Evaluation of Less Shock Sensitive Minimum Smoke Propellants in High Performance Composite Cases

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ABSTRACT

The U.S. Army (Redstone Arsenal, AL), U.S. Navy (China Lake, CA) and ATK (Rocket Center, WV) are conducting joint efforts aimed at achieving Insensitive Munitions (IM) compliance of tactical minimum smoke rocket motors under slow cookoff (SCO), fragment impact (FI), bullet impact (BI) and fast cookoff (FCO). This effort builds upon ATK's effort to develop lower shock sensitivity minimum smoke propellants. This family of propellants has been successfully subjected to processing development, limited aging, stabilizer depletion, mechanical property characterization, and sensitivity testing.

The solid propellants developed and characterized were scaled-up and loaded into 178 mm (7 in.) diameter composite-cased test motors. The test motors were fitted with a thermally activated, passive venting device for slow cookoff mitigation. The completion of full-scale testing has provided exceptional results. The development program beginning with propellant development and culminating with full-scale testing will be discussed along with lessons learned.

BACKGROUND

Attempts to solve the IM problem from a case or propellant solution alone are misguided. While each can improve IM response, the maximum extent of IM compliance may only be achieved through a systems approach. An understanding of the mechanisms at work for each of the IM threats is essential to undertaking the design challenges of IM propulsion systems.

Fast Cookoff (FCO) response is dominated by the significant weakening of composite case due to direct exposure to the fuel fire, where the surface temperature greatly exceeds the glass transition temperature of the composite case. Under these conditions, little residual confinement remains for thin-walled composite cases. Apparent reduction in heating rate is possible due to storage condition (e.g., containerized, round pallet config., etc.) which leads toward an intermediate-rate cookoff scenario where heat paths to the composite case must be considered in the design process.

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There is a much more limited benefit from a composite case alone under Slow Cookoff (SCO) conditions. A composite case generally provides a less severe reaction due to slump and inherently lower dynamic yield strength. Conditions leading to increased thermal soak (i.e., slowest heating rates, packaging) can lead to more violent reactions. A mitigation device is required to address SCO in either composite or metal cases. For tactical ground and aviation-launched missiles, motor-level built-in passive SCO mitigation devices are desired from a cost and ease of integration standpoint. End venting offers an attractive solution for motor configurations with low length-to-diameter ratios.

Propellant shock sensitivity provides the more dominant effect for Bullet Impact (BI) and Fragment Impact (FI); however, composite cases have been shown to reduce the severity of reaction. Improvements to impact reactions from composite case construction stem from the elimination of metal spall into the propellant and from the reduction in post-reaction lethal fragments. Even when combining less shock-sensitive propellants and composite cases, reaction violence under fragment impact conditions are very dependent on fragment velocity. High velocity fragment impact remains a significant challenge for minimum smoke propellants when attempting to balance IM characteristics and propellant performance.

The current effort, which began under U.S. Army funding and continues through the U.S. Department of Defense Joint Insensitive Munitions Technology Program (JIMTP), is focused on combining less shock-sensitive propellants, composite case technology, and passive venting techniques to effect the highest degree if IM compliance possible.

PROPELLANT SELECTION

The propellant selection for this effort was focused on building upon the ATK cross-linked double base (XLDB) heritage to arrive at a propellant solution that provided a good balance between ballistics, shock sensitivity, and mechanical properties. The current family, or Second Generation, of XLDB propellants represents an evolutionary development from state-of-the-art high performance minimum smoke propellants (Table 1). Past formulations had shown improved IM performance; however, that performance was only obtained at the expense of ballistic and mechanical property performance. The current generation has addressed these deficiencies while maintaining good energy and excellent mechanical properties. Of particular note, is that these propellant formulations exhibit strain capabilities approaching 90% at -54ºC.

The primary less-sensitive propellant chosen utilizes a RS-RDX co-oxidizer and has a NOL card gap of 70 cards. Two additional propellant variants were studied. One replaces the RS-RDX co-oxidizer with CL-20, and the other eliminates the co-oxidizer in favor of additional ammonium nitrate. The CL-20 containing formulation is also 70 cards in the NOL gap test, and the formulation with no co-oxidizer achieves 63 cards. All other formulation parameters were held constant. All three formulations exhibit similar specific impulse with the CL-20 formulation seeing a 0.7% increase and the formulation with no co-oxidizer seeing a 0.9% decrease when compared the RS-RDX formulation.

Table 1. ATK XLDB Propellant Heritage

Ingredient/Property	Current Production	First Generation	Second Generation	
Category	Sensitive Class 1.1	Reduced Sensitivity MS Propellant Candidates		
DOB	1979	1992	2002	
Formulation type	XLDB binder with high nitramine	XLDB binder with AN and Casting Powder modifier	XLDB binder with AN and Co-oxidizers , Metal Salt modifiers	
Isp (% of baseline) Card Gap (cards) Critical Diameter (in)	100% 145 <0.5	95% 65 1.0	93-94% 65-80 0.5 – 0.75	
Mix Scale Manufactured (lbs)	2,000	1,000	100	100
Application	Fielded Tactical Motors	Development & Advanced Development Motors	Fixed Throat Advanced Development Motors	Controllable Thrust RDT&E Motors
Deficiencies	Sensitive	Limited ballistics & mechanicals	*Excellent mechanical properties, cold strain capability & processibility, higher operating pressure*	

DEVELOPING A DESIGN APPROACH FOR SLOW COOKOFF RESPONSE MITIGATION

The initial focus of this effort was to implement an engineering solution for slow cookoff mitigation. Inherent to this task was to determine the autoignition response of the propellant under confinement. An instrumented sub-scale cookoff chamber (Figure 1) was designed and utilized to obtain thermal profiles at the surface (T0), the propellant interface (T1, T2), and the center of the grain (T3). Heating was applied via a fitted thermal heating jacket with electronic controller. The XLDB propellant formulation containing RS-RDX was utilized.

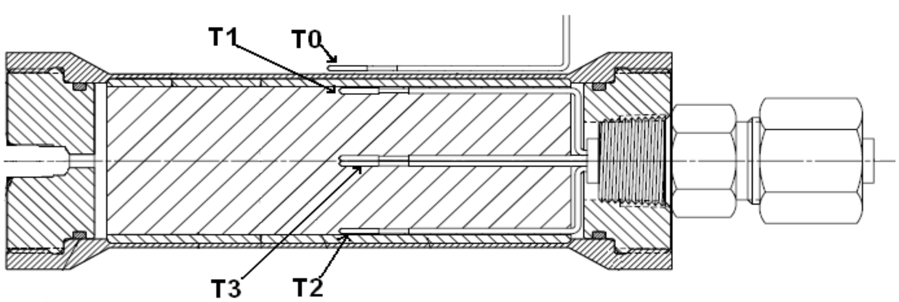

Figure 1. Instrumented Sub-scale Cookoff Chamber (propellant charge 45.7 mm diameter x 114.3 mm long)

The original test series utilized the alternate heating rate of 25ºC/hr, and the test series was later repeated using the standard 3.3ºC/hr (Table 2). Case material and thickness appeared to have little effect on reaction temperature; however, the thicker cases required slightly higher external temperatures to reach the reaction temperature.

Table 2. Sub-scale Cookoff Chamber Test Data

S/N	**Chamber Material**	**Wall Thickness** (mm)	**Heating Rate** (ºC/hr)	**T0** (ºC)	**T1** (ºC)	**T2** (ºC)	**T3** (ºC)
MS-5	Aluminum	2.54	25	144	143	142	128
MS-6	Aluminum	1.27	25	139	136	141	128
MS-7	Steel	1.27	25	141	138	133	124
MS-8	Steel	0.76	25	133	129	134	123
MS-17	Aluminum	2.54	3.3	127	123	123	144*
MS-18	Aluminum	1.27	3.3	119	117	117	118
MS-19	Steel	1.27	3.3	126	126	125	143*
MS-20	Steel	0.76	3.3	121	123	121	123

* *thermocouple data indicates reaction at or near thermocouple tip for MS-17 and MS-19*

Table 3 details the average surface, propellant interface, and center temperatures for each heating rate tested. The thermal gradient between the grain interface and the center thermocouple averaged 11ºC for the 25ºC/hr tests and only 1ºC for the 3.3ºC/hr tests. Both heating rates resulted in similar center temperatures at the time of reaction; however, the 3.3ºC/hr rate resulted in a near isothermal propellant grain. The 3.3ºC/hr sub-scale cookoff chamber data was compared to Differential Scanning Calorimeter (DSC) data for a propellant sample heated at the same rate. The observed autoignition temperature in the sub-scale chambers is found to be depressed by approximately 10ºC compared to the DSC data.

Table 3. Average Temperature Data

Heating Rate (ºC/hr)	Surface Temp. (ºC)	Interface Temp. (ºC)	Center Temp. (ºC)	DSC Initiation Temp. (ºC)
25	139	137	126	-
3.3	123	122	121*	131

* *MS-17 and MS-19 center thermocouple excluded*

The 3.3ºC/hr tests exhibited significantly more violent reactions than did the 25ºC/hr tests. Figures 2 and 3 show post-test views of sub-scale chambers of identical material and thickness subjected to 25ºC/hr and 3.3ºC/hr, respectively.

Figure 2. Post-test View of MS-7

Figure 3. Post-test view of MS-19

The sub-scale chamber design was modified to incorporate a shape memory alloy (SMA) actuated closure release mechanism. The SMA is configured such that one of the chamber end closures is unlatched by the SMA reaching its activation temperature during the test. Eight additional chambers were tested to verify the effectiveness of this approach. The sub-scale chambers were 2.54 mm thick steel. Table 4 shows the data from these tests performed at 3.3°C/hr. The temperature data correlates well with the 3.3°C/hr data from the previous tests; however, the venting device allowed the closure to release from the chamber to prevent a violent reaction (Figure 4).

Table 4. Thermal Data from Chambers with Installed Venting Device

S/N	T0 (°C)	T1 (°C)	T2 (°C)	T3 (°C)
MS-21	120	121	121	121
MS-22	122	122	123	121
MS-23	128	126	126	137
MS-24	120	124	119	119
MS-25	120	123	124	126
MS-26	126	-	-	-
MS-27	127	123	124	126
MS-28	122	-	119	112
Average	123	123	122	123
STDEV	3	2	3	8

Figure 4. Post-test View of Chamber with Venting Device

The SMA-based SCO venting approach was implemented in a 178 mm (7 in.) diameter composite-cased test motor and subjected to a 3.3°C/hr heating rate. As with the sub-scale chambers, the XLDB propellant containing RS-RDX was utilized. When the oven air temperature reached approximately 130°C, the expanding propellant grain gently pushed the aft closure away from the motor. At some time prior to this event, the passive venting feature had released the nozzle closure from the rocket motor case as intended. About 14 minutes later, the remaining propellant burned. The motor case and nozzle were intact and remained inside the test oven. Pre-test and post-test photos are shown in Figures 5 and 6.

Figure 5. Pre-test Photo of Full-scale SCO Test with Venting Device

Figure 6. Post-test View of Full-scale SCO Test

The SCO testing performed under this study serves to demonstrate that this family of minimum smoke propellants can pass SCO without secondary autoignition devices. The motor geometry chosen was selected to represent the typical size and configuration of tactical ground-launched or aviation-launched propulsion systems.

IMPACT PERFORMANCE EVALUATION

A test series was initiated to benchmark propellant performance against impact threats in a composite case. The test motor configuration was the same as the one used in the full-scale SCO test. Additionally, the least shock-sensitive propellant evaluated (no co-oxidizer) was tested in an aluminum-cased motor to establish comparable data in a metal case. The results are provided in Table 5.

Table 5. Impact Test Results for Second Generation XLDB Propellants

Propellant	XLDB MS Propellant (no co-oxidizer)	XLDB MS Propellant (no co-oxidizer)	XLDB MS Propellant w/ RS-RDX	XLDB MS Propellant w/ CL-20
NOL Card Gap	63	63	70	70
Case	178mm dia. Aluminum	178mm dia. Composite		
Grain type	CP	Boost-Sustain		
Shotline	Center	Center		
BI	No Reaction	No Reaction	No Reaction	--
FI (6000 fps / 1829 m/s)	> 85% of material recovered. Multiple fragments beyond 15 m	--	No Reaction Motor cut in half. All material within 15 m	--
FI (8300 fps / 2530 m/s)	Detonation	No Reaction	--	No Reaction

The propellants tested exhibited no reaction to impact with single 50 caliber bullet impact in either aluminum or composite cases. When subjected to low-velocity fragment impact (1829 m/s), the reaction in the aluminum case still remained benign; however, multiple fragments were thrown to distances up to 33 meters (Figure 7). The aluminum case resulted in a detonation under high-velocity fragment impact (2530 m/s).

Figure 7. Major Case Fragments (with propellant attached) and Recovered Propellant from Aluminum Case Low-velocity Fragment Impact (1829 m/s).

When tested in composite cases, the XLDB propellants demonstrated the ability to achieve no reaction to fragment impact velocities up to 2530 m/s (Figures 8 and 9). Additional testing is planned to explore variables in grain design and their impact on fragment impact performance.

Figure 8. Post-test Photo of 1829 m/s FI Test with Composite Case

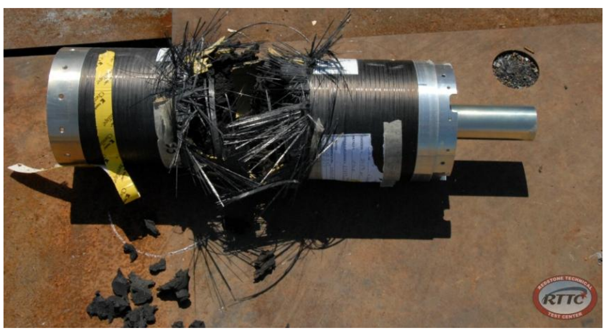

Figure 9. Post-test Photo of 2530 m/s FI Test with Composite Case

The bullet and fragment impact results presented here begin to illustrate the incremental improvements available from composite case construction and less shock-sensitive propellants. It is the hypothesis of the authors that IM compliance for a reasonably energetic propellant under high-velocity fragment conditions is unlikely in a metallic case. Likewise, there is a limit to the secondary benefits of the composite case. The future challenge is to improve ballistic performance and tailorability while maintaining IM characteristics. Composite case technology is readily available and has been shown to improve IM performance for bullet and fragment impact when coupled with a less shock-sensitive propellant.

CONCLUSION

This effort has focused on technology that is reaching the requisite level of maturity for transition to propulsion system development efforts. Demonstration motors utilized flightweight hardware, and testing focused on developing a practical understanding of critical parameters. This effort represents the beginning of a larger effort to demonstrate an IM propulsion system in a relevant environment. There is a desire to improve the performance of less shock-sensitive propellants; however, the propellants investigated in this study represent the best compromise currently available between ballistic performance, IM, and mechanical properties.