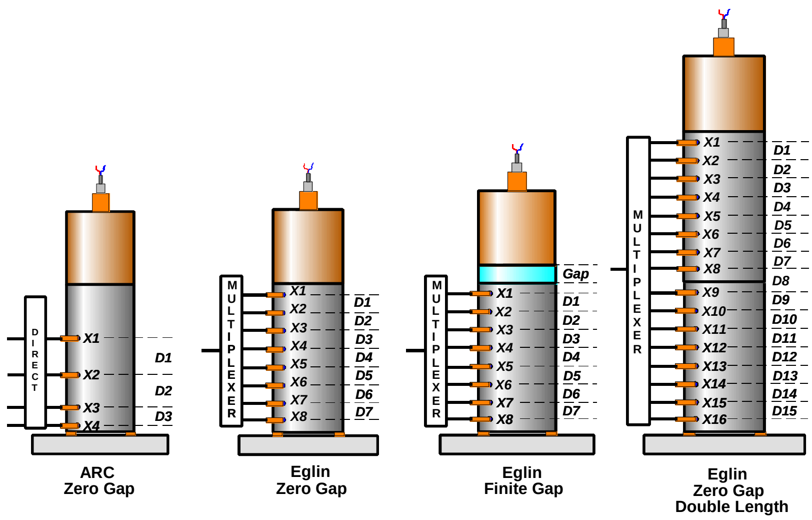


Figure 9. Four Different Types of Super-Large Scale Gap Tests Performed on Propellants A and B.

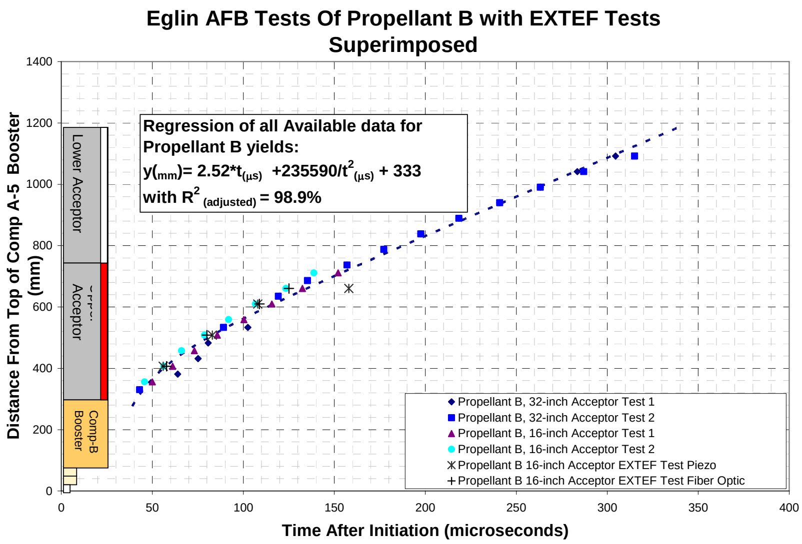


Figure 10. Super Large-Scale Testing of Propellant B at Eglin AFB. (Position vs. Time Data)

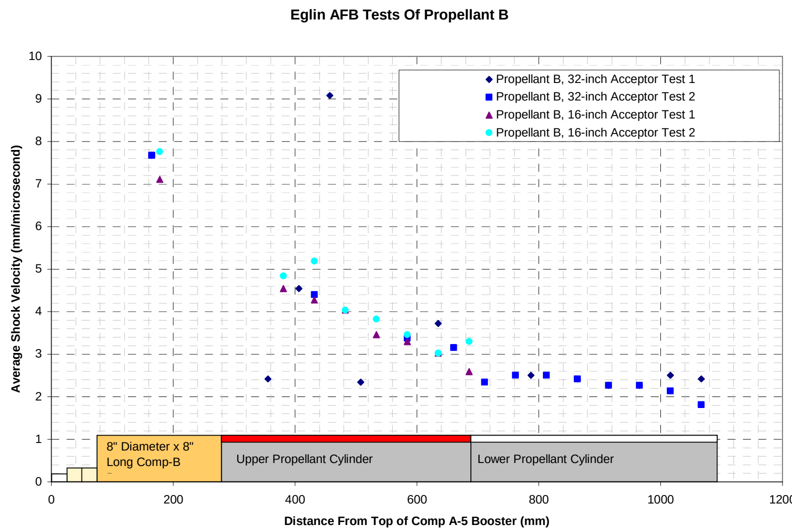


Figure 11. Super Large-Scale Testing of Propellant B at Eglin AFB (Velocity vs. Distance)

Aerojet personnel then began to explore the effects that nitramine addition would have on a propellants performance in the SLSGT. Propellant D was a composite AP/Al/HTPB propellant formulated to contain a level of nitramine such that the propellant exhibited a “no-go” reaction in the LSGT with zero cards of shock attenuation. The same propellant, when exposed to a zero card SLSGT yielded a clear detonation reaction. Successive trials using the 16.0-inch single length acceptor SLSGT, each with varying thickness of attenuator, were performed, finally defining a shock sensitivity range of between 2.975-inches and 3.775-inches of attenuator. From witness plate deformation and fracture data, the critical initiation pressure was judged to be between 70 and 75 kilobar in this heavily confined condition.

Aerojet has also tested a non-aluminized composite propellant containing a decreased level of ammonium perchlorate in a HTPB binder rich system, Propellant C. Propellant C had a theoretical maximum density that was approximately 25% lower than propellant A or propellant B. For the test, twelve piezoelectric pins were used along with seven fiberoptic probes, with the test setup given in Figure 12.

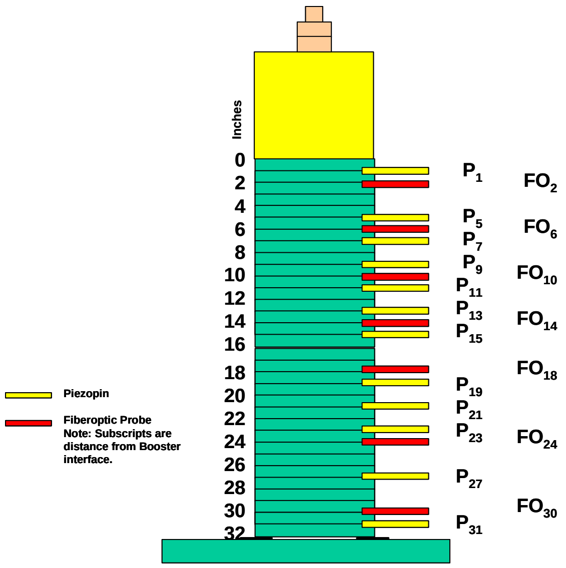


Figure 12. Test Setup for SLSGT of Propellant C.

In the test, the shock velocity dropped so rapidly that only data for the top 8 pins was able to be captured on the oscilloscope. Additionally, the witness plate was left fully intact, undeformed on the test stand. Piezoelectric pins in the decay region also gave multiple signals, which had to be isolated and interpreted as compared to the clear fiberoptic data. Isolated pin data and fiberoptic data are given in Figure 13, as compared to Propellant B. It is apparent from the data that the shock velocity decayed much more rapidly in the low-density, binder-rich propellant than in the propellant with high solids loading.

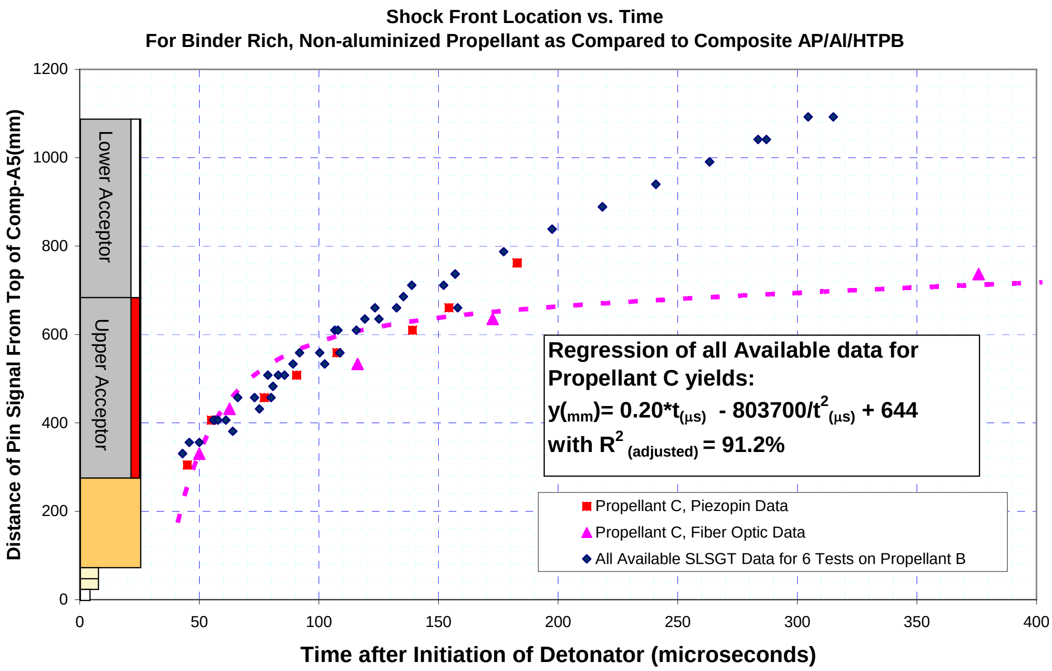


Figure 13. Piezoelectric Pin Data and Fiberoptic Probe Data for Propellant C SLSGT

Following the EXTEF testing of propellant C, a standard testing apparatus was adopted by Aerojet, which uses two 16-inch long acceptor cylinders, outfitted with holes every inch. Data probes are typically spaced in every other hole. The test fixture is given in Figure 14.

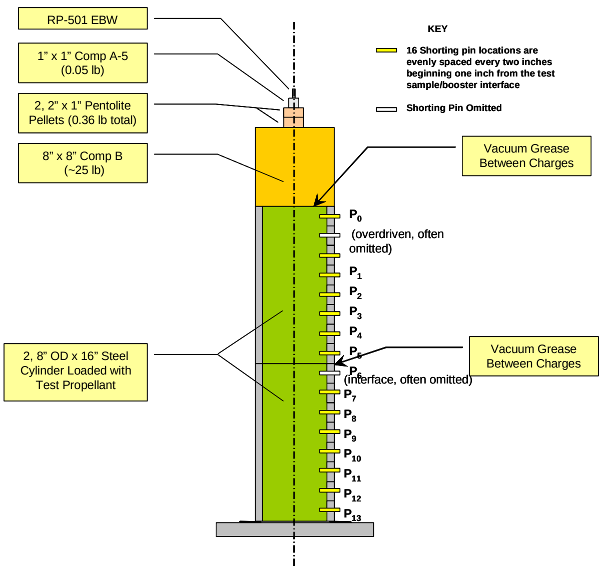


Figure 14. Current Aerojet Set-up for the Super Large-Scale Gap Test.

In addition, Aerojet adopted the use of Dynasen shorting pins; model CA-1058, to reduce the electrical confounding that was occurring with piezoelectric pins. The shorting pins, depicted in Figure 15, consist of a thin, fixed copper wire inside of an insulated stainless steel outer jacket. The wire is surrounded with approximately 0.005" of air-space at the cap. When contacted by a pressure front, the cap begins to move before the copper wire, causing the wire to form a closed circuit on contact with the cap. The voltage produced when this circuit is formed is recorded on an oscilloscope, yielding a sharp peak in areas of high pressure.

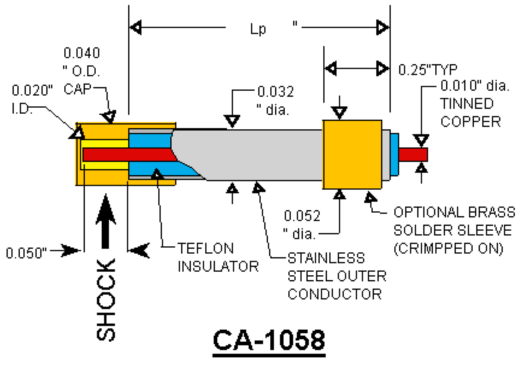


Figure 15. Schematic of Dynasen Shorting Pin Model CA-1058

Aerojet has tested a number of propellants in configuration given in Figure 14, with all non-nitramine containing composite AP/Al/HTPB propellants yielding no detonation. A Typical pre-test photograph of one such test is given in Figure 16. A typical post-test photograph of the witness plate and recovered casing fragments for a passing reaction is given in Some of the diagnostics results for the composite AP/Al/HTPB propellants are given in Figure 17. Some of the diagnostics results for the composite AP/Al/HTPB propellants are given in Figure 18.

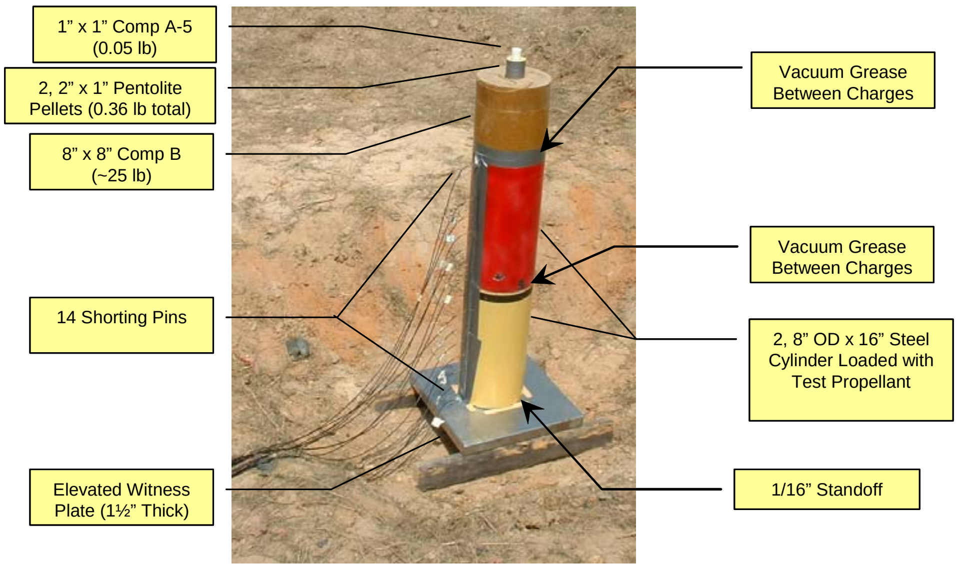


Figure 16. Typical Aerojet Set-up of the 32-inch Acceptor, Super Large-Scale Gap Test.

Figure 17. Typical Post-test Photograph of the Witness Plate and Fragments for a "Passing" Reaction.

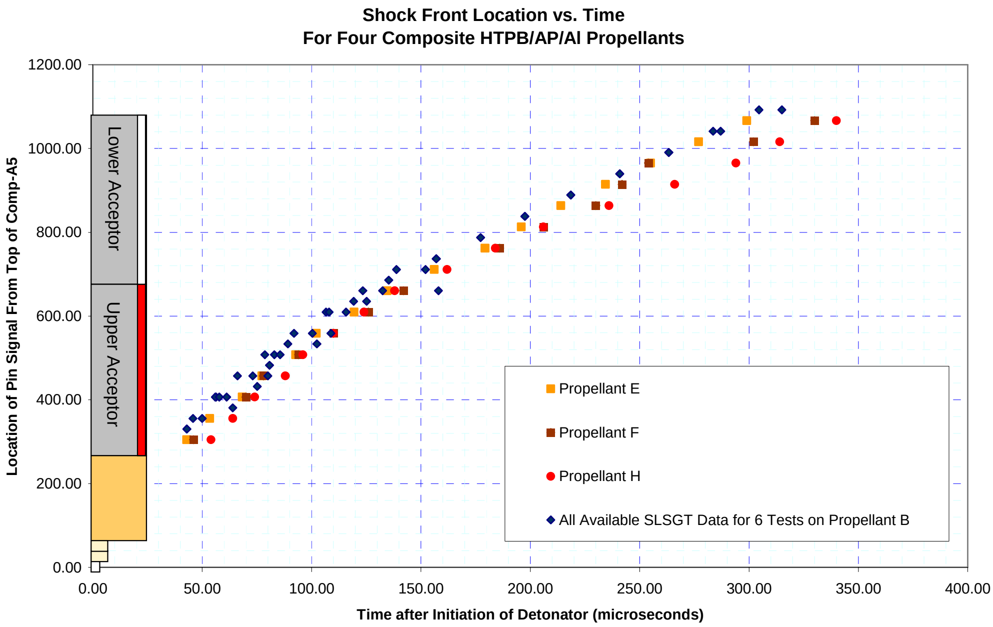


Figure 18. Compiled Super Large-Scale Gap Test Data for 4 Composite AP/Al/ HTPB Propellants

Aerojet has included blast overpressure measurements using side-on gauges in all of the recent SLSGT at the request of sponsors. This has necessitated that blast overpressure measurements be taken by detonating an analogous booster train alone, prior to testing the all-up SLSGT unit. It is desired to quantify the contribution of the propellant to the blast wave over that of the booster train. Because of the portion propellant that is overdriven by the shockwave, the contribution for a non-detonating propellant can be significant. A typical overpressure record for is given in Figure 19.

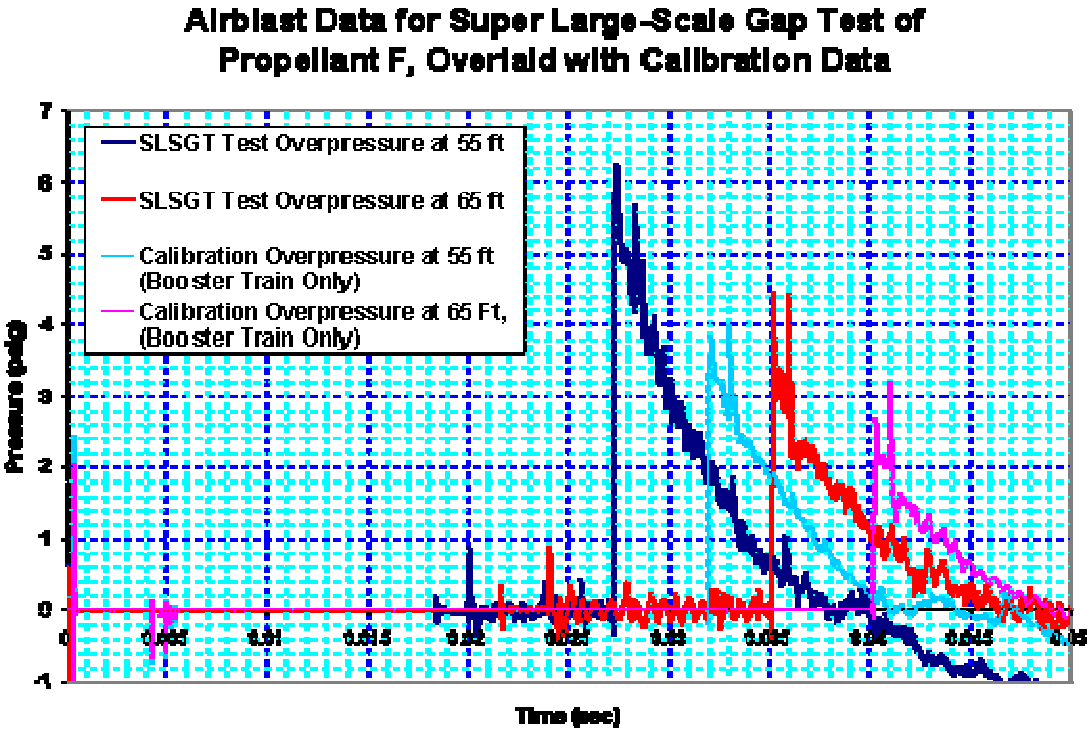


Figure 19. Overpressure record for SLSGT of Propellant F, Overlaid with Booster Calibration Shot

As part of an hydroxyl-terminated polyether (HTPE)-binder based propellant development effort, Aerojet has also tested a composite AP/Al/HTPE propellant in a zero card SLSGT, yielding no detonation. These results are given in Figure 20, as compared to a similar HTPB-based propellant.

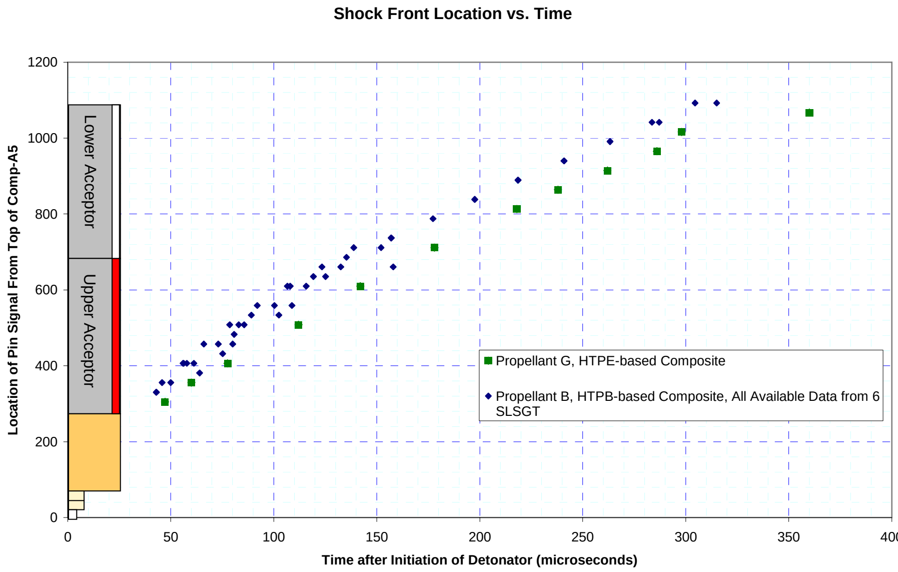


Figure 20. Comparison of Super Large-Scale Gap Test Data for HTPB-based and HTPE-based propellants

Discussion

Instrumentation

Aerojet has used a number of diagnostics in the super large-scale gap test. For detonation velocity measurements, fiberoptic probes detect the position of the luminous shock front. Piezoelectric pins and shorting pins detect the position of the compressive front. Pins are typically multiplexed, such that all of the pin signals to a given multiplexer are recorded on the same channel of the oscilloscope. In an energetic material that is detonating, we have seen virtually identical results between fiberoptic probes and pins. However, if the shock-induced reaction is failing and the material under test begins to break up, mixed results occur. If the sample fractures and there is flame intrusion into the crack and it is near the fiberoptic probe, an apparent increase in detonation velocity may be observed. Pins may show a decrease in detonation velocity, or more commonly, mixed and generally uninterpretable results. Some of these mixed results can occur in failing detonations when a single pin sends multiple signals as it encounters rarefaction waves coming off of the steel casing/propellant interface.

Other diagnostics assist in interpretation. The witness plate will be punched in a detonation, but bowed or even left undistorted if there is no detonation. Fragments from the side wall of the steel cylinders will be "blued" and be chevron shaped and small if detonation occurs, while for a failing reaction, the fragments from the lower portion of the cylinders will be quite large (perhaps the length of the second 16-inch cylinder in the current 32-inch test, as in Figure 17) and will be torn rather than sheared.

Blast measurements on propellants are of limited value. If the propellant truly detonates, a sharp air shock is produced, and if a side-on blast gauge array is used, the arrival times and pressure-time wave shape can be informative. However, in an explosion of propellant, the pressures can be up to ½ the detonation pressure, but the duration is generally longer. It is ineffective to try to determine a "TNT-equivalence" for a failing reaction since this has no meaning except for truly detonating energetics. Additionally, the desire to obtain these "TNT-equivalence" measurements has lead to a need to expose the high fragmentations test units above ground and without barriers. The end result in failing detonations is an arrival front that includes some contribution of overdriven propellant and a longer duration pressure resultant from the exploding propellant. Divining how much propellant was part of the added pressure front is not wise.

Likewise, trying to interpret the "sound" of the reaction is generally of no value, since the donor charge does detonate, and even partially reacting propellant charges generate a huge sound on reaction. High-speed photography and videography can give evidence of partial or failing reactions, showing the presence or absence of flaming firebrands. Finally, for very unreactive propellants and explosives, there can be a "carrot" of left-over, unreacted material at the test location – a strong indicator of a failed reaction (and a passing score in the alternate hazard classification test).

Modeling

Hydrocodes, in general, have been historically used to model physical systems in order to explain or predict events that occur on a level that cannot be easily measured in the physical systems. Specifically, hydrocode is most reliable in examining infinitesimal interactions that, in aggregate, lead to some known end result. By solving an inverse problem, hydrocode can be used to define specific behavioral characteristics of different materials in defined circumstances. Hydrocode analysis is especially useful in examination of systems involving explosive shock, in which physical experimentation of multiple scenarios is often difficult or impossible.

In an effort to understand the physical behavior of the shock front in a non-detonating super large-scale gap test, Aerojet has used the reactive hydrocode PCSMERF, developed by Eric Lundstrom for the Naval Air Warfare Center Weapons Division at China Lake, California and New Mexico Institute of Mining and Technology, Socorro, NM. PCSMERF combines the procedures of several well-established hydrocodes and high explosive burn models to achieve a robust analytical modeling package. A modified Lax-Wendroff method is used to solve the continuity equations in the Lagrangian phase, while van Leer's advection scheme is used in concert with the Simple Line Interface Calculation (SLIC) algorithm to calculate material flux in the Eulerian phase.

In order to understand the shock interactions and mechanics that were due strictly to the contributions of the booster system and the physical response of the materials, a model was developed for the super large-scale gap test that used unreactive polyurethane rubber as the acceptor propellant. "Gauge" variables were placed at all of the pin locations and used to measure the predicted diagnostic response of a super large-scale gap test performed on such a system, given in Figure 21. Predictably, the acceleration rate of each pin as it is contacted by the shock front decreases as the pressure wave decays. This is important to note, as the aforementioned shorting pins require the outer cap to traverse 0.005" of space before the signal is produced. Thus the delay increases slightly as the shock velocity decreases. Accounting for this delay, model pins were given a predicted signal time based their initial velocity upon contact with the shock front. Predicted pin response for urethane rubber is given on the same plot as all of the previously reported composite propellant in Figure 22.

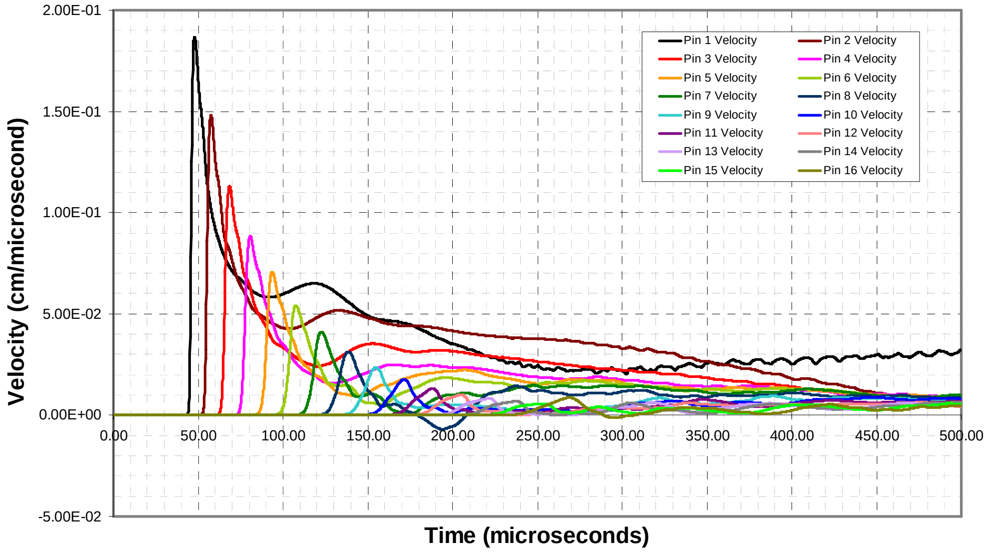


Figure 21. Hydrocode Model of the SLSGT with Inert Polyurethane Rubber Acceptor, Acceleration at Pin Locations

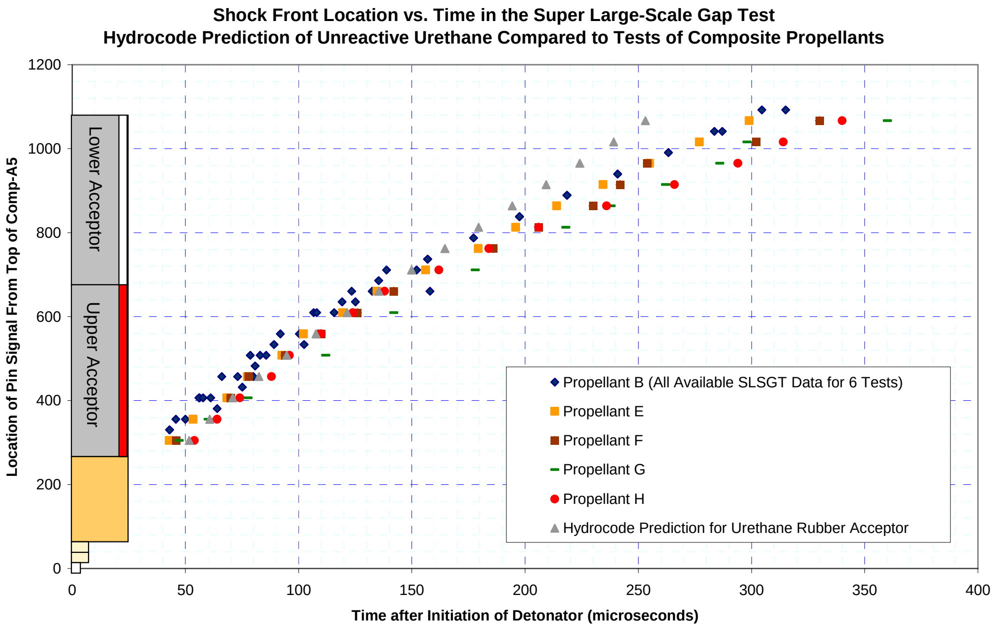


Figure 22. Hydrocode Prediction of Pin Response for Polyurethane Acceptor Compared to Know Composite Propellant Response

Regression analysis can be used to plot the location of the pressure front as a function of time as in Figure 10. Taking the derivative of the regression equation can yield a velocity decay equation, but one must be careful to understand that the equation must be bounded by the data range for the propellant measurement locations, and that discrete velocity measurements may be higher or lower than this equation suggests.

Notably, constant in the decay equation should be the sound speed through the propellant.

Table 1. Regression Analysis of SLSGT Test Data

Propellant Formulation	Regression Equation (y is distance from top of booster)	Velocity Decay Equation
B	$y_{(mm)} = 2.52{*}t_{(\mu s)} + 235600/t^2_{(\mu s)} + 333$	$^{dy}/_{dt\ (mm/\mu s)} = 2.52 + 471200/t^3_{(\mu s)}$
D	$y_{(mm)} = 0.197{*}t_{(\mu s)} - 803700/t^2_{(\mu s)} + 644$	$^{dy}/_{dt\ (mm/\mu s)} = 0.197 + 1607400/t^3_{(\mu s)}$
E	$y_{(mm)} = 2.59{*}t_{(\mu s)} - 236200/t^2_{(\mu s)} + 307$	$^{dy}/_{dt\ (mm/\mu s)} = 2.59 + 472400/t^3_{(\mu s)}$
F	$y_{(mm)} = 2.33{*}t_{(\mu s)} - 321300/t^2_{(\mu s)} + 336$	$^{dy}/_{dt\ (mm/\mu s)} = 2.33 + 642600/t^3_{(\mu s)}$
G	$y_{(mm)} = 2.32{*}t_{(\mu s)} - 255800/t^2_{(\mu s)} + 294$	$^{dy}/_{dt\ (mm/\mu s)} = 2.32 + 511600/t^3_{(\mu s)}$
H	$y_{(mm)} = 2.00{*}t_{(\mu s)} - 663800/t^2_{(\mu s)} + 399$	$^{dy}/_{dt\ (mm/\mu s)} = 2.00 + 1328000/t^3_{(\mu s)}$
Urethane (Hydrocode Prediction)	$y_{(mm)} = 3.38{*}t_{(\mu s)} - 204900/t^2_{(\mu s)} + 333$	$^{dy}/_{dt\ (mm/\mu s)} = 2.52 + 409800/t^3_{(\mu s)}$

Effect of Nitramine on Shock Sensitivity and Critical Diameter

Propellant D is an 89% solids containing 57% AP, 18% aluminum and 14% RDX in an HTPB binder system. Shock sensitivity was studied in three scales of gap tests – LSGT, ELSGT, and the 16-inch long SLSGT (See Table 2). It has an unconfined critical diameter of about 7-inches. It is of note that it is zero cards (7 replicates) in the LSGT and that it passes the UN Hazard Class 1.6 ELSGT criterion by a wide margin. In the SLSGT, it failed the option 1 test of zero cards (***ca.*** 280 kbar input shock), and ½-inch steel confinement, detonating at 5400 m/s. Repeating the test with the steel confinement and Plexiglas attenuators between the booster and acceptor gave a critical shock initiation pressure of nominally 70-75 kbar. It is expected that if this test were conducted with a composite container, shock sensitivity would be significantly decreased.

Addition of RDX to an AP/Al/HTPB propellant has the effect of decreasing the critical diameter for sustained detonation, and generally makes it more shock sensitive and more inclined to fail the gap test requirements (figure 23). However, utilizing smaller RDX instead of the larger “as received” material has much less of an effect on critical diameter. Where 10% RDX substituted for AP in the SOPHY propellant gave a critical diameter of about 2 inches, Aerojet has shown that over 14% of smaller RDX can be added while still maintaining a nominal 7-8-inch critical diameter. Adding 1% more binder can compensate for as much as 2% of fine RDX (figure 24).

Table 2. Shock sensitivity testing of Propellant D in various gap tests.

Test Type	Dimensions, inches	GO/NO GO Gap, inches	Input Shock Pressure, kbar	Comments
NOL Large-Scale Gap Test (LSGT)	1.44 id x 5.5 length	-0 (7 replicates)	280	No detonation at zero gap. Below critical diameter.
Extended Large Scale Card Gap (ELSGT)	2.88 id x 11 length	+1.125/-1.200 (7 tests)	+98/-96	Passes the UN Hazard Class 1.6 ELSGT criterion of 2.75-inches.
Super Large Scale Gap Test (SLSGT) No Attenuator	7.0 id x 16 length	+0	280	-Detonates at zero gap with average detonation velocity of 5408 m/s (σ = 98 m/s or 1.8%; n=3).
Super Large Scale Gap Test (SLSGT) With Attenuator	7.0 id x 16 length	+ 2.975/- 3.775	+77/-63	- Detonates at 2.975 in. gap with D = 5350 m/s (σ = 53 m/s or 1%; n=3). Judging from plate deformation, critical initiation pressure is 70-75 kbar.
Critical Diameter Test (Unconfined Cylinder)	6 diameter x 18 length 4 diameter x 14 length		280	Both fail to propagate (unconfined). Wave decays rapidly toward sound speed.

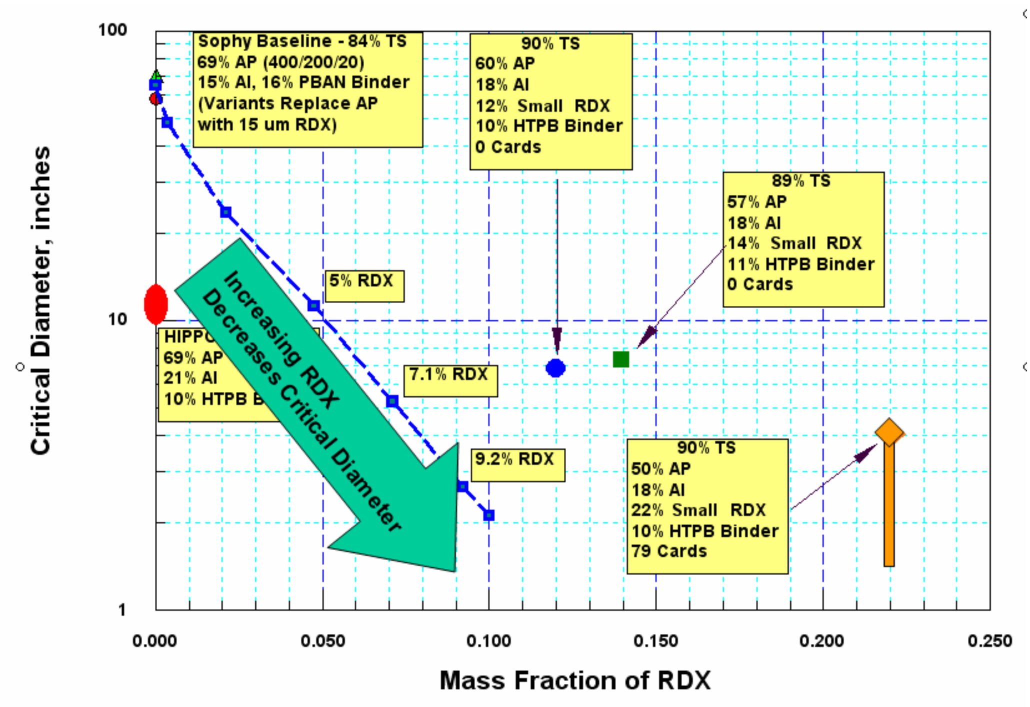


Figure 23. Effect of Increasing RDX on Critical Diameter

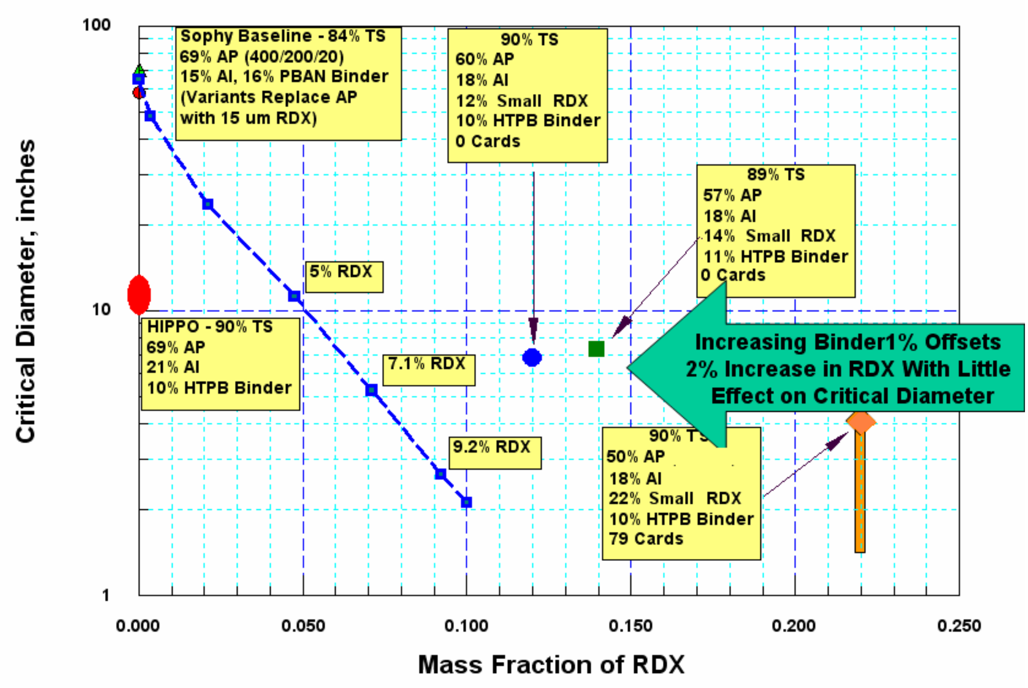


Figure 24. Effect of Increasing Binder on Critical Diameter

Summary and Conclusions

Many modern rocket propellants have a large critical diameter for sustained detonation and pass the highly confined option 1 shock sensitivity test of TB 700-2. In this test, the propellant is placed in direct contact with the Composition B booster, giving a shock input of approximately 280 kbar. In the results reported for propellants containing ammonium perchlorate and aluminum in an HTPB finder system, Aerojet demonstrated that all exhibited a pressure wave that rapidly decreased to sound speed. All diagnostics confirmed that shock-to-detonation transition did not occur.

When the binder system was changed to HTPE, which gave an AP/Al/HTPE propellant with higher binder percentage than the composite AP/Al/HTPB propellant, the result was even more rapid drop to sonic velocity.

Adding RDX to an AP/Al/HTPB reduces the critical diameter for sustained detonation and increases shock sensitivity. However, if the particle size of the nitramine is small, usable propellants can be made to load relatively large-diameter rocket motors while still maintaining low shock sensitivity and large critical diameter. Note that addition of nitramine in quantities that would allow a zero card LSGT “no-go” can yield transition to detonation in the SLSGT.

Low density propellants, particularly those that are binder rich, may exhibit rapidly decaying shock front velocity, and conversely, propellants with higher density may allow the shock front to maintain velocity longer, increasing the chance that the propellant will transition to detonation.

In order to obtain interpretable test results, it is recommended that the test facility use a broad combination of diagnostic tools:

- Shorting pins tend to produce less noise than piezoelectric pins in propellant reactions that fail to transition to detonation.
- Fiberoptic probes in conjunction with a fiberoptic timer tend to yield the most easily interpretable results for propellant reactions that fail to transition to detonation.
- The witness plate remains the clearest delineator between a go and a no-go reaction.
- The condition of case wall fragments, particularly those of the lower propellant cylinder, can show reaction violence.
- Blast overpressure can be a good indicator of TNT equivalence of a propellant that rapidly transitions to detonation, but should be viewed with skepticism for non-detonating propellants.

The data presented here should add significantly to the alternate hazard classification database for large rocket motors that are needed by the hazard classifiers.

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