SOAR

STATE-OF-THE-ART REPORT (SOAR)
NOVEMBER 2018

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ADVANCEMENTS IN MINIMUM SIGNATURE (MS) PROPELLANTS FOR INSENSITIVE MUNITIONS (IM) ROCKET MOTORS

By Dr. Albert DeFusco and
Dr. Jamie Neidert
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DR. ALBERT DEFUSCO (DSIAC) AND
DR. JAMIE NEIDERT (AMRDEC)

State-of-the-Art Report

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13. ABSTRACT
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ABSTRACT

An extensive summary of contemporary research and development into MS rocket motor propellants is provided, with emphasis on achieving IM compliance. MS propellants have existed since the late 1800s and continue to progressively improve. Developing cast-cure formulations in the 1970s, as opposed to extruded compositions, has opened avenues for developing highly energetic compositions for advanced rockets in use today. However, high energy has led to high sensitivity, especially to shock and impact stimuli. The need for less-sensitive munitions and the advent of IM policies and requirements since the early 1980s have led to a wide range of research and development into reducing the sensitivity of MS rocket propellants. This report covers the development and testing of a variety of MS propellants occurring among many government laboratories and defense contractors over the past 30+ years. It summarizes propellant compositions and properties, while mainly focusing on methods for reducing shock sensitivity and achieving IM characteristics. Information and IM test data on formulations based on energetic binders and oxidizers are discussed, along with compositions that use less-sensitive new materials. Although significant progress has been realized, especially in providing less-sensitive propellants readied for qualification in new propulsion systems, strict compliance to all IM criteria has yet to be achieved. Insensitivity to high-velocity impact tests has been especially difficult to solve and has been achieved with limited compositions. Research continues in modifying existing materials and creating new, less materials, which may aid in progressing toward less sensitive MS propellants for future applications.

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SECTION 01 Introduction

During the late 1800s, the discovery of smokeless powder led to the replacement of sooty and corrosive black powder in military rifles and artillery. Soldiers and commanders quickly realized the advantages of unobstructed, smoke-free battlefields. Today, this advantage remains throughout many military weapons, including guns, artillery, and rockets. Two fundamental smokeless compositions now reside in the U.S. arsenal for rocket motors: (1) extruded propellants used in small-diameter rockets and (2) cast cure compositions used in rockets for tactical missiles. Both types of propellants are based on clean-burning ingredients that do not create primary or secondary smoke in their exhaust.

Since the middle 1900s, extrusion of compositions based on nitrocellulose (NC), and often nitroglycerin (NG), has yielded solid propellants for igniters and main charges in rocket motors. These compositions have been historically categorized as hazards Class 1.3 propellants (HC 1.3C) based on their relative insensitivity to shock stimulus. Compositions developed in the 1940s for the Hydra 70 rocket, for example, were used extensively in the 1960s during the Vietnam War and continue to be used today.

More advanced formulations based on polymeric binders and solid fillers developed in the 1970s provided improvements in manufacturing capability and energy output. These compositions provided cast-cured propellants with nearly unlimited size capability. While maintaining smokeless characteristics (also called minimum signature), these compositions replaced the NC binder with curable polymers and energetic plasticizers (NG and other nitrate esters). Nitramine solid fillers such as RDX and HMX were added to increase energy well beyond levels achievable by unfilled extruded grains. Although benefits in energy output and processing allowed larger, more powerful rocket motors, these filled compositions traditionally suffered from high sensitivity to shock and impact stimuli, as well as loss in burning rate flexibility and tailoring. Although used extensively in current tactical missiles such as HELLFIRE, tube-launched, optically-tracked, wire-guided (TOW)-2, and Javelin, they have found limited use in larger systems for land and air warfare due to their hazards Class 1.1 (HC 1.1) sensitivity. Unfortunately, they have the potential to cause extensive collateral damage when subjected to unplanned stimuli from shock, impact, or heat.

Although not directly attributable to the sensitivity of smokeless or minimum signature propellants, many military accidents have been caused by violent response of munitions to unplanned stimuli or enemy threats over the past half century. Raymond L. Beauregard provided a summary of several of these incidents in "The History of Insensitive Munitions" [1]. Violent response of munitions under exposure to thermal events (e.g., shipboard fuel fires) and other stimuli were cited where extensive collateral damage and loss of many lives occurred. In a single stunning and tragic event in July 1967 aboard the U.S.S. Forrestal flight deck, inadvertent discharge of a 5-inch Zuni rocket caused a dramatic fire and subsequent unplanned ignition of many ammunition rounds. That single event cost the lives of 134 sailors. A series of similar events through the 1970s on Navy ships and land-based storage depots prompted research to reduce the sensitivity of explosives and propellants to various stimuli. Eventual funding by the Navy in the late 1970s for a study on insensitive high explosives gave rise to the present day efforts on insensitive munitions and the series of specifications under MIL-STD-2105D [2].

An incident in May 1981 on the U.S.S. Nimitz further solidified the need for reducing the sensitivity and improving the violent response of munitions to unplanned stimuli. Because several air-launched missiles with warheads and Class 1.3 rocket motors were directly responsible for catastrophic detonations and many lives were lost, the immediate need for insensitive munitions was reinforced. Over the next several years, awareness among the U.S. Department of Defense (DoD) heightened but funding lagged. In 1986, the first policy order was released as OPNAV Instruction 8010.13A "U.S. Navy Policy on Insensitive Munitions" [3]. Subsequently in 1986, NAVSEA issued NAVSEAINST 8010.5A "Technical Requirements for Insensitive Munitions," which outlined the test and pass criteria describing an insensitive munition [4]. Since these beginnings, many DoD laboratories, contractors, and universities focused considerable attention and funding to insensitive munitions and their components, including warheads, fuzes, bombs, guns, and rocket motors. The work resulted in developing less sensitive materials and formulations, mechanical devices to minimize violent response and collateral damage from rocket motors, and sensors to predict the onset of reaction to avoid violent and catastrophe response.

This SOAR addresses advancements made in minimum signature propellants for military applications over the past 30+ years, with focus on cast-cure propellants. Work on extruded compositions will be discussed where necessary, showing that these propellants are reasonably insensitive to shock, impact, and thermal stimuli. Development of less-sensitive cast-cure minimum signature propellants has focused on reducing shock and impact sensitivity through selecting and using less-sensitive ingredients. Advancements in rocket motor hardware and mechanical features have also provided solutions to insensitive munitions and become necessary components for successful development of advanced rocket motors. For example, using a systems approach, composite cases and venting devices have allowed newly developed rocket motors to maintain current performance while performing well in impact and thermal tests.

This report starts with the early development in the 1970s of cast-cure, minimum signature propellants and the work on characterizing their shock sensitivity. Subsequent efforts in the 1980s for reducing shock, impact, and thermal sensitivities, while striving to maintain needed performance levels, follows. Although some advancement was achieved, meeting MIL-STD-2105D [2] specification requirements at high-performance levels has been difficult using existing energetic ingredients and material processing techniques. However, the research and development community within the DoD constantly recognized the need for less-sensitive ingredients that would not sacrifice energy as an important way to achieve their goals.

As work continued beyond the 1980s, new less-sensitive ingredients and formulations became available for study. While test techniques for subscale and full-scale articles matured, a multitude of alternative propellant formulations was developed and tested at various scales. The work sought to identify promising compositions and increase the understanding of ingredient and formulation parameters on sensitivity. Efforts under programs such as the Joint Insensitive Munitions Technology Program (JIMTP) and the Army Rocket Propulsion Technology program continue addressing this difficult task of achieving high performance with insensitivity. Some success has been realized with less-sensitive and lower performance compositions where several promising future rocket motors have been under advanced development and nearing qualification in weapons systems.

The goal of comfortably meeting high-performance levels while achieving complete insensitive munitions characteristics has continued to be elusive for several minimum signature propellants and rocket motors. New ingredients have shown limited success and not yet presented sufficient opportunities for creating entirely new formulations. However, new techniques for processing existing energetic materials (RDX, HMX, and CL-20) have shown promise by allowing particle-size reductions to reach the nanometer scale. This approach has been successful for reducing shock sensitivity of cast cure propellants using micrometer-scale particles and is predicted to improve insensitivity further using nanometer-scale materials. However, insensitivity to high-velocity impact has remained challenging but may be aided by these new particle size reduction techniques. Other recent advances have been addressed and are discussed in terms of prospects for achieving insensitive munitions compliance without sacrificing performance.

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SECTION 02 Response of Munitions to Unplanned Stimuli

Military specification MIL-STD-2105D [2] has specified insensitive munitions as follows:

> *Munitions which reliably fulfill (specified) performance, readiness, and operational requirements on demand but which minimize the probability of inadvertent initiation and severity of subsequent collateral damage to the weapon platforms, logistic systems, and personnel when subjected to unplanned stimuli.*

The specification has addressed a series of stimuli (tests) for which munitions must be subjected to and respond to in order to be classified as an insensitive munition. It has provided a set of requirements that established test conditions and reaction violence to munitions when tested according to its guidelines, as shown in Tables 2-1 and 2-2. Criteria for basic safety tests, additional tests, and tests for hazards classifications have also been addressed in the specification. Tests (stimuli) can be divided into three categories—thermal, impact, and sympathetic. Vulnerability of any munition to each of these stimuli depends on many factors, including the intrinsic sensitivity of the energetic material (e.g., propellant), degree of confinement (e.g., case material), and configuration (e.g., diameter, length, grain geometry, and vent path). As such, designing an insensitive munition can become complex and costly very quickly when these factors are considered.

Threat hazards assessments (THAs) can be developed for specific munitions based on the service environment and hostile threats experienced during the life of a munition or weapon system. A THA can specify acceptable reaction response to these threats for developing insensitive munitions requirements for specific weapons. Each defense service (U.S. Army, Navy, and Air Force), along with other agencies (e.g., Missile Defense Agency), has developed overall Plans of Action and Milestones (POA&Ms) based on weapons systems priority needs for addressing insensitive munitions requirements [5–7]. These documents have assisted in focusing work on developing solutions related to insensitive munitions problems.

Table 2-1 summarizes the three stimuli addressed in MIL-STD-2105D, respective tests, general conditions for each test, and referenced North Atlantic Treaty Organization Standardization Agreement (STANAG) specifications describing the details of each test. Thermal stimuli are represented by fast- and slow-heating tests, commonly referred to as fast cook-off (FCO) and slow cook-off (SCO). Impact tests ranged from low-velocity bullet impact (BI) to direct shaped charge jet (SCJ) impact, which is a very violent stimulus. Fragment impact (FI) can be considered as a test with intermediate violence and is often driven by a weapons THA such that lower velocity tests have been used when appropriate or when attempting to understand a response threshold of a munition. Spall impact was included in this summary. It is not considered a significant threat to minimum signature rocket motors but rather for munitions enclosed in aluminum-armored vehicles (e.g., medium-caliber munitions and small, minimum signature rockets aboard Bradley fighting vehicles).

The reaction types listed in Table 2-2 provide a measure of severity of the response of a munition to the tests in MIL-STD-2105D. Rocket motors using minimum signature propellants have spanned the entire range of responses to all three categories of tests, depending on propellant hazards class and confinement (i.e., case material). To alleviate violent responses to thermal stimuli, much of the work done over the past 30+ years relied on mechanical devices, such as composite cases, as well as active- and passive-case venting solutions. Reducing the shock sensitivity of hazard Class 1.1 minimum signature propellants has improved response to impact and sympathetic stimuli. Most recently, work using insensitive solid oxidizers in cast-cure minimum signature propellants to replace sensitive explosives like RDX has brought the need to expand the list of responses to a reaction type beyond Type V, Burning. Type VI, No Reaction, was the result of a lack of response of some new, reduced sensitivity minimum signature propellants to impact stimuli and is an example of progress recently made in this field.

The Munitions Safety Information Analysis Center has compiled an extensive database on responses of many munitions to the stimuli listed in MIL-STD-2105D [8]. Compiled by Neidert, Table 2-3 shows the response of some minimum signature rocket motors to these stimuli [9]. The data clearly indicated the sensitivity of hazard Class 1.1 propellants compared to less-sensitive classes. Confinement due to case material was a strong factor affecting

Table 2-1. Test Criteria for Insensitive Munitions in MIL-STD-2105D

	Test	Description and Conditions	Reference Specification
THERMAL	Fast Cook-off, Liquid Fuel/External Fire)	Test specimen is surrounded by fuel-rich flames from a large open hearth containing liquid fuel with average flame temperature of at least 800 °C.	STANAG-4240, Including Annex A
	Slow Cook-off (Slow Heating)	Test specimen is exposed to a gradually increasing thermal environment at a change rate of 3.3 °C per hour.	STANAG-4382, Procedure 1 (Standard Test)
IMPACT	Bullet Impact	Test specimen is subjected to impact from a three-round burst of M2, 0.50-caliber, armor-piercing projectiles at a velocity of 850 ± 20 m/s.	STANAG 4241, Procedure 1 (Standard Test)
	Fragment Impact	Test specimen is subjected to impact of a right-circular cylindrical body with a conical nose at a velocity of 2,530 ± 90 m/s (8,300 ± 300 ft/s).	STANAG-4496, Standard Procedure
	SCJ Impact	Test specimen is directly impacted with a shaped charge jet, with jet velocity and diameter (V^2d) guided by the THA.	STANAG-4526, Procedure 2
	Spall Impact[a]	Determines the response of munitions to the impact of hot spall fragments.	Applicability Based on THA
SYMPATHETIC	Sympathetic Reaction (SR)	Test specimen is subjected to the effects of the worst-case credible reaction of an identical donor munition.	STANAG-4396

[a] Not a threat for minimum signature rocket motors.

Table 2-2. Reaction Response Criteria as Described in MIL-STD-2105D

Severity	Reaction Type	Response	Description
MOST SEVERE	I	Detonation	The most violent type of munition reaction where the energetic material is consumed in a supersonic decomposition.
	II	Partial Detonation	The second most violent type of munition reaction where some of the energetic material is consumed in a supersonic decomposition.
	III	Explosion	The third most violent type of munition reaction with subsonic decomposition of energetic material and extensive fragmentation.
	IV	Deflagration	The fourth most violent type of munition reaction with ignition and burning of confined energetic materials, leading to a less-violent pressure release.
	V	Burning	The fifth most violent type of munition reaction where the energetic material ignites and burns nonpropulsively.
LEAST SEVERE	VI	No Reaction	The least violent type of munition response where any reaction is self-extinguished immediately upon removing the external stimulus.

Table 2-3. Reaction Types for Some Minimum Signature Rocket Motors [9]

	Motor	FCO	SCO	BI	FI	SCJ	SR	Approximate Diameter[a]	Case Material
HC 1.1	HELLFIRE M120E5	V	I	V	I	[F]	P	7	Aluminum
	TOW-2B Flight	I	I	I	I	[F]	F	6	Steel
HC 1.2.1E	Javelin-Flight	IV	II	IV	[I]	[F]	P	5	Aluminum
HC 1.3C	TOW 2B Launch	V	I	V	IV	[F]	P	2	Steel
	Hydra 70 Mk 66 Mod 4	IV	III	IV	I	F	F	2.75	Aluminum

[a] OD of motor case.

response of the motor to the stimuli. Propellant grain diameter and configuration also influenced the responses. Furthermore, no minimum signature motor in Table 2-3 passed the SCJ impact test. However, the data indicated that minimum signature motors can respond mildly to the FCO threat.

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SECTION 03

First Development of Cast-Cure MS Propellant

(Effects From Ingredients and Characterization of Shock Sensitivity)

Development work in the 1970s on cast-cure propellants allowed a transition away from extruded and solvent-cast propellants based primarily on NC and NG due to their potential use in more advanced motor designs. Those new designs required higher performance (energy) and volumetric loading, with the latter design feature favoring direct bonding of the propellant to insulation or motor case as opposed to cartridge loading. A new category of urethane-based, cast-cure compositions showed improved structural (viscoelastic, as opposed to thermoplastic) properties and provided high mass fractions and increased energy for new case-bonded motors. The basic constituents for this new category of cast-cure formulations are shown in Table 3-1 (currently the production standard for minimum signature Class 1.1 propellants). High levels of NC used in extruded and solvent-cast propellants were replaced with inert polymers and energetic plasticizers. Very low levels of NC were retained to provide crosslinking of the isocyanate-curable polymer systems (i.e., polyurethanes) and some burning rate effects. These new binders provided viscoelastic properties with sufficient strain capability at low operating temperatures to allow propellants to bond directly to insulators or case materials. These new designs expanded the use of cast-cure propellants in rocket motors with larger diameters and satisfied a need for higher performance. High energy was primarily a result of the solid fillers, consisting of highly energetic nitramine (e.g., RDX and HMX). Other minor ingredients retained from extruded and solvent-cast propellants performed well in these new compositions for tailoring burning rate and eliminating acoustic instability. However, early work in this field also revealed the inherent sensitivity of these propellants, particularly to shock and impact stimuli.

Under contract with the Air Force in the mid-1970s, Herriott and Foster performed extensive parametric studies to evaluate the effects of formulation variables on the ballistic, mechanical, and thermal stability properties of these new formulations [10]. Properties useful for case-bonded rocket motors performing at operational temperatures from -65 °F to 165 °F, along with acceptable service life, were demonstrated. This technology base for these new propellants was expanded by Herriott to include a parametric study to characterize shock sensitivity by way of card gap, No. 8 cap, and critical diameter testing [11]. (Note: See the Appendix for a description of the card gap test method used in the studies described throughout this report.) An Mk 36 Sidewinder rocket motor with a selected propellant from this study **using HMX exclusively** as the energetic solid and having a volumetric impulse of 14.9 lb_f-s/in^3 was exposed to impact by a 23-mm high-energy-incendiary (HEI) round. **The motor detonated.**

The results documented in these reports have relevance today and have guided more contemporary work in this field. A useful chart extracted from this work, shown in Figure 3-1, describes the relationship between nitramine content and binder energy (heat of explosion, H_{ex}) to shock sensitivity of the propellants. Interestingly, the data could also be described in terms of propellant impulse,

Table 3-1. Effect of Constituents on Cast-Cure Class

Constituent	Example	Effect on Sensitivity	Mitigation Approach
Solid Filler – Nitramine	RDX HMX CL-20	Primary contributor to shock, impact, and sympathetic reactions Considered stable under thermal exposure	Less-sensitive energetic fillers None needed
Binder Plasticizer – Nitrate Ester	NG BTTN TMETN	Contributor to shock, impact, and sympathetic reactions Assists with mild-to-moderate reactions to thermal exposure	Less-sensitive nitrate esters with lower heat of explosion (H_{ex}) Potentially, less-sensitive nitrate esters with lower H_{ex}
Binder – Energetic Polymer	NC (<1%)	Not considered a significant contributor to sensitivity due to low concentration	None needed
Binder – Inert Polymer	PGA PCP PEG Isocyanate	Does not contribute to sensitivity; aids in desensitization during manufacture	None needed
Additive – Acoustic Stabilizer	ZrC Aluminum Oxide	Contributor to shock and impact and potentially sympathetic reactions Contribution to reaction under thermal exposure not known	Less-dense additives Potentially, none needed
Additive – Ballistic Modifier	Lead Citrate Lead Oxide Tin Oxide Carbon Black	Secondary contributor to shock, impact, and potentially sympathetic reactions	Potentially, binder-soluble materials

although values were not reported. Higher propellant impulse coinciding with higher levels of HMX correlated with higher sensitivity. Interestingly, early work in the late 1960s by Elwell under Project SOPHY showed that HMX sensitizes even hazard Class 1.3 nondetonable (0 cards) ammonium perchlorate (AP) composite propellants such that critical diameters starting at about 60 in were quickly reduced to a few inches, with small amounts of HMX (<10%) [12]. (Note: The historic demarcation between hazard Class 1.1 and 1.3 is 0.7-inch standoff, 70-card standoff, or ~70-kBar pressure for this test, with values above this division designated as hazard Class 1.1 and those below Class 1.3, as described in the Appendix.)

The following excerpt has been extracted from Herriott's report [11] and includes a collection of general findings related to ingredient effects on shock sensitivity of minimum signature propellants, which continue to be relevant today.

> *The effects of the various formulation parameters on the shock sensitivity of minimum smoke propellants were as follows:*
>
> 1. *HMX strongly increased the sensitivity, even at HMX levels as low as 5%.*
> 2. *Certain commonly used ballistic and acoustic additives strongly sensitize the propellants when HMX is not present. The effects are less pronounced in the presence of HMX.*

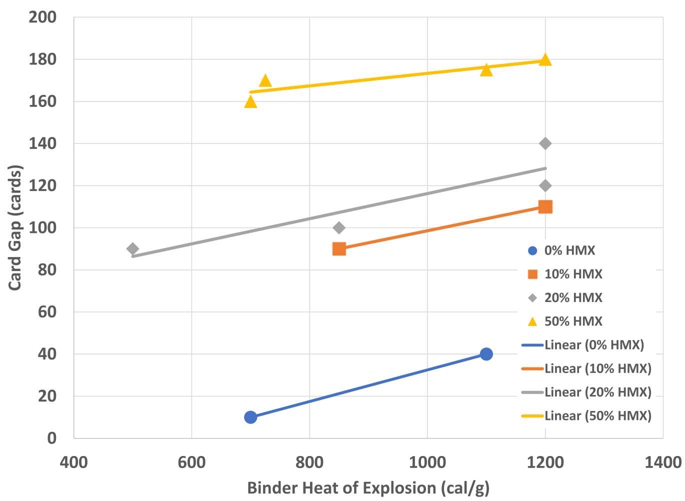

Figure 3-1. Relationship of Nitramine Content and Binder Energy to Propellant Shock Sensitivity [11].

3. *Although binder energy tends to increase the sensitivity, the tradeoff between binder energy and HMX level at a given performance level favors a high binder energy and low HMX content.*
4. *At a given binder energy, the plasticizer type, viz., NG, TMETN, FEFO, and BDNPA/F, has no effect on the sensitivity.*

The work ultimately demonstrated that a less-sensitive, nondetonable propellant tested against a 23-mm HEI round can be obtained using an HMX (4 µm), ammonium nitrate (AN), and AP tri-oxidizer blend. This alternative propellant was reported to maintain minimum signature characteristics and met the volumetric impulse goal of 14.9 lb_f-s/in^3. Critical diameter and No. 8 cap tests correlated well with the HEI tests of Mk 36 Sidewinder motors. **An Mk 36 motor did not detonate under impact with an HEI round using this alternative propellant with an HMX, AN, and AP solids blend.**

More recent work by Eisentrout et al. has shown that a high-energy hazard Class 1.1 propellant used in the TOW-2 missile rocket motor, GCV, can be desensitized slightly by using alternative RDX materials [13]. Reduced-sensitivity RDX (RS-RDX) offered by Chemring Nobel [14], and I-RDX offered by Eurenco [15] were evaluated. Simply replacing all standard RDX (~62%) in GCV propellant with equivalent, less sensitive RDX materials (equal concentration and particle size) provided reduced shock and impact sensitivity, as shown in Table 3-2. Compared to an explosion with standard RDX, shock sensitivity was reduced by about 20–30 cards, while BI sensitivity was reduced to a mild burn reaction. Rocket motors remained sensitive to FI regardless of RDX material, while FCO was also unchanged. The work clearly showed how partial insensitive munition (IM) solutions can be gained by energetic materials choice. A review of less-sensitive RDX materials has been reported [16].

Table 3-2. Effect of Less-Sensitive RDX Materials on GCV Propellant Sensitivity in a TOW-2 Steel Case[a] [12]

Test/Test Item	Standard RDX	RS-RDX	I-RDX
Shock/Card Gap Tube	161–175 Cards	138 Cards	142–144 Cards
BI/Rocket Motor	Explosion (Type III)	Burn (Type V)	Burn (Type V)
FI/Rocket Motor (~4,000 ft/s)	Not Tested	Deflagration (Type IV)	Deflagration (Type IV)
FI/Rocket Motor (~5,000 ft/s)	Not Tested	Not Tested	Detonation (Type I)
FI/Rocket Motor (~6,000 ft/s)	Detonation (Type I)	Detonation (Type I)	Detonation (Type I)
FCO/Rocket Motor	Explosion (Type III)	Explosion (Type III)	Not Tested

[a] A 5-inch outside diameter (OD), current production propellant grain geometry.

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SECTION 04

Approaches for Reducing the Sensitivity of MS Propellants and Achieving IM Rocket Motors

Approaches for achieving IM, in general, have involved reducing the sensitivity of the energetic material coupled with alterations to rocket motor hardware. Commonly referred to as a "systems approach," combining chemical and mechanical changes to a minimum signature rocket motor has been considered the most effective method for solving IM problems. Replacing or supplementing sensitive energetic materials like RDX and HMX in hazards Class 1.1 propellants with less-sensitive materials has been evaluated for the past 30 years and continues today. Using epoxy/fiber composite and steel strip laminate rocket motor cases has provided several advantages that could not be realized through propellant approaches alone. Composite cases have allowed higher operating pressure to enhance lost energy with less-sensitive propellants and provided mechanical venting (softening) under thermal loads, leading to pressure relief and mild responses to IM stimuli. Other proven, successful methods for pressure relief are venting devices and low-temperature thermal initiators, which have also assisted in reducing reaction violence to thermal stimuli. Table 4-1 provides a general gauge of effectiveness for these approaches for each IM stimulus, with the most effective solution encompassing all features in a single rocket motor. Protective devices, such as armor and transportation containers, have provided additional layers of protection for impact stimuli, especially SCJ impact, which has yet to be resolved at the rocket-motor level. However, additional layers of protection can lead to undesirable results under thermal exposure due to added confinement and expulsion of debris.

The following discussions primarily focus on propellant solutions but will include information on each of these approaches and combinations where appropriate. Due to the level of activity (support funding) within the DoD and contractor communities, the work described has been divided into two categories—from the 1980s through the 1990s representing early work and after 2000 for more recent accomplishments. Although progress has been made, limitations in energetic ingredient

Table 4-1. Efficacy for Some Mitigation Approaches

IM Stimulus	Reduced Sensitivity Propellant	Composite Case	Forward/Aft Venting Device	Low-Temperature Thermal Initiator
BI	Effective	Effective	Not Effective	Not Effective
FI	Partially Effective	Partially Effective	Not Effective	Not Effective
SCJ	Not Effective	Not Effective	Not Effective	Not Effective
FCO	Partially Effective	Effective	Partially Effective	Partially Effective
SCO	Partially Effective	Partially Effective	Effective	Effective
SD	Effective	Effective	Not Effective	Not Effective

technology have hampered achieving the goal of complete IM without performance degradation. Composite cases and venting devices have become essential features (tools) for achieving minimum signature rocket motors with IM characteristics.

4.1 EARLY WORK (1980s – 1990s)

Much of the work during the 1980s through the 1990s focused on developing less-sensitive minimum signature propellants based on using AN and phase-stabilized AN (PSAN) to replace sensitive nitramines. Various binders based primarily on laboratory preference and previous successes were evaluated. At the time, the Air Force was especially interested in the energetic polymer, glycidyl azide polymer (GAP), due to projected performance enhancement and potential for reducing the shock sensitivity of minimum signature propellants. Other agencies, including the Navy and Army, showed interest in AN for similar reasons and funded considerable efforts towards developing propellants and rocket motors based on these formulations using nitrate-ester-based binders.

4.1.1 GAP/PSAN Propellants

Under funding by the Air Force, Comfort et al. explored the use of PSAN in GAP-based and inert polyester (polyglycol adipate, PGA) binders [17]. As with the fundamental work by Herriott [10, 11] Comfort's work generated a considerable amount of data correlating propellant performance (impulse, I_{sp}) to shock sensitivity (card gap). Both studies formed the basis for further, and more recent, work that proved successful in creating minimum signature propellants and rocket motors showing significant advancements in IM characteristics. Some of Comfort's work is reproduced here to show progress made by using insensitive PSAN oxidizer and low concentrations of RDX with fine particle size. Overall, the work developed propellants with hazards Class 1.3 sensitivity (<70 cards) and I_{sp} values around 240 lb_f-s/lb_m, which were significant achievements.

Theoretical impulse calculations showed an advantage in propellant impulse when GAP was used as the polymer binder, as shown in Figure 4-1. Considerable effort was made to assess processability, mechanical properties, burning rate, and aging characteristics of GAP- and PGA-based propellants; however, it is not summarized here. More importantly, extensive studies on formulation variables and card gap sensitivity were documented. Figure 4-2 shows early test data generated under this project where propellant impulse clearly correlated with card gap sensitivity. Figure 4-2 includes values for two hazard Class 1.1 propellants used in TOW-2 and Chaparral M121 rocket motors. Achieving a propellant impulse of 240 lb_f-s/lb_m with a card

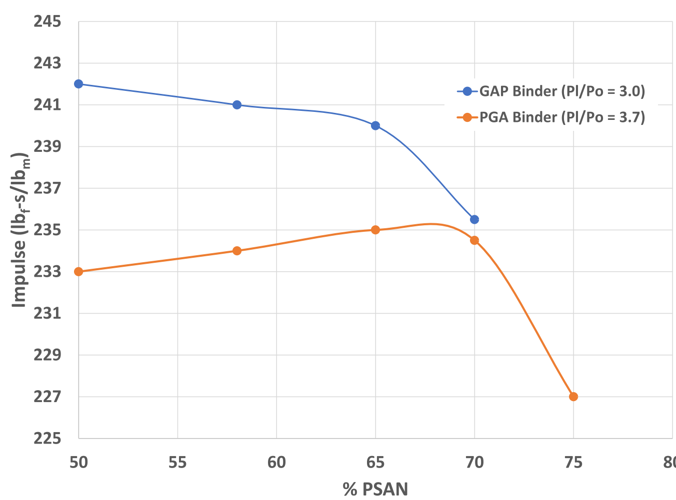

Figure 4-1. Impulse Advantage of GAP Over PGA Polymer (Binders Also Used 70/30 NG/BTTN Nitrate Ester Plasticizer Blend) [16].

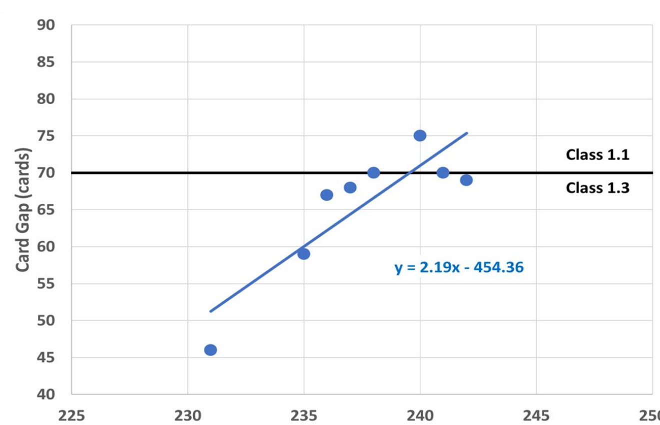

Figure 4-2. Correlation of Propellant Impulse to Card Gap Sensitivity (PSAN-Only Oxidizer) [17].

gap value of ≤70 cards was challenging. The work showed that this correlation was valid regardless of polymer type, plasticizer type, and plasticizer concentration when PSAN was used as the solid filler. The work also revealed that zirconium carbide (ZrC), used as an acoustic stabilizer, sensitizes these propellants by as much as 25 cards. Less-dense stabilizers like aluminum oxide and aluminum were preferred in this study. The study culminated in generating GAP and PGA-based propellant formulations that met all goals using PSAN as the primary oxidizer, along with 15%–20% of RDX, with a particle size of 1.4 µm, as shown in Table 4-2. Adding fine RDX was essential to achieving all propellant goals. It demonstrated that a nitramine with a small particle size (<2 µm) did not significantly sensitize these minimum signature propellants and formed the basis for continued work in this area.

Booth also pursued GAP/PSAN propellants, with the same goal of providing high energy and Class 1.3 sensitivity [18], where that work primarily focused on KNO_3-stabilized AN and BTTN/TMETN co-plasticizers. The work also involved using AP (~7% by weight) as a co-oxidizer to improve performance while attempting to maintain minimum signature characteristics. Interestingly, the study evolved to address mechanical properties via the use of amine-containing bonding agents and burning rate modifications based on lead-copper salt modifiers rather than understanding the shock sensitivity of candidate formulations. Table 4-3 provides a summary of early candidate propellants tested for go/no-go response at 64 cards. Some initial conclusions from this work indicated that high plasticizer content should be avoided to maintain Class 1.3 sensitivity, higher I_{sp} led to higher sensitivity, and higher PSAN content may be preferred to provide a good balance between sensitivity and energy.

Although not addressed here, the project was refocused to involve a significant amount of effort on tailoring selected propellants for processing mechanical properties and burning rates to pro-

Table 4-2. Final Propellant Minimum Signature Formulations Demonstrating Class 1.3 Sensitivity [17]

Ingredient/Property	GAP-1	GAP-2	PGA-1	PGA-2
PSAN (%)	48.5	43.5	48.5	43.5
RDX, 1.4 µm (%)	15.0	20.0	15.0	20.0
Copper Chromite (%)	1.0	1.0	1.0	1.0
Aluminum (%)	0.5	0.5	0.5	0.5
Binder H_{ex} (cal/g)	665	665	897	897
I_{sp} (lb_f-s/lb_m)	239.6	241.7	239.2	240.2
Card Gap (Cards)	65	65	60	60

Table 4-3. Early Candidate GAP/PSAN Propellants Without AP [18]

Ingredient/Property	1	2	3	4	5	6	7
GAP (%)	35	22.5	10	10	10	22.5	16.6
BTTN/TMETN (%)	30	42.5	55	42.5	30	30	41.7
PSAN (%)	35	35	35	47.5	60	47.5	41.7
Plasticizer/Polymer Ratio	0.9	1.9	5.5	4.2	3.0	1.3	2.5
I_{sp} (lb_f-s/lb_m)	214.5	213.0	246.1	243.7	241.2	228.7	237.3
Volumetric I_{sp} (lb_f-s/in^3)	11.3	12.5	13.1	13.7	13.8	12.5	13.1
Card Gap Test @ 64 Cards	Negative	Negative	Positive	Positive	Negative	Negative	Negative

vide a composition suitable for a motor demonstration. Metal salt ballistic modifiers, NC in the binder, amine containing bonding agents, inert co-polymers, and alternative PSAN oxidizers were evaluated in formulations while optimizing for all properties, including performance. Unfortunately, no additional data was provided on shock sensitivity of these propellants or the final formulation designed for an eventual motor demonstration, as shown in Table 4-4.

Earlier work by Jones demonstrated the use of extruded minimum-smoke propellant granules (i.e., CP) and tri-ammonium guanidine nitrate (TAGN) for increasing the burning rate of minimum signature propellants [19]. Along with using AN oxidizer, Naylor et al. took advantage of the accomplishment with CP and applied it to the development of a reduced-sensitivity minimum signature propellant for an IM HELLFIRE rocket motor application [20]. Continued work by DeFusco et al.

Table 4-4. Candidate GAP/PSAN Propellant for Motor Demonstration [18]

Ingredient/Property	Demonstration Propellant
GAP/NC/Curative/Stabilizer (%)	11
BTTN/TMETN (3/1, %)	25
PSAN (%)	64
LC-11 Ballistic Modifier (Added, %)	4
Carbon Black (Added, %)	0.5
Volumetric I_{sp} (lb_f-s/in^3)	14.06
Card Gap (Cards)	Not Reported[a]

[a] Assumed to be negative at 64 cards, based on previous data.

4.1.2 Casting Powder (CP)/AN Propellants

After this work, the Army showed interest in conducting a project for developing an IM rocket motor for the HELLFIRE missile. The project presented significant challenges to motor designers by requiring no performance degradation and no change to the motor envelope and missile interfaces. The work also focused on modifying production hazard Class 1.1 HELLFIRE propellant, designated GEU, while replacing RDX with AN oxidizer to promote insensitivity (goal of hazard Class 1.3). Propellant development work with ballistic modifiers was critical to meeting burning rate requirements for the motor and was another challenging aspect of the project. To meet performance and IM goals using a less-sensitive, reduced-energy propellant (I_{sp} ~235 lb_f-s/lb_m), the project also focused on developing a graphite composite case that could operate at high pressure and incorporate a passive venting device. These design features were used to address impact and thermal stimuli for IM tests.

realized the goal of obtaining a Class 1.3 minimum signature propellant with sufficient impulse and IM characteristics for a new IM HELLFIRE rocket motor [21]. Incorporating a composite case allowed this new motor to pass many IM tests in simulator motors [22]. Summaries of important findings from these works are provided next. Among them, nickel oxide (NiO) PSAN was revealed to interfere with polyurethane binder cure chemistry and was eventually abandoned due to propellant off-gassing during processing. The researchers favored using anhydrous AN and found that this material was less sensitive than NiO-PSAN, remained phase stabilized, and did not lead to propellant volume growth under thermal cycling conditions through the HELLFIRE motor operating temperatures of -45 °F to 145 °F.

Compared to a variety of other modifiers evaluated, CP proved to be an effective ballistic modifier for reduced sensitivity minimum signature propellants, as shown in Figure 4-3 and Table 4-5.

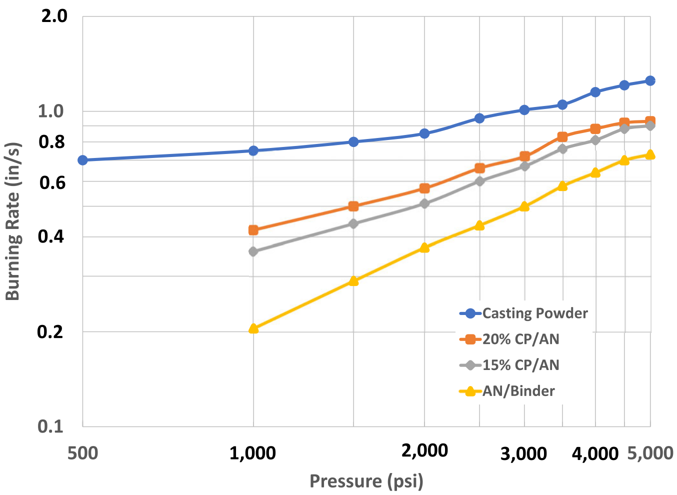

Figure 4-3. Burning Rates for CP and AN Propellants [20].

Burning rates for the CP/AN propellants were satisfactory for operating an IM HELLFIRE motor and provided sufficient aging (service life) characteristics.

AN proved to be less sensitive to SCJ impact compared to NiO-PSAN, as shown in Table 4-6, when tested in motor simulators using graphite epoxy composite cases and varying propellant web thicknesses. The data indicated critical diameter differences between the two oxidizers, which was supported by additional testing shown in Figure 4-4, making AN less sensitive to shock initiation than NiO-PSAN.

This work led to the development of two CP/AN Class 1.3 minimum signature propellants, shown in Table 4-7, that were tested for shock sensitivity and IM characteristics in 7-inch OD composite cases analogous to the HELLFIRE motor envelope. Card gap values for these new CP/AN propellants were in the range of 58–60 cards and had I_{sp} values of ~235 lb_f-s/lb_m. These data were consistent with the I_{sp}-card gap trend established by Comfort et al. [17] (see Figure 4-2). Although subscale SCO tests were performed on other smaller simulators with these new CP/AN propellants and gave mild burn reactions with venting devices, no venting devices were used in these larger 7-inch OD case simula-

Table 4-6. SCJ Impact Results for Unmodified Propellants in 5-inch OD Composite Cases [21]

Propellant Web Thickness	NiO-PSAN Oxidizer	AN Oxidizer
One Inch	No Detonation	No Detonation
Two Inches	Detonation	No Detonation

Table 4-5. Modifiers and Burning Rates for NiO-PSAN and AN Propellants [20]

Modifier	Modifier (%)	Oxidizer	Burning Rate (in/s) at 1,000 psi
None	—	NiO-PSAN	0.21
$Cr_2Cu_2O_4$ [a]	1	NiO-PSAN	0.36
$(NH_4)_2Cr_2O_7$ [a]	4	NiO-PSAN	0.68
$BaCr_2O_7$	3	NiO-PSAN	0.25
CuPhth[a,b]	4	NiO-PSAN	0.40
CP	15	NiO-PSAN	0.46
None	—	AN	0.17
$(NH_4)_2Cr_2O_7$ [a]	4	AN	0.59
$BaCr_2O_7$	3	AN	0.22
$PbCr_2O_7$	3	AN	0.25
CuPhth[a,b]	4	AN	0.19
CP	10	AN	0.36
CP	15	AN	0.41
CP	20	AN	0.46

[a] Failed thermal aging criteria.

[b] Copper phthalocyanine.

tors. The 7-inch OD simulator motors used 22 lbs of propellant, with 2.3-inch web thicknesses (0.65 web fraction). Ported cylinder grain configurations were used. An aluminum simulator case was used for the tests on the Class 1.1 propellant.

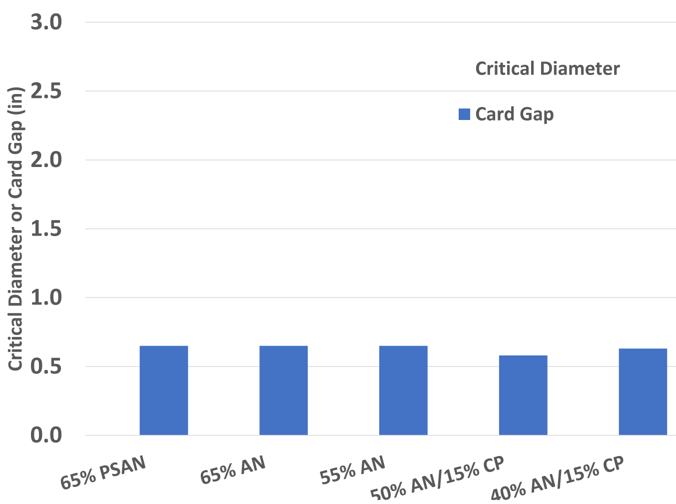

Figure 4-4. Shock Sensitivity of NiO-PSAN and AN Propellants [21].

4.1.3 IMAD Propellants

Under Navy funding, Chan et al. evaluated four different PSAN materials created specifically for this work [23], again with the goal of providing a Class 1.3 minimum signature propellant for IM motor application. The materials included 3% CuO-PSAN, 3% ZnO-PSAN, 3% $ZnSO_4$-PSAN, and AN/TAGN co melted crystals, which were tested for phase stabilization and effects from moisture. Propellants using 70% loading of these materials were prepared and evaluated for processability using GAP and polycaprolactone (PCP) binders. All propellants processed easily with bimodal PSAN particle sizes of 160 and 55 µm. Propellant samples were subjected to thermal cycling and showed no weight loss or dimensional changes, indicating phase stability. The AN/TAGN composition had the highest burning rate at 0.5 in/s at 1,000 psi, while others ranged from 0.1 to 0.2 in/s, typical of AN propellant. PSAN materials were later abandoned

Table 4-7. CP/AN Propellants Shock Sensitivity and Simulator Motor Tests [22]

Ingredient/Property	Class 1.1 Propellant	Class 1.3 CP/AN Propellants	
		GGS-1	GGY-1
Casting Powder (%) AN (%) Energetic Binder (%) Additives (%) Total Solids (%)	FORMULATION CLASSIFIED	15.0 40.4 44.0 0.6 56.0	20.0 36.4 43.0 0.6 57.0
Card Gap (Cards) Critical Diameter (in) Detonation Velocity (mm/µs)	145 <0.5 >8,000	60 ~1.0 ~4,500	58 ~1.0 ~6,000
IM Tests			
Case Material (7-inch OD)	Aluminum	Graphite Composite	Graphite Composite
BI	Detonation	No Reaction	No Reaction
FI	Detonation	Case Rupture, Extinguished	Case Rupture, Extinguished
FCO	Burn	Burn	Burn
SCO	Detonation	Mild Burn[a]	Case Rupture, Closure Ejection[b]
SD (3.75-inch Standoff)	—	No Detonation[c]	—

[a] Temperature at onset of cookoff = 230 °F.
[b] Temperature at onset of cookoff = 233 °F.
[c] Recovered propellant = 0.5 lbs.

by several researchers in favor of anhydrous AN due to toxicity and the absence of complete phase stabilization.

This initial work led to additional studies under the Navy's Insensitive Munitions Advanced Development (IMAD) program on minimum signature propellants using anhydrous AN oxidizer combinations with RDX and HMX. Development work led to IMAD-301 propellant and its variations [24, 25]. Nitramines with fine particle sizes (1.4 µm) were used, along with nitrate ester-based binders. Although specific formulations were not identified, the compositions contained <60% total solids and GAP energetic polymer with high levels of nitrate ester plasticizers BTTN and TMETN. Data on processing, aging, and mechanical properties were provided but are not addressed here. However, low-temperature strain capability for a typical IMAD-301 propellant tested at –65 °F, and a high-speed rate of 20.0 in/min was 8%. This result is typical for minimum signature propellants showing brittle behavior at low temperatures and limits their operational capability for some tactical rocket motor applications. More importantly, shock sensitivity data was provided for two variations, as shown in Table 4-8, which proved to be hazard Class 1.3. No information on propellant impulse was provided for any variation of IMAD 301.

Another variation of IMAD-301 (formulation not reported) was subjected to the Burn-to-Violent-Reaction (BVR) test, as shown in Table 4-9. The test consisted of firing steel spheres onto separated propellant slabs at various gaps to simulate impact tests on rocket motors with various bore diameters. Propellant reactions to this test were reported as mild burning for all air gaps, and the damaged propellant extinguished after impact. The absence of detonations or explosions is noteworthy.

Table 4-8. Shock Sensitivity of IMAD-301 Propellants [24]

Property	IMAD-301 With RDX and Lead Carbonate	IMAD-301 With RDX and No Lead Carbonate	TPQ-7030[a]
Card Gap (Cards)	80	58	145
Critical Diameter (in)	~0.5	~0.5	—

[a] Early HELLFIRE propellant developed and produced by Thiokol Corporation.

Table 4-9. IMAD-301 BVR Test Results [24]

Air Gap (in)	Reaction
0.5	Transient Burn
1.0	Transient Burn
2.0	Transient Burn
3.0	Transient Burn

Subscale slow cookoff bomb (SCB) tests were performed on two IMAD-301 propellant variations, as shown in Table 4-10. The heating rate was reported as 6 °F/hr and gave burning reactions for both propellants. As expected, similar cookoff times and temperature onsets were observed, indicating no difference from nitramine type.

In attempts to increase the burning rate and energy of these Navy IMAD propellants, Chan and Turner evaluated compositions using combinations of AN with CL-20 and TAGN, as shown in Table 4-11 [26]. Again, anhydrous AN was selected as the primary oxidizer, along with the elimination of lead salt ballistic modifiers. Some findings included the following: (1) CL-20 particle size significantly affected pressure-rate exponent where 3 µm gave

Table 4-10. Subscale SCO Test Results for IMD-301 Propellants [25]

Propellant	Time to Cookoff (hr)	Temperature at Cookoff (°F)	Reaction
IMAD-301 With RDX	33	277	Burn
IMAD-301 With HMX	33	270	Burn

Table 4-11. AN/Co-oxidizer Propellant Variables From Navy I MAD Program [26]

Ingredient	Weight % Range
GAP/PCP	5.5–6.5
Nitrate Ester Plasticizer	18–25
AN	35–45
CL-20 or TAGN	22–35
Curative and Other Additives	2

0.65-inch IMAD-303 propellant and 140 µm gave 0.94-inch IMAD-303 propellant, and (2) TAGN particle size affected burning rate but not pressure-rate exponent in IMAD-301-T propellant where 3.8 µm gave 0.45 in/s and 90 µm gave 0.32 in/s.

Shock sensitivity test results for chosen IMAD propellants are shown in Table 4-12. As with previous GAP/AN propellants tested, these compositions proved to be hazard Class 1.3. Quoted impulse values ranged from 238 to 247 lb_f-s/lb_m for these types of formulations.

Chan et al. also evaluated propellants containing only low levels of CL-20 [27]. The propellants, IMAD-303 and variations, used GAP polymer with BTTN and TMETN plasticizers. One variation used PCP polymer to enhance mechanical properties. Table 4-13 provides impulse and shock sensitivity data for these compositions. IMAD-303 and IMAD-303-I were only tested for go, no-go reactions at 70 cards by single tests, whereas IMAD-303-II used a full test series to provide the 50% point data shown. An SCB test was performed on IMAD-303-II and potentially gave an explosion reaction based on observed damage to the test vessel and witness plates. A heating rate of 6 °F/hr was used where the time to reaction was 13.8 hr, with an onset of reaction temperature of 268 °F. Selected IMAD-303 propellants (formulations not identified) showed good processability and mechanical properties, giving 60% strain capability at –45 °F under a slow-speed test rate of 2 in/min.

Table 4-12. Shock Sensitivity of IMAD Propellants With AN and Co-oxidizers [24, 26]

Propellant	Card Gap (Cards)
IMAD-303 (GAP/AN/CL-20)	58
IMAD-303 (PCP/AN/CL-20)	60
IMAD-301-T (GAP/AN/TAGN)	60
TPQ-7030[a]	141–173

[a] Early HELLFIRE propellant developed and produced by Thiokol Corporation.

4.1.4 Rugged Nondetonable Propellants

The U.S. Army Missile Command (MICOM) announced a campaign in the mid-1980s to develop "Rugged Non-Detonable (RND)" (0-card) minimum signature propellants, first starting with lower energy formulations with I_{sp} ~230 lb_f-s/lb_m and then attempting to develop higher energy compositions with I_{sp} approaching 250 lb_f-s/lb_m [28]. Melvin and Warren evaluated the effect of AN concentration on shock sensitivity by screening the five propellants shown in Table 4-14 at the 0-card level in the standard card gap test [29]. Interestingly, the lowest energy propellant (1) gave a positive test (detonation), whereas the higher energy compositions using higher levels of AN proved to be nondetonable at 0 cards. They developed a nondetonable formulation, shown in Table 4-15, having an I_{sp} of 237 lb_f-s/lb_m by using boron and aluminum

Table 4-13. IMAD-303 Propellant Shock Sensitivity [27]

Ingredient/Property	IMAD-303	IMAD-303-I	IMAD-303-II
Binder Ingredients	GAP/BTTN/TMETN	GAP/BTTN/TMETN	GAP/PCP/BTTN/TMETN
CL-20 (%)	20	28	35
I_{sp} (lb_f-s/lb_m)	247.0	243.7	244.0
Card Gap (Cards)	<70	<70	60
SCB Test	—	—	Explosion

Table 4-14. Propellants Screened at 0 Cards Based on AN Concentration [29]

Ingredient/Property	1	2	3	4	5
Polymer Type	PGA	PGA	PGA	PGA	PGA
Plasticizer Type	TMETN/ TEGDN	TMETN/ TEGDN	TMETN/ TEGDN	TMETN/ TEGDN	TMETN/ TEGDN
Plasticizer %	23.4	22.0	21.1	19.9	18.3
Plasticizer/Polymer Ratio	3.0	3.0	3.4	3.6	3.6
Total Solids	68	70	72	74	76
I_{sp} (lb_f-s/lb_m)	225.6	227.3	228.9	229.3	230.1
0-Card Test	Positive	Negative	Negative	Negative	Negative

Table 4-15. Nondetonable Higher Energy Formulation [29]

Ingredient/Property	Baseline Formulation
Polymer Type	PGA
Plasticizer Type	TMETN/TEGDN
Plasticizer %	17.5
Plasticizer/Polymer Ratio	3.0
AN %	73.0
Boron %	2.0
Aluminum %	1.0
I_{sp} (lb_f-s/lb_m)	237.0
0-Card Test	Negative

fuels. However, minimum signature characteristics were degraded. Work was also performed on GAP and other energetic polymers in these types of formulations; however, nondetonability was sacrificed. IM tests were conducted on a selected rugged nondetonable propellant with I_{sp} = 228 lb_f-s/lb_m, as shown in Table 4-16, compared to a hazards Class 1.1 propellant. These tests used 3-lb propellant grains cast into composite tubes 5.0 inches in diameter and 4.0 inches long, with a web thickness of 1.6 inches.

Warren pursued work under Army funding on potentially nondetonable higher energy formulations using AN oxidizer with CL-20 (2-µm particle size) and silicone to promote energy [30]. A baseline formulation, shown in Table 4-17, employing the energetic polymer ORP-2 (nitramine-containing polyester) synthesized by Olin and bis(fluoro dini-

Table 4-16. IM Test Results on Nondetonable and Class 1.1 Propellant Samples [29]

Propellant Type	BI	FI	SCJ	FCO
Rugged Nondetonable	Pass	Pass	Pass	Pass
Class 1.1	Pass	Fail	Fail	Pass

troethyl) formal (FEFO) plasticizer was the starting point. As expected, CL-20 enhanced energy, while silicone degraded minimum signature characteristics. Nondetonability (0 cards) was not achieved. Silicone, like CL-20, promoted sensitivity in these AN-based propellants.

4.1.5 Alternative Co-Oxidizers

The use of novel energetic organic compounds beyond nitramines in minimum signature propellants has presented interesting possibilities for increased energy and possibly reduced sensitivity. Several known compounds from explosives research were investigated on a theoretical basis [31]. One compound, 7 amino-4,6-dinitrobenzofuroxan (ADNBF), was chosen for synthesis in large quantities and assessed in propellant. Although small-scale shock sensitivity testing showed that ADNBF was at least as sensitive as HMX in an inert binder, formulation work was pursued with energetic binders using GAP and nitrate ester plasticizers. However, no propellant shock sensitivity data on those GAP propellants was reported in that study. Subsequently, using an alternative difurazan compound, di-(4-nitrofurazan, 3-oxalamide), DNFOA, was applied to

Table 4-17. Baseline Propellant and Modifications With CL-20 and Silicone [30]

Ingredient	Baseline	Modification 1	Modification 2	Modification 3
ORP-2	10.0	10.0	10.0	10.0
FEFO	29.0	29.0	29.0	29.0
AN	58.0	48.0	41.5	55.0
Additives	1.0	1.0	1.0	1.0
Curative	2.0	2.0	2.0	2.0
CL-20	—	10.0	15.0	—
Silicone	—	—	1.5	3.0
I_{sp} (lb_f-s/lb_m)	238	242	247	241
Card Gap				
36 Cards	Positive	—	—	—
40 Cards	Negative	—	—	—
50 Cards	—	Positive	—	Positive
69 Cards	—	Negative	Positive	Negative
80 Cards	—	—	Negative	—

an AN-containing Class 1.3 minimum signature propellant. However, at only a 5% by weight concentration, the compound increased shock sensitivity of the propellant to 96 cards from the baseline 63 cards [32]. Although work was performed on reducing the particle size of DNFOA, needle-like crystals persisted and were partially attributed to its sensitivity. Similar findings were revealed using other furoxan and furazan compounds, as well as other novel energetic structures [33–39]. The data suggested that even at low levels, these chemical structures sensitized Class 1.3 propellants. A partial list of evaluated compounds is shown in Table 4-18, where subscale shock, and sometimes cookoff, sensitivity was evaluated. Although some of these new materials with low hydrogen content displayed favorable energy and low impact sensitivity, the correlation between minimum signature propellant energy and shock sensitivity remained unchanged, regardless of chemical structure of the new material.

4.1.6 Unfilled Castable Propellants

An alternative approach by Martins to reduced sensitivity of minimum signature propellants was attempted by removing all solid filler and developing castable compositions based on pelletized (aka plastisol) NC (PNC) and nitrate ester plasticizers [40, 41]. This approach had merit since ballistic tailoring allowed application in a variety of tactical motors, but mechanical properties across the operating temperature range were poor. Two final formulations were prepared and tested, as shown in Table 4-19, and proved to be hazard Class 1.3 with volumetric impulse values of ~13 lb_f-s/in^3, translating to ~230 lb_f-s/lb_m impulse. As expected and without solid filler, these viscoelastic propellants had card gap values in the range of 40 to 60 cards, similar to extruded (thermoplastic) double-base propellant. Subscale cookoff and FI tests were also performed on these GIO propellants and gave mild reactions. Specimen dimensions were 2.75-inch OD x 8 inches long, with a 0.75-inch bore and 0.5-inch web thickness.

Full-scale IM tests were also performed on 7-inch OD propellant grains of GIO in graphite composite cases, as shown in Table 4-20. In these tests, GIO with a combustion stability additive as solid end burner grains (no bore) were used. The data indicated that minimum signature propellants without solid filler have the potential for improved IM properties over filled compositions, possibly even

Table 4-18. Some Novel Chemical Structures Evaluated

Compound	Type	Chemical Formula	Impact Sensitivity (cm)
AN	Nitrate Salt	NH_4NO_3	>120 cm
RDX	Cyclic Nitramine	$C_3H_6N_6O_6$	41–64 cm (200 µm)
HMX	Cyclic Nitramine	$C_4H_8N_8O_8$	26–51 cm (150 µm)
CL-20	Caged Nitramine	$C_6H_6N_{12}O_{12}$	17 cm (2 µm)
TAGN	Guanidine Nitrate Salt	$CH_8N_7O_3$	18 cm [42]
ADNBF	Furoxan	$C_6H_3N_5O_6$	28–33 [30]
ADN	Dinitramide Salt	$NH_4N_3O_4$	3.5–6.9
FOX-7	Nitro Olefin	$C_2H_4N_4O_4$	81–163 cm [34]
BTF	Trifuroxan	$C_6N_6O_6$	16 cm [29], 46 cm [34]
LLM-200	Difurazan	$C_8N_{10}O_8$	95 kg-cm (17 µm) [38]
MBANF	Difurazan	$C_5H_4N_8O_6$	220–280 kg-cm [38]
DNFOA	Difurazan Amide	$C_6H_2N_8O_8$	64 cm [31]

Table 4-19. Sensitivity Properties for GIO Unfilled Propellant [40, 41]

Propellant	Card Gap (Cards)	VCCT[a] Reaction Temperature (°F)	Subscale FI[b] (Aluminum Case)	Subscale FI[b] (Composite Case)
GIO Without Combustion Stabilizer	41	—	Burn (Recovered Propellant)	Burn (Recovered Propellant)
GIO With Combustion Stabilizer	58	>450 (Propellant Extinguished)	Burn (Recovered Propellant)	Burn (Recovered Propellant)

[a] Variable confinement cookoff test.
[b] Velocity ~6,000 ft/s.

Table 4-20. Full-Scale IM Tests With GIO Propellant With Combustion Stabilizer [40, 41]

IM Test	Test Condition	Test Result
BI	Single 12.7-mm Bullet @ 2,805 ft/s, 40-ft Stand-off	No Reaction
FI	Single Fragment @ 5,576 ft/s Velocity, 50-ft Stand-off	No Reaction
FCO	Fuel (JP-8) Fire	Burn

compared to AN-filled systems. GIO propellant was abandoned due to its poor mechanical properties at hot (very low modulus) and cold (very low strain) temperatures, along with marginal service life [41].

Neidert also summarized IM test results of alternative unfilled propellants known as elastomer modified cast double base (EMCBD), which are products of the United Kingdom's defense industry [43]. Table 4-21 summarizes these results compared to a Class 1.1 where 7 x 14-inch motor simulators with graphite composite or steel strip laminate (SSL) cases were used. The work again showed that Class 1.1 propellants were sensitive to FI but responded mildly to BI and FCO, regardless of case material. However, EMCDB propellants reacted mildly under all tests and with both graphite composite and SSL cases, even under medium-velocity FI. The SSL cases were designed to yield (unzip in a spiral fashion) under both thermal and impact loads.

Table 4-21. IM Test Results for EMCDB Unfilled Propellants in 7 x 14-inch Cases [43]

IM Test	Baseline Class 1.1		EMCDB	
Case Material	Graphite Composite	SSL	Graphite Composite	SSL
BI	No Reaction	No Reaction	No Reaction	Burn
FI (6,200 ft/s)	Detonation	Detonation	Burn	Burn
FCO	Burn	Burn	Burn	Burn

Table 4-22. Candidate Castable Double-Base Propellant [18]

Ingredient/Property	Candidate Propellant
NC/Stabilizer/Curative/ BTTN/TMETN (%)	73
NC Ball Powder (%)	5
AN (%)	20
LC-11 (%)	1–2
Carbon Black (%)	0.5
Volumetric I_{sp} (lb_f-s/in^3)	14.06
Card Gap (Cards)	Not Reported[a]

[a] Assumed negative at 64 cards, based on previous data.

Booth also conducted work on castable double-base (CDB) propellants based on NC [18]. Interestingly, a final candidate propellant using both a metal salt ballistic modifier and a ball powder modifier, along with AN, was developed for an eventual demonstration effort, as shown in Table 4-22. Plateau ballistics were achieved while maintaining Class 1.3 sensitivity (actual data not reported) and minimum signature characteristics.

Early work on CDB propellants was conducted at Atlantic Research Corporation by Harrod, who described test results for a formulation designated as ARCOCEL 440 [44]. A later version, ARCOCEL 440B, was demonstrated under pre-flight readiness testing for the Army as the boost propellant for the enhanced fiber-optic guided missile (EFOG-M). This propellant had a theoretical I_{sp} of 242.3 lb_f-s/lb_m and volumetric I_{sp} of 13.2 lb_f-s/in^3; it contained two types of nitrocellulose, BTTN and DEGDN, and LC-12-15/carbon black burning rate modifiers. The large-scale gap test (LSGT) value for this propellant was 69 cards. The propellant performed very well in early hazards testing by passing FI at 6,000 ft/s in a roll bonded steel case and SCO at 45 °C/hr [45].

4.2 RECENT DEVELOPMENTS AND APPLICATION IN ADVANCED ROCKET MOTORS (2000 AND BEYOND)

Based on the successes described, several propellants have been the focus of attention for advancing the state-of-the-art in minimum signature compositions that can meet the demands of future rocket motors. While a considerable portion of the work during this time has assessed promising AN containing propellants in several motor applications, other compositions based on alternative oxidizers and unfilled PNC-based propellants have been tested. Much of the work since early 2000 has been devoted to advancing these formulations in terms of lowering shock sensitivity and maximizing energy, while obtaining acceptable mechanical properties, burning rates, and service life (aging). Due to the amount of information available, data primarily related to reducing sensitivity and evaluating IM properties are provided here. Other information is included to highlight significant advancements with these propellants where necessary.

4.3 OVERALL PROGRESS IN REDUCED SENSITIVITY PROPELLANTS

As supported by the earlier data described, reduced sensitivity minimum signature propellants, coupled with advanced rocket motor components like high-strength composites cases and venting devices, have performed well in IM tests such as BI, low velocity FI, FCO, and SCO. Much of the basic propellant work described led to advanced development for specific tactical motor applications. Since the Army, Navy, Air Force, and Marines have shared small tactical missile systems, IM solutions for TOW, HELLFIRE, Javelin, and the new Joint Common Missile (JCM, aka Joint Air-to-Ground Missile [JAGM]) were sought and funded. For example, the Joint Insensitive Munitions Technology Program (JIMTP), established in 2007, funded a large variety of research and development in five munitions areas, including minimum signature propellants [42, 46]. Each JIMTP munitions area developed progressive goals and technology road maps through 2033 to advance the state of technology for IM. Minimum signature propellants lie in the Munitions Area Technology Group II (MATG-II) lane. Neidert described goals achieved so far and future requirements for MATG-II IM, which become progressively challenging over time, as shown in Table 4-23 [9, 47]. Recent work focused primarily on solving SCO and high-velocity FI.

To address these goals, Esslinger provided a concise view of the success of AN-containing minimum signature propellants, as shown in Figure 4-5 [48]. A velocity boundary for impact tests in full-scale motors was identified based on propellant shock sensitivity (card gap), propellant impulse, and motor case material. The chart summarizes the positive effect of using a venting device to pass

Table 4-23. IM and Performance Goals for Cast-Cure Minimum Signature Propellant Through 2033[a,b] [47]

IM Test	Prior to 2023	2023	2028	2033
Goals and Demonstrated Achievements				
BI	Type V			
FCO	Type V			
SCO	Type IV			
Goals Yet to Be Achieved				
SCO		Type V	Type V	Type V
FI	Type IV	Type V	Type VI	Type VI
SCJ	Pass (With Barrier)	Pass (40 mm)	Pass (81 mm)	Pass
SD				Pass

[a] Theoretical volumetric I_{sp} = 15.3 lb_f-s/in^3 for development projects.
[b] Delivered volumetric I_{sp} = 13.1 lb_f-s/in^3 for advanced development projects.

Propellant	Oxidixer/ Co-Oxidizer	Case	BI	Fragment Impact 4000 fps	5000 fps	6000 fps	7000 fps	8300 fps	NOL Card Gap	Isp (lbf-s/lbm)
TOW	RDX	6" Steel (TOW)	III						170	247
TOW	RS-RDX	6" Steel (TOW)	V	IV			I		140	247
GIR-1	AN/RS-RDX	6" Steel (TOW I/b/s)			IV				65	229
GIZ	AN	7" Al (HELLFIRE)		VI		IV			63	227
GIR-1	AN/RS-RDX	7" Composite					IV		65	229
GIZ	AN	7" Composite							63	227
GIW	AN/CL-20	7" Composite							70	231
			FCO		SCO		FCO/SCO w/venting			
		Metallic	III		III		V		63-170	227-247
		Composite	V		III		V		63-170	227-247

Figure 4-5. IM Test Results for RDX- and AN-Containing Minimum Signature Propellants [48].

thermal IM tests. Table 4-25 in section 4.4.1 provides descriptions of these AN-containing propellants.

Under JIMTP funding, Esslinger also described IM test results for propellants that contain alternative oxidizers FOX-7 and CL-20 used in the NWC-472 formulation, as well as unfilled propellants, AFD-3778, and RASP-9, which are based on PNC [49–51]. Impulse, card gap, and IM test data are shown in Table 4-24 for these propellants in 7-inch motor cases. All had favorable impulse-to-card gap relationships. The unfilled propellants performed well in the high-velocity FI tests since they did not contain sensitive solid fillers, indicating that they potentially behaved more like extruded double-base propellants. The NWC-472 propellant tended to react violently in FI tests, even with composite cases and under lower velocity impact. Comparing these results to those in Figure 4-5 for GIZ propellant (AN and no co oxidizer) at 8,300 ft/s fragment velocity (which gave Type VI, no reaction), the data shows that card gap values below 70 cards indicate FI sensitivity. However, card gap was not the single driving factor for predicting IM response. Rather, the combination of card gap and using an insensitive oxidizer such as AN or no oxidizer was important for achieving very mild responses to FI.

4.4 MOTOR APPLICATIONS USING ADVANCED PROPELLANTS

The following discussions have been divided by missile system for ease of description. However, work directed toward a specific application has not limited the potential application in other weapons systems. For example, a suitable propellant developed for the HELLFIRE rocket motor could find application in a TOW-2 rocket motor. Furthermore, the new JCM (aka JAGM) requirements have placed added burdens on minimum signature rocket motors since they are destined to be carried on fixed-wing (fighter aircraft) and rotary-wing (helicopters) platforms. As such, the need for extended operational temperature extremes in hot and cold environments has been required. Insensitivity and performance have continued to be essential goals for these future missile systems and programs. New propellants must be capable of operating at high pressures to achieve suitable performance and survive extreme operational thermal and mechanical loads while ensuring survivability by unplanned stimuli (IM requirements).

Table 4-24. Propellants Under Development and IM Test Results [49–51]

Propellant	Alternative Oxidizer	Unfilled	
Source	Navy	Aerojet/Rocketdyne	Army
Designation	NWC-472	AFD-3778	RASP-9
Binder Type	Polyester	PNC	PNC
Oxidizer Type	FOX-7/CL-20	—	—
Impulse (lb_f-s/lb_m)	242	242	243
Card Gap (Cards)	79–80	65–69	66–69
IM Test in 7-inch Composite Case			
FI (6,000 ft/s)	Type IV[a]	—	—
FI (8,100–8,300 ft/s)	Type I	Type V	Type V[b]
IM Test in 7-inch Aluminum Case			
FI (8,300 ft/s)	Type I	—	—
SCO	Type IV	—	—

[a] Test item and extensive firebrands thrown to 170 ft.

[b] Test #1: fragment thrown 170 ft; Test #2: fragment thrown 40 ft.

4.4.1 Joint Common Missile (JCM)

The Army and Navy undertook a cooperative effort to develop and demonstrate a JCM for armored and maritime targets as well as military operations in urban terrain. The JCM can launch from fixed- and rotary-wing aircraft, with the intent of replacing several missiles such as TOW-2, HELLFIRE, and Maverick. A concept for the JCM is shown in Figure 4-6 and displays many similarities to the HELLFIRE missile but with added motor length for added range [52]. To achieve extended range, a boost/sustain propellant grain configuration was proposed by researchers and companies. Developing reduced sensitivity minimum signature propellants capable of sustained combustion during high thrust turn down (from high-boost pressure to low-sustain pressure) and at long-duration low-pressure sustain operation was needed, along with IM capability.

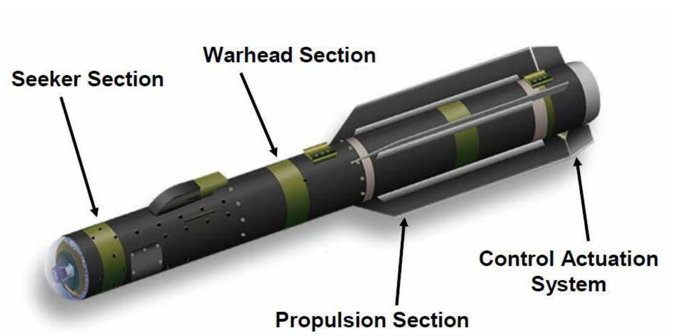

Figure 4-6. Concept for the JCM [52].

During the early to mid-2000s, Army and Navy researchers and commercial defense companies participated in propellant development activities to supply a fully capable minimum signature propellant for the JCM. Johnsen and Clubb have described work undertaken from 2002 to 2006 at the U.S. Naval Air Warfare Center, China Lake, CA for this purpose [52]. Again, propellants using PSAN were heavily investigated. To meet JCM motor requirements for energy, burning rate, and low-pressure combustion, the work focused on using ZnO-PSAN, TAGN, and CL-20 tri-oxidizer blends. An extensive amount of work was performed to characterize ballistic and mechanical properties of a variety of formulations. The work was successful in meeting requirements and showed that a propellant designated as JCM 303-4-58-4 had a card gap value of 50–55 cards and an impulse of 220 lb_f-s/lb_m. Unfortunately, the program was cancelled such that no IM testing of full-scale motors was performed. However, other programs and efforts described next accomplished preliminary IM testing of similar designs.

Similar work for the JCM described by Clawson et al. [53–55] led to a new family of reduced sensitivity minimum signature propellants. These AN-containing propellants can adapt to a variety of rocket motor designs, including all-boost, boost/sustain, and controllable thrust configurations [53, 54, 56]. Starting in 2002, developing these formulations has continued and provided potential applications in future IM rocket motors, including the IM Air-to-Ground Missile System (AGMS, aka IM HELLFIRE), TOW Next Generation, and IM Javelin. General descriptions of these 2nd Generation propellants are provided in Table 4-25 and compared to the 1st Generation (CP/AN) and Class 1.1 propellants. GIR, GIW, and GIZ are similar in composition apart from the secondary oxidizer, RS-RDX, CL-20, or none, respectively. Differences in impulse and card gap values resulted, while all remained as Class 1.3 compositions. These propellants were considered suitable for conventional rocket motors with fixed throats due to their burning rates and exponents. Using no ballistic modifier, GIX was desirable for controllable thrust motors using variable area (pintle) nozzles (unpublished work performed by Orbital ATK) and was also a Class 1.3 propellant. Figure 4-7 shows the burning rate trends for these new propellants.

Work on these 2nd Generation propellants led to successful boost/sustain motor firings applicable to JCM. A representative heavyweight motor design shown in Figure 4-8 demonstrates boost/sustain firings at the hot and cold temperature extremes. Figure 4-9 shows pressure-time and thrust-time profiles for this motor having sustainable combus-

Table 4-25. New Family (2nd Generation) of Reduced Sensitivity Propellants [53, 54, 56]

Ingredient	2nd Generation				1st Generation	Current Class 1.1
	GIR	GIW	GIZ	GIX	CP/AN	
Energetic Binder (%)	65.5	65.5	65.5	65.5	34	34.5
AN (%)	20	20	30	34	40.5	—
RS-RDX (%)[a]	10	—	—	—	—	62.5
CL-20 (%)[b]	—	10	—	—	—	—
Ballistic Modifier (%)	4	4	4	—	15	2
Acoustic Stabilizer (%)	0.5	0.5	0.5	0.5	0.5	1
Property/Motor Application						
I_{sp} (lb_f-s/lb_m)	229	230	227	228	234	247
Card Gap (cards)	70	70	63	63	65	145
Burning Rate (in/s)[c]	0.40	0.41	0.38	0.20	0.40	0.40
Exponent[d]	0.45	0.50	0.50	0.80	0.50	0.30
Motor Application	Fixed Throat, Boost, Boost/Sustain			Variable Area Throat	Fixed Throat, Boost, Boost/Sustain	

[a] At 3.5 µm.
[b] At 2.1 µm.
[c] Approximate value at 1,000 psi.
[d] Approximately 1–4.5 kpsi.

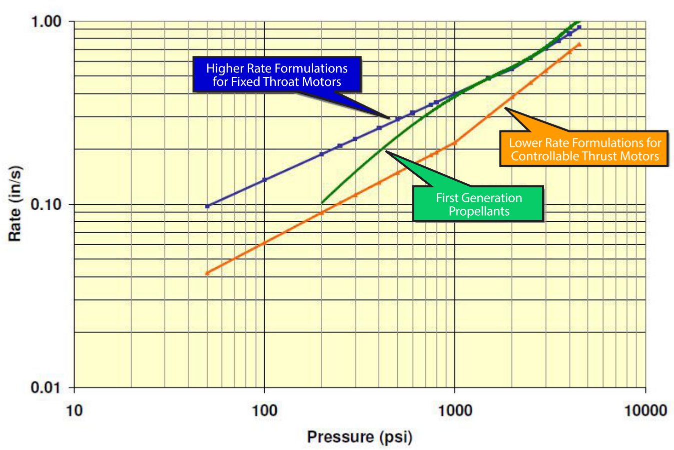

Figure 4-7. Burning Rate Trends for 2nd and 1st Generation Propellants [56].

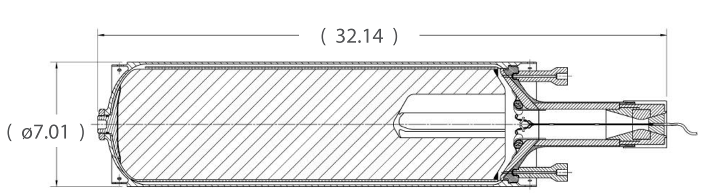

Figure 4-8. Heavyweight Boost/Sustain Motor With GIR Propellant for JCM [56].

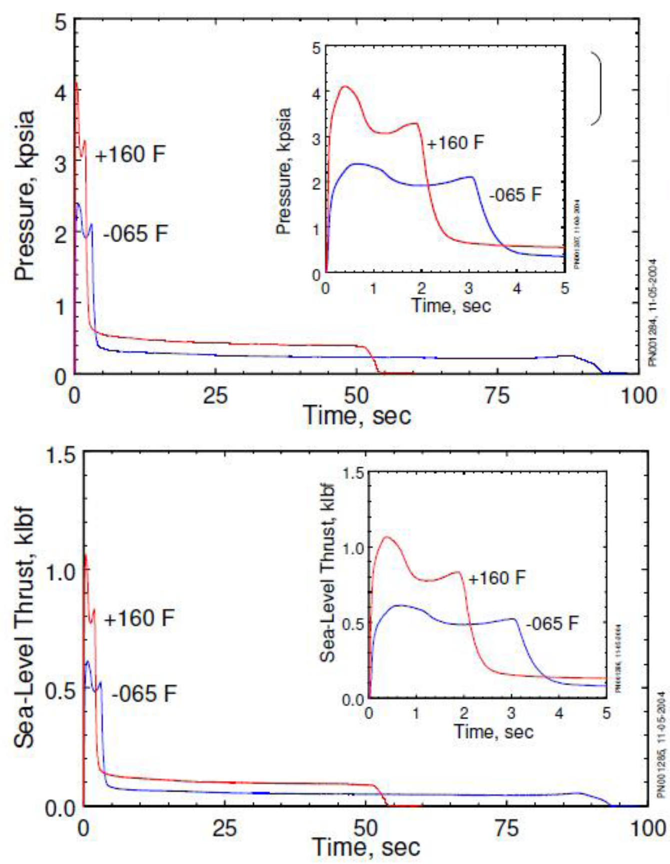

Figure 4-9. Heavyweight Motor Pressure-Time and Thrust-Time Results Using GIR Propellant [56].

tion at 300 psi at –65 °F and a thrust turn-down ratio of ~6/1. These firings also show that the 2nd Generation GIR propellant had low-temperature sensitivities, with σ_P = 0.10%/°F and π_K = 0.17%/°F, while 1st Generation CP/AN propellants had higher values of 0.14 and 0.28%/°F, respectively.

Another interesting feature of these 2nd Generation AN-containing propellants was their superior mechanical properties, especially strain capability under cold temperatures. For example, GIR propellant produced strain values over 80% when tested at –65 °F, as shown in Figure 4-10. Such values were vastly superior to current Class 1.1 and other new reduced sensitivity propellants where strain values under these conditions were generally 10% or less, indicating brittle behavior [56].

IM testing was performed on the 2nd Generation propellants GIR, GIW, and GIZ, as shown in Table 4-25 [54]. Near-tactical composite cases incorporating a bonded metal end closure design were used. This case design, shown in Figure 4-11, was capable of handling up to 7,000 psi internal pressure loads to accommodate a grain configuration analogous to the heavyweight motor shown in Figure 4-8 (see approximate locations of sustain and boost grain sections). These near-tactical cases were 7 inches in diameter and 22 inches long. Simulated nozzles were attached like Figure 4-8. However, the nozzle simulators did not use insulation but only metal shells. For all motors tested in this study, the simulated nozzle closures also used a venting device (shaped memory alloy retaining ring) capable of retracting under thermal loads. This device proved essential to release the nozzle shell for yielding mild reactions during SCO tests by providing vent area prior to igniting the propellant.

IM test data for this study are shown in Table 4-26. Clear differences were observed due to the choice for two of the more important design features for IM rocket motors—propellant ingredients (in this case, the co-oxidizer) and the degree of confinement from case material. Comparing GIR and GIW, CL-20 proved to be less sensitive than RS-RDX, even when fine particle sizes were used for both materials. The least-sensitive propellant, GIZ without any co-oxidizer, produced more violent reactions (Types IV and V) under FI when confined in an aluminum case as opposed to a composite case. All propellants gave mild response to BI, regardless of co-oxidizer type or case material, which has been consistently supported by much of the work previously described by others. In fact, when this motor was impacted at the metal end adapter, mild reactions ensued for GIR and GIW propellants. Photographs of some selected post test results from this study are provided in Figures 4-12 through 4-16.

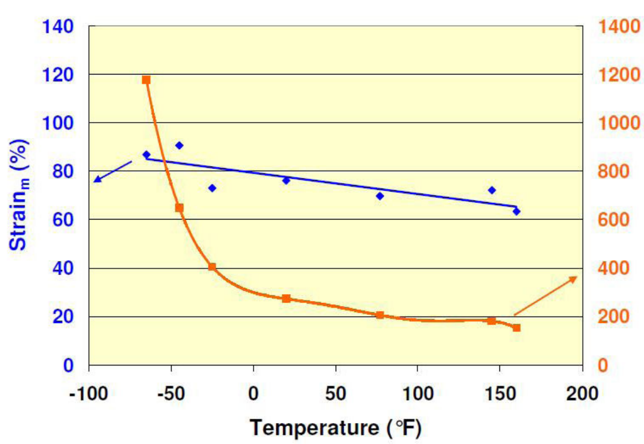

Figure 4-10. Strain and Stress Values for GIR Propellant at Various Temperatures (Strain Rate = 0.74 in/in/min) [56].

Figure 4-11. JCM Composite Case for IM Testing With Bonded Metal End Closure Design [54].

Table 4-26. IM Test Results for 2nd Generation AN-Containing Propellants [54]

IM Test	Condition	Impact Shotline	GIR	GIW	GIZ	
Propellant Co-oxidizer	—	—	RS-RDX (3.5 µm)	CL-20 (2.1 µm)	None	
Case Material	—	—	Composite	Composite	Composite	Aluminum[d]
BI	2,800 ft/s	Base of Boost Section[b]	Type VI	—	Type VI	Type VI
	2,800 ft/s	Center of Boost Section[c]	Type VI	Type VI	—	—
FI	6,000 ft/s	Base of Boost Section[b]	Type VI	—	Type VI	Type IV[6]
	8,300 ft/s	Base of Boost Section[b]	Type I[5]	Type VI	Type VI	Type I
SCO	6 °F/hr[a]	—	Type V	—	—	—

[a] Passive venting device at nozzle closure.
[b] Through composite section of case.
[c] Through aft metal adapter of case.
[d] At 7-inch OD x 14-inch L.
[e] At 6,900 ft/s fragment velocity.
[f] With 85% of propellant recovered.

Figure 4-12. Post-Test Low-Velocity FI of Motor With GIR Propellant [54].

Figure 4-13. Post-Test High-Velocity FI of Motor With GIW Propellant [54].

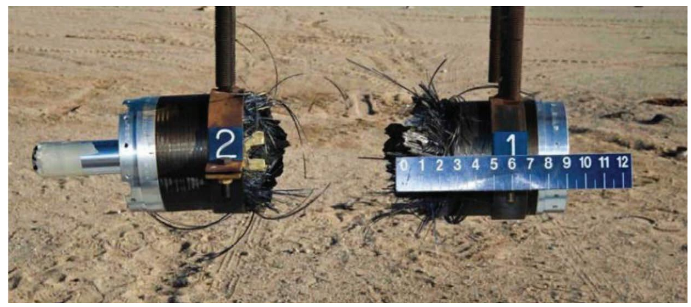

Figure 4-14. Post-Test High-Velocity FI of Motor With GIZ Propellant [54].

4.4.2 IM Javelin

Esslinger has provided several progress updates on work performed under JIMTP tasks directed toward developing an IM Javelin rocket motor. Aerojet/Rocketdyne and Orbital/ATK have been developing motors designed to meet current performance requirements while demonstrating progressive IM characteristics compared to the current production motor [55, 57–60]. A summary of the work from both companies is provided next and focuses on motor designs for "drop-in" replacements, propellant characteristics, and IM testing primarily for FI and SCO. Both designs used nitramine-filled propellants that did not contain AN for achieving desired energy.

The Aerojet/Rocketdyne design for the IM Javelin motor shown in Figure 4-17 uses a composite case with a reduced sensitivity propellant compared to the current production motor with an aluminum case and high-energy Class 1.1 propellant. The

Figure 4-15. Post-Test High BI of Motor With GIW Propellant (Shotline Impact at Base of Boost Section Through Metal End Adapter) [54].

design also uses a passive venting device (labeled as Thermal Venting Forward Closure) for improving response to SCO. The propellant designation, ADM-C26173, was a variation of the Arcocel-432 propellant using a reduced concentration of fine HMX, along with polyester polymers and nitrate ester plasticizers in the binder. ADM-C26173 met mass and performance requirements for the IM Javelin motor. A summary of the IM test results for both propellants is shown in Table 4-27, along with the current production motor in an aluminum case.

Figure 4-16. Post-Test SCO Motor With GIR Propellant, Where Motor Fell From Stand and Burned Mildly [54].

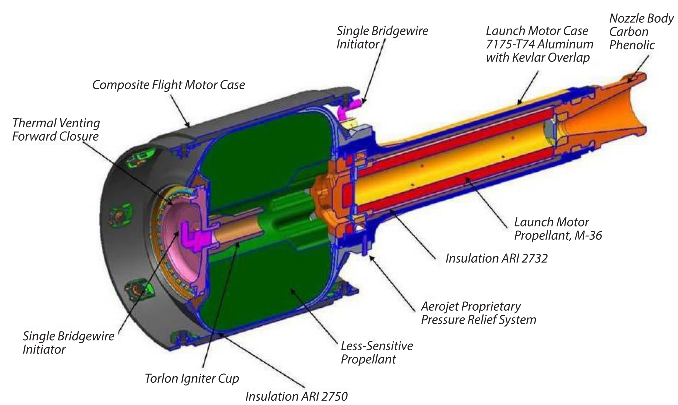

Figure 4-17. Aerojet/Rocketdyne IM Javelin Motor Design [57].

Card gap sensitivity was only slightly reduced in the new propellant formulation ADM-C26173 over the production Arcocel-430B. Improvements to FI sensitivity were demonstrated, primarily due to the use of a composite case. The high-velocity FI test continued to remain unsolved. Aerojet/Rocketdyne considered a dual-propellant configuration as a future variation where a less-sensitive outer grain encases a more sensitive inner grain. The outer propellant grain under consideration also used a reduced nitramine content but with insensitive NTO as a co-oxidizer. The goal for the card gap sensitivity of the outer propellant was 60 cards, or less, which might be needed in combination with a 120-card inner propellant grain. This combina-

Table 4-27. IM Characteristics of a Javelin Motor With Arcocel-430B and ADM-C26173 Propellants [57–60]

Propellant/Case	Arcocel-430B	Arcocel-430B	ADM-C26173
I_{sp} (lb_f-s/lb_m)	244	244	235
Card Gap (Cards)	140	140	110
Case Material	Aluminum	Composite	Composite
IM Test			
BI	Type V	Type V	Type V
FI (6,000 ft/s)	Type IV	—	—
FI (7,200 ft/s)	Type IV	Type IV	—
FI (7,700 ft/s)	—	—	Type I
FI (8,300 ft/s)	Type I	Type I	Type I
SCO	Type III[a]	Type V[b]	Type V[b]
FCO	Type IV[a]	Type V[b]	Type V[b]

[a] No venting, production case design.
[b] Venting, new case design.

tion might be needed to pass the high-velocity FI test in a composite case. Data are pending on the NTO-containing propellant and the dual propellant concept for FI tests.

Orbital/ATK has shown similar results with their IM Javelin motor design shown in Figure 4-18. This design uses a composite case, a reduced sensitivity propellant (GJQ), and an aft closure venting device based on a contracting snap ring (J-ring) to provide a large vent area under thermal loads. GJQ propellant uses lower solids loading of fine RS-RDX relative to production Class 1.1 propellant with standard RDX. Table 4-28 provides the card gap and FI test results for their candidate GJQ propellant in the IM Javelin motor design. Although GJQ propellant had a 92-card shock sensitivity, the motors still detonated under high-velocity FI tests at 6,800 ft/s or greater. The data also reinforced the need for further reducing shock sensitivity of these minimum signature propellants to values near 60 cards for passing high-velocity impact tests (see GIZ propellant data in Tables 4-25 and 4-26). An early version of this propellant was GJM, which had I_{sp} = 235 lb_f-s/lb_m and a card gap of 112 cards, but it displayed less favorable FI results.

Additional testing of the Orbital/ATK motor for response to SCO was performed. Figure 4-19

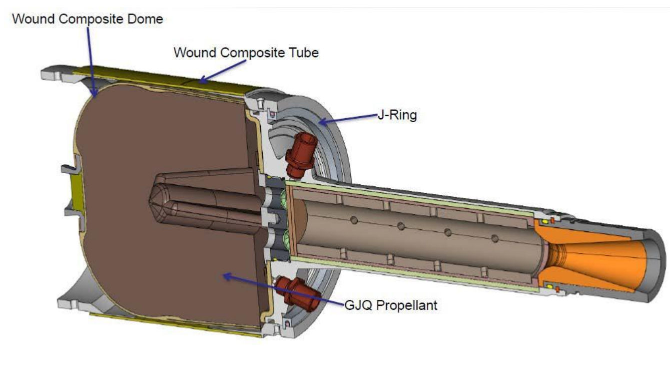

Figure 4-18. Orbital/ATK IM Javelin Rocket Motor Design [57].

Table 4-28. Orbital/ATK GJQ FI Test Results in an IM Javelin Motor [59, 60]

Test	Result
I_{sp} (lb_f-s/lb_m)	230
Card Gap (Cards)	92
FI (6,200 ft/s)	Type IV
FI (6,800 ft/s)	Type I

shows pre- and post-test photos. After the reaction event, which was classified as a Type V burn, motor remnants remained in the oven chamber. Reaction violence, leading to a very mild burn, was minimized using a contracting J-ring as part of the aft closure (nozzle and launch motor combination), allowing a large vent area to generate prior to

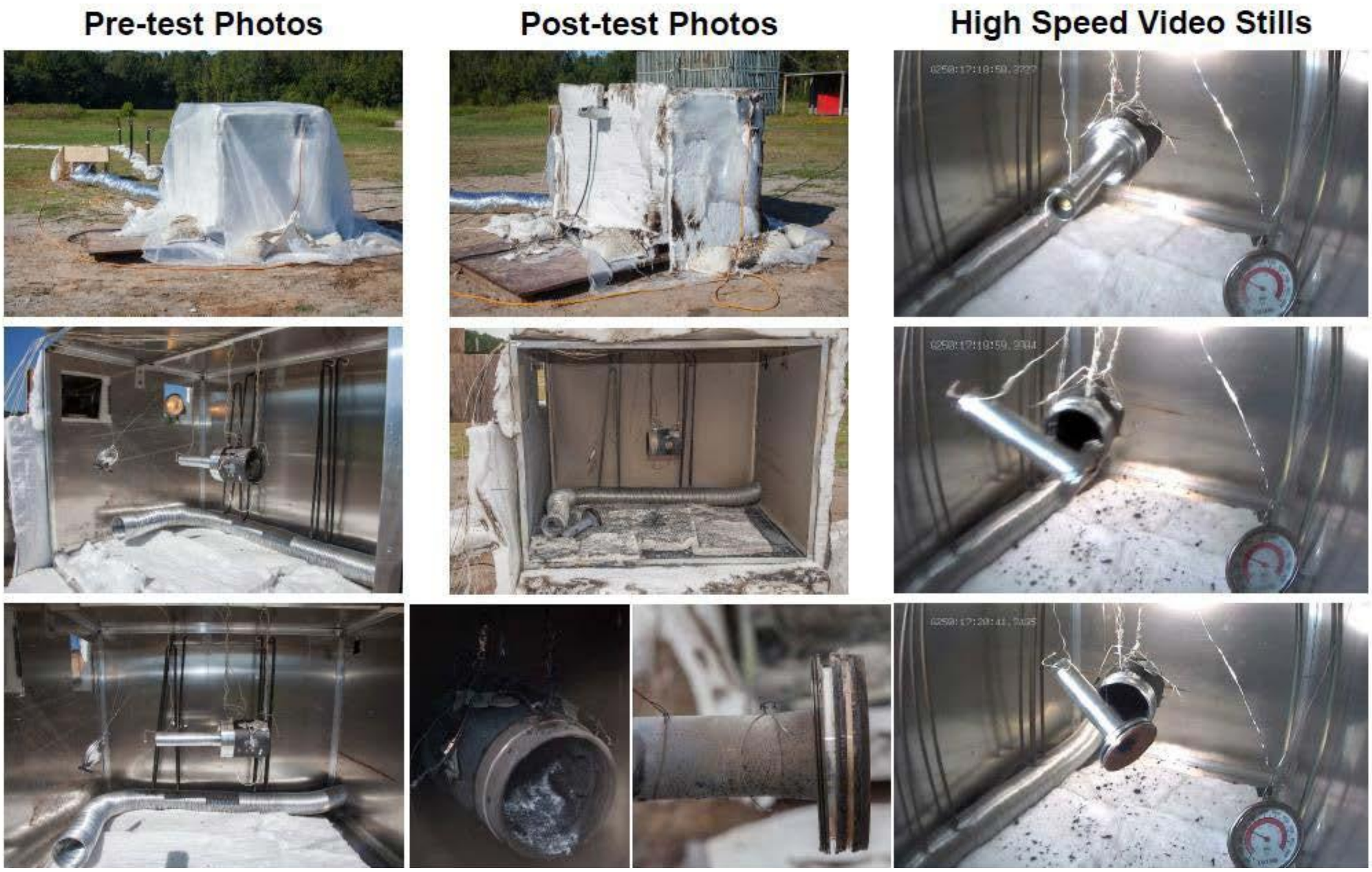

Figure 4-19. SCO Test Photos for Orbital/ATK IM Javelin Motor [59, 60].

reaction. Reaction temperature was approximately 260 °F, as shown in Figure 4-20, which is typical for minimum signature propellants under a SCO test environment.

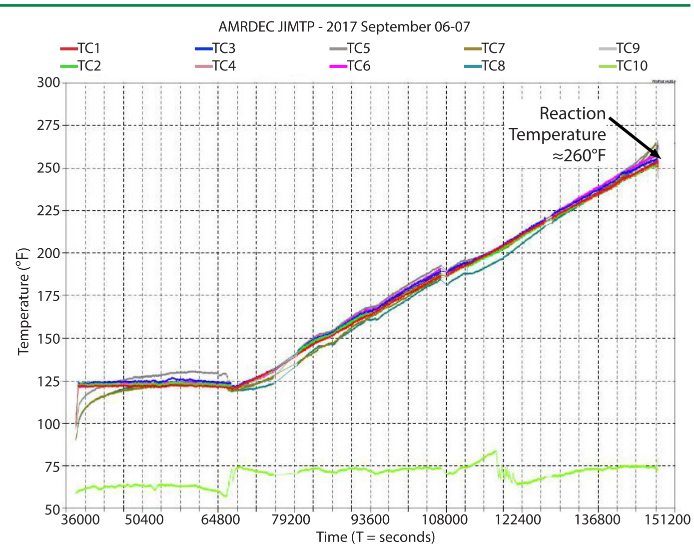

Figure 4-20. SCO Temperature Profile for Orbital/ATK IM Javelin Motor [59, 60].

4.4.3 IM TOW

A unique approach to an IM TOW motor has been described by Esslinger using a dual-flight motor design by Orbital/ATK [55], as shown in Figure 4-21. The design also incorporates the existing production launch motor to complete the propulsion section for the current development effort. Both flight motors used graphite composite cases, while the launch motor used a steel case with extruded double-base propellant. Initial work by Orbital/ATK employed GJQ propellant in the flight motors, which used fine RS-RDX as the oxidizer and no AN and had a card gap value of 92 cards (see IM Javelin discussion). Although GJQ passed the high-velocity FI test at 8,300 ft/s in the sustain flight motor configuration as a solid end burner (no bore), poor FI test results were observed in the boost flight motor with a configured bore. Development work continued with the Class 1.3 GIR propellant (see

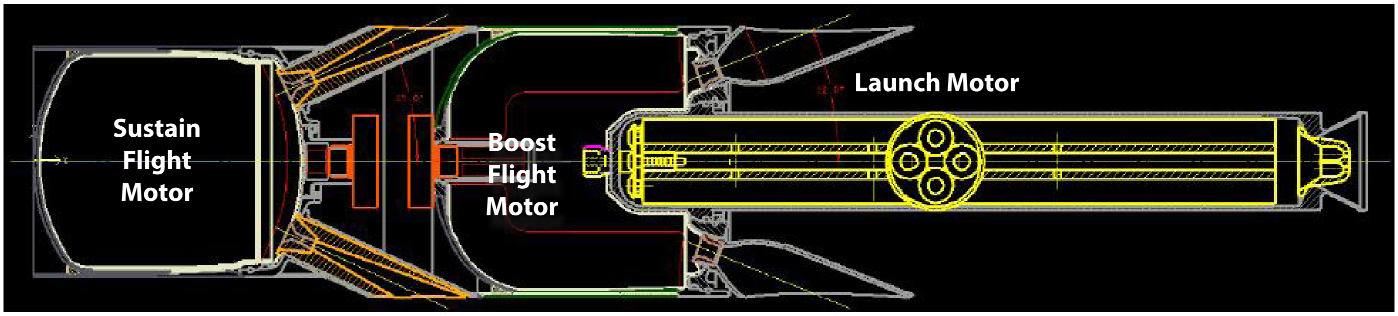

Figure 4-21. Orbital/ATK Dual Flight Motor Design for IM TOW [55].

JCM discussion), where high-velocity FI tests for the sustain and boost flight motors are planned [61].

4.4.4 IM HELLFIRE (aka IM AGMS)

Esslinger has also documented recent work conducted by Orbital/ATK and Aerojet/Rocketdyne on an extended range IM HELLFIRE rocket motor, IM AGMS, which continues today [55]. Designs by both companies are shown in Figures 4-22 and 4-23 and display similarities in propellant grain configuration, along with using graphite composite cases. Some available ballistic and IM test data are provided.

Figures 4-24 and 4-25 show thrust-time profiles for each motor to achieve extended range through a boost/sustain propellant grain configuration. Both motors showed similar nominal performance at ambient temperature (70 °F), while the Orbital/ATK

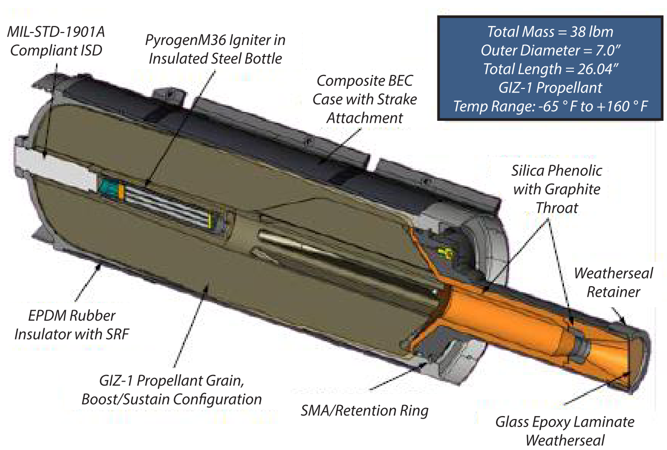

Figure 4-22. Orbital/ATK IM AGMS Rocket Motor [55].

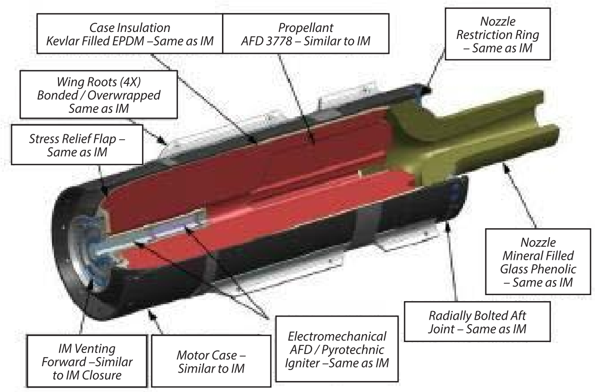

Figure 4-23. Aerojet/Rocketdyne IM AGMS Rocket Motor [55].

motor showed acceptable performance at the hot and cold temperature extremes for this new application.

IM test data for the Orbital/ATK motor are provided in Table 4-29, while data for the Aerojet/Rocketdyne design are unavailable at the time of this writing. The Orbital/ATK motor used the GIZ propellant as described, which contained AN as the oxidizer and no nitramine co-oxidizer. GIZ was a Class 1.3 propellant, with 63 cards shock sensitivity. IM tests were performed on two motor configurations with and without a live igniter. In these initial tests, bare motors were used unless noted otherwise.

Motors without igniter material used empty steel igniter chambers in the sustain (forward) section of the bore. Motors with live igniters used M36 extruded propellant in the steel igniter chambers. FI tests showed similar results, deflagration (Type III),

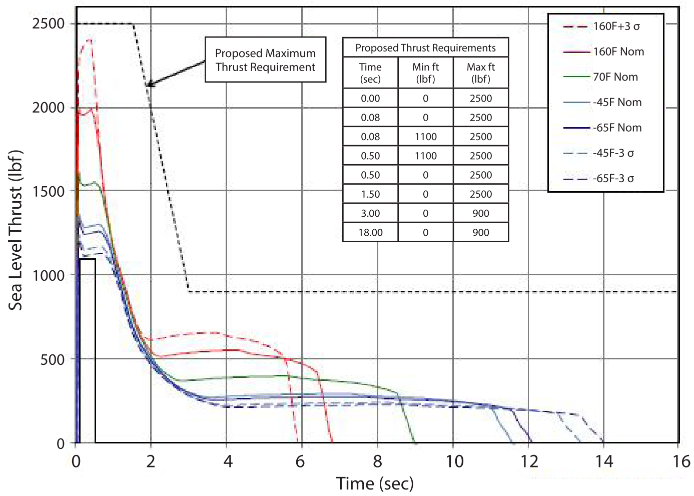

Figure 4-24. Orbital/ATK IM AGMS Motor Thrust-Time Profile [55].

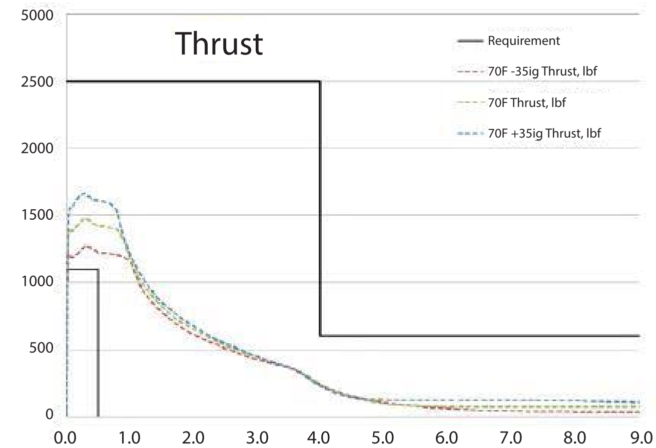

Figure 4-25. Aerojet/Rocketdyne IM AGMS Motor Thrust-Time Profile [55].

Table 4-29. IM Test Data for the Orbital/ATK IM AGMS Motor [55]

Propellant/Motor Property	Without Igniter Material	Live Igniter
Propellant Designation	GIZ	
Propellant Card Gap (Cards)	63	
Motor Case Diameter (in)	7	
Motor Case Material	Graphite Composite	
Propellant Grain Configuration	Boost/Sustain	
IM Test and Result		
BI (2,800 ft/s)	No reaction	—
FI (8,100–8,300 ft/s)	Deflagration	Deflagration
FCO	Burn[a,b]	—
SCO (6 °F/hr)	Burn[b]	Deflagration[b,c]
SCO (6 °F, in Shipping Container)	Burn[b]	Deflagration[b–d]

[a] By analogy to GIW, as previously described.
[b] Nozzle aft closure with passive venting device.
[c] Aft missile control actuation system (CAS) installed.
[d] All-up round (AUR) with warhead simulator.

regardless of the use of an inert (no M36) or a live igniter. Figure 4-26 shows the shotline for these tests through the sustain section of the grain and steel igniter chamber. Figure 4-27 shows typical damaged motor remnants when the M36 igniter material is present and indicates over-pressurization of the composite motor cases due to propellant combustion. Extinguishment allowed some propellant to remain in the sustain sections after the motor cases ruptured. Furthermore, using an inert (empty) igniter vs. a live igniter showed that

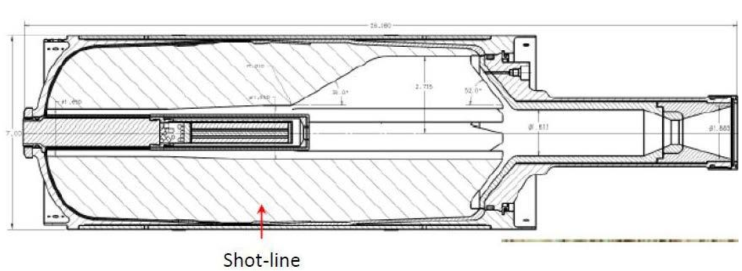

Figure 4-26. FI Shotline Through the Orbital/ATK Motor Sustain Section and Steel Igniter Chamber [55].

Figure 4-27. FI Post-Test Motor Without Igniter Material [55].

both configurations resulted in motor fragments propelled outside the maximum 50-ft radius, as shown in Figure 4-28. However, the live igniter appeared to enhance combustion of the main propellant forward section, causing it to propel at a greater distance.

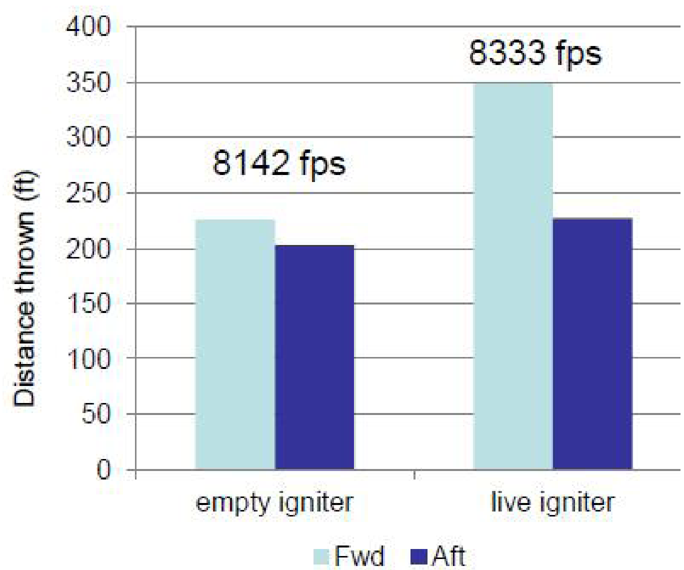

Figure 4-28. Distance for Motor Fragments Propelled From FI Testing of IM AGMS Motors [55].

Photographs in Figure 4-29 show the pre-test setup (outside and inside the SCO oven) and post-test motor remnants with damage. In this test, motor sections were thrown many feet away from the test site. The nozzle was hurled 16 ft, the CAS propelled 26 ft, and the motor case ejected 77 ft. These results were indicative of a more violent reaction compared to bare motors without attached missile components. Similar response was observed when an AUR with a CAS and warhead simulator was tested, as shown in Figure 4-30, while missile components propelled and landed considerable

Figure 4-29. SCO Test of Orbital/ATK Motor With Attached CAS [55].

distances from the test site (motor case thrown up to 171 ft). These data clearly indicated that less-sensitive propellants can promote IM motor characteristics. However, consideration must be given to the missile configuration, location and movement of components, and shipping container structures when attempting to resolve IM issues using a systems approach.

4.5 SUMMARY OF AVAILABLE CARD GAP DATA FOR PROPELLANTS IN THIS REPORT

An assessment has been made for all post-2000 propellant candidates previously described. This assessment consolidated available propellant impulse and card gap data for understanding ingredient effects and energy level (impulse) of the compositions regarding shock sensitivity and potential response to some IM stimuli. Most of the data available related card gap to propellant impulse, which has historically guided propellant formulators. Table 4-30 provides a summary of these candidate propellants, where the data have been segregated by oxidizer type. The plot in Figure 4-31 provides a visual interpretation of the effects of oxidizer type and propellant impulse on shock sensitivity. The original relationships, described by Herriott and Foster [10] and Comfort et al. [17], between propellant impulse and card gap remained in the newer propellants where nitramines and AN have been used. However, it has been found that compositions using the FOX-7/CL-20 oxidizer combination and those that do not use solid oxidizers, but rather PNC binders, showed deviations from this behavior. For those propellants, higher impulse and lower shock sensitivity was found.

Propellants using standard RDX or HMX showed the highest impulse and card gap expected from historic data, even when combined with insensitive AN oxidizer seen by the AN/nitramine trend. Using reduced sensitivity nitramines (RS-nitramine) effectively lowered card gap values by ~25 cards throughout the I_{sp} spectrum, while the trendlines were identical in slope. This trend was true regardless of AN content for these compositions with low solid filler content (see Table 4-25). (Note: propellants with higher I_{sp} were associated with higher nitramine content, while those with lower I_{sp} were associated with higher AN content for both trends in Figure 4-31.) An earlier trend established by Comfort for GAP/PSAN and PGA/PSAN propellants gave $y = 2.19x - 454$ (Figure 4-2), while higher impulse values near 240 lb_f-s/lb_m were achieved through higher solids loadings.

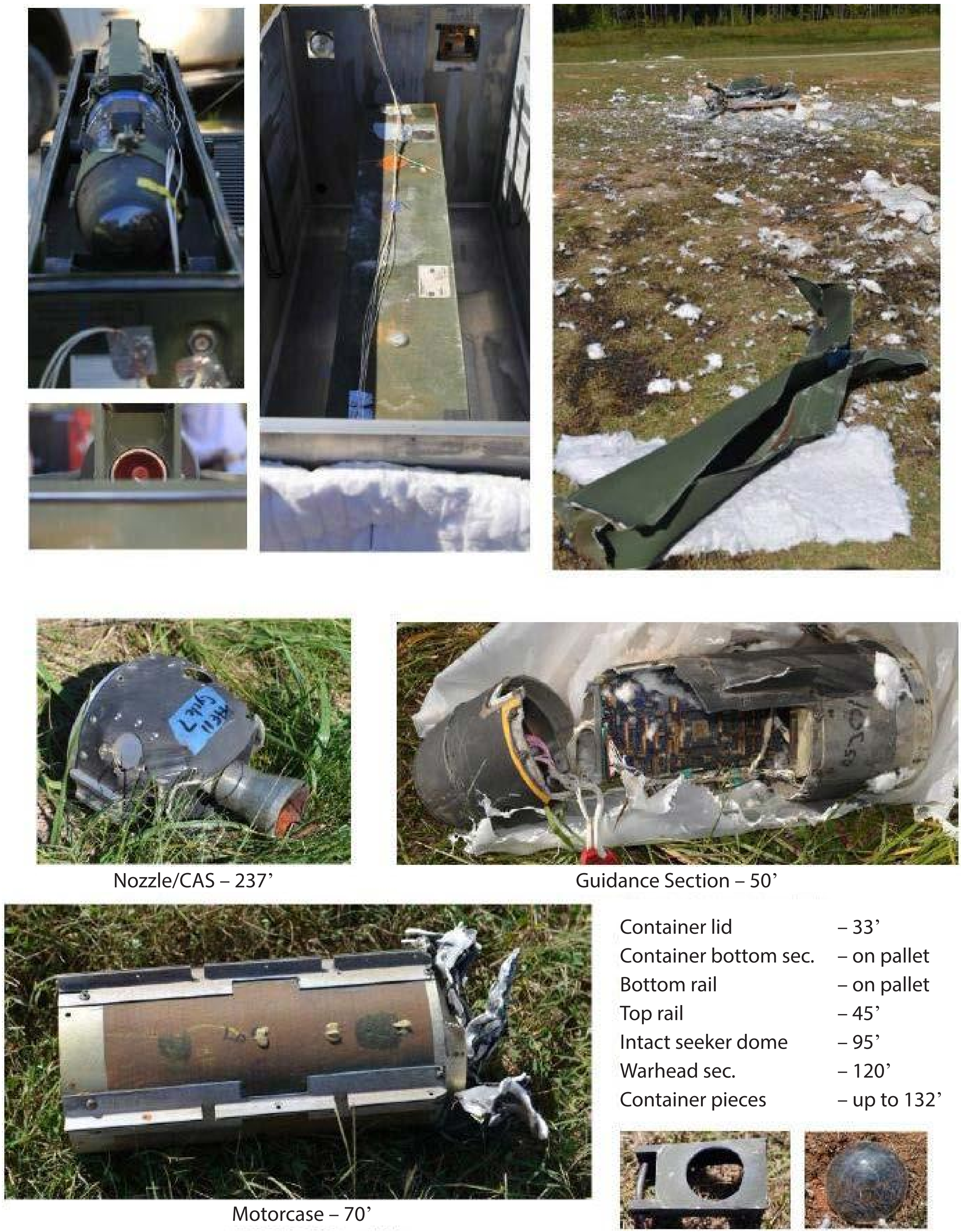

Figure 4-30. SCO Test of Orbital/ATK Motor as an AUR With CAS and Warhead Simulator [55].

Table 4-30. Summary of Post-2000 Candidate Propellant Impulse and Card Gap Values

Designation	I_{sp} (lb_f-s/lb_m)	Card Gap (cards)	Oxidizer
GIR Mod	229	100	AN/RDX
ADM-C26173	230	110	HMX
Arcocel 430B	244	140	HMX
GCV	247	150	RDX
JCM-303-4-58-4	220	55	PSAN
GIZ	227	63	AN
GIR	229	70	AN/RS-RDX
GIW	230	70	AN/CL-20
GCV Mod	247	120	RS-RDX
GJQ	230	92	RS-RDX
GJM	235	112	RS-RDX
NWC-471	241	79	FOX-7/CL-20
NWC-472	242	80	FOX-7/CL-20
RASP-6	238	69	None
AFD-3778	242	69	None
Arcocel©440B	242	50 (69[a])	None
RASP-9	243	69	None

[a] LSGT.

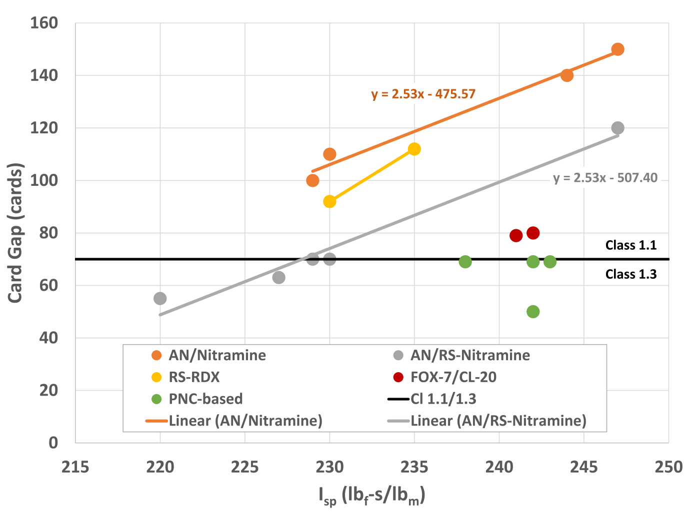

Figure 4-31. Effects From Oxidizer Type on Propellant Card Gap.

The use of RS-RDX exclusively in propellants shown in Figure 4-31, with moderate I_{sp}, fell approximately in the range of 90–110 cards (GJQ and GJM propellants) and somewhat followed the expected trend. This work showed that using nitramines (either RS-RDX or CL-20) with particle sizes in the range of ~2–4 µm reduced propellant shock sensitivity compared to those using standard RDX or HMX. The most effective method for reducing shock sensitivity was using higher concentrations of AN, but at the expense of propellant impulse for these compositions.

A group of data was observed for propellants using FOX-7/CL-20 and no oxidizer (PNC-based), where higher I_{sp} and moderate card gap values were seen. Unfortunately, the FOX-7/CL-20 compositions did not perform well in high-velocity FI tests, as just described. To date, only GIZ and the PNC-based propellants, AFD-3778 and RASP-9, gave mild responses to the high-velocity FI test. Furthermore, the PNC-based propellants provided a significant deviation from earlier I_{sp}-card gap trends and may give future success under other IM tests. These propellants may also find success if desirable mechanical and ballistic properties can be realized for tactical motor operations in a variety of environments. For example, RASP-9 had burning rates and aging characteristics appropriate for tactical motor applications but suffered from poor strain capability at cold temperatures [49, 50].

4.6 SUMMARY OF AVAILABLE MOTOR IM TEST DATA IN THIS REPORT

A summary of available IM test data for full-scale motors described in this report is provided in Table 4-31. The data are organized by motor diameter from smallest to largest for MS tactical motors and then subdivided by propellant and case material. For the small 2 and 2.75-inch motors using Class 1.3 propellants, mixed results were seen for BI, FI, SCO, and FCO due to factors such as case material, degree of confinement, and motor configuration. For 5-inch motors with Class 1.1 and 1.3 propellants, mild response to BI, SCO, and FCO was generally observed. Sensitivity to FI was observed unless fragment velocities were reduced to around 7,000 ft/s or lower, regardless of the propellant used and case material.

Table 4-31. Summary of Available IM Test Data Provided in This Report

Motor	Propellant Designation	Case Material	Dia.	Length	BI	FI (Velocity)	SCO	FCO
TOW 2B Launch	Class 1.3	Steel	2	9	V	IV (8,300 ft/s)	I	V
Hydra 70 Mk 66 Mod 4	Class 1.3	Aluminum	2.75	40	IV	I (8,300 ft/s)	III	IV
Javelin Flight	Class 1.2.1E	Aluminum	5	4	IV	I (8,300 ft/s)	II	IV
Javelin Flight	Arcocel-430B	Aluminum	5	4	V	IV (6,000 ft/s) IV (7,200 ft/s) I (8,300 ft/s)	III	IV
Javelin Flight	Arcocel-430B	Graphite Composite	5	4	V	IV (7,200 ft/s) I (8,300 ft/s)	V[a]	V
Javelin Flight	ADM-C26173	Graphite Composite	5	4	V	I (7,700 ft/s) I (8,300 ft/s)	V[a]	V
Javelin Flight	GJQ	Graphite Composite	5	4	N/A	IV (6,200 ft/s) I (6,800 ft/s)	V[a]	N/A
TOW-2B Flight	Class 1.1	Steel	6	5	I	I (8,300 ft/s)	I	I
TOW-2B Flight	Class 1.1, Standard RDX	Steel	6	5	III	I (6,000 ft/s)	N/A	III
TOW-2B Flight	Class 1.1, RS-RDX	Steel	6	5	V	IV (4,000 ft/s) I (6,000 ft/s)	N/A	III
TOW-2B Flight	Class 1.1, I-RDX	Steel	6	5	V	IV (4,000 ft/s) I (5,000 ft/s) I (6,000 ft/s)	N/A	N/A
EFOG-M	Class 1.3, Unfilled	Roll-Bonded Steel	6.5	6	N/A	I (6,000 ft/s)	I[b]	N/A
HELLFIRE M120E5	Class 1.1	Aluminum	7	14	V	I (8,300 ft/s)	I	V
IM HELLFIRE	Class 1.1	Graphite Composite	7	14	VI	I (6,200 ft/s)	N/A	V
IM HELLFIRE	Class 1.1	Steel Strip Laminate	7	14	VI	I (6,200 ft/s)	N/A	V
IM HELLFIRE	GIZ	Aluminum	7	14	VI	IV (6,000 ft/s) I (8,300 ft/s)	N/A	N/A
IM HELLFIRE	GGS-1, CP/AN	Graphite Composite	7	14	VI	IV (8,300 ft/s)	V[c]	V
IM HELLFIRE	GGY-1, CP/AN	Graphite Composite	7	14	VI	IV (8,300 ft/s)	IV[c]	V
IM HELLFIRE	Class 1.3, EMCDB	Graphite Composite	7	14	VI	V (6,200 ft/s)	N/A	V
IM HELLFIRE	Class 1.3, EMCDB	Steel Strip Laminate	7	14	V	V (6,200 ft/s)	N/A	V
IM HELLFIRE	NWC-472	Graphite Composite	7	14	N/A	IV (6,000 ft/s) I (8,300 ft/s)	N/A	N/A
		Aluminum			N/A	I (8,300 ft/s)	IV	

Table 4-31. Summary of Available IM Test Data Provided in This Report (continued)

Motor	Propellant Designation	Case Material	Dia.	Length	BI	FI (Velocity)	SCO	FCO
IM HELLFIRE	AFD-38778 (Unfilled)	Graphite Composite	7	14	N/A	V (8,300 ft/s)	N/A	N/A
IM HELLFIRE	RASP-9 (Unfilled)	Graphite Composite	7	14	N/A	V (8,300 ft/s)	N/A	N/A
JCM	GIR	Graphite Composite	7	21	VI	VI (6,000 ft/s) I (6,900 ft/s)	V[c]	N/A
JCM	GIW	Graphite Composite	7	21	VI	VI (8,300 ft/s)	N/A	N/A
JCM	GIZ	Graphite Composite	7	21	VI	VI (6,000 ft/s) VI (8,300 ft/s)	N/A	N/A
IM AGMS (Empty Igniter)	GIZ	Graphite Composite	7	21	VI	IV (8,300 ft/s)	V[c] V[c,d]	V
IM AGMS (Live Igniter)	GIZ	Graphite Composite	7	21	N/A	IV (8,300 ft/s)	IV[c–e] IV[c–f]	N/A

[a] Case venting device used.
[b] Tested at 45 °C/hr.
[c] Case venting device used.
[d] In shipping container.
[e] Aft missile CAS installed.
[f] All-up round with warhead simulator.

Class 1.1 propellant in 6-inch-diameter steel cases showed poor sensitivity to all tests in Table 4-31. Confinement and intrinsic propellant sensitivity (high-card gap value) contributed to those results. Interestingly, improvements in BI and FI were observed simply by replacing standard nitramine (RDX) with less-sensitive nitramines (both RS-RDX and I-RDX), indicating future potential for these new materials.

As shown by the amount of IM test data in Table 4-31, the 7-inch IM HELLFIRE, JCM, and IM AGMS motors received the most attention, with good prospects for achieving IM compliance and eventual qualification and deployment. In general, Class 1.1 propellant performed well under BI and FCO tests, regardless of case material. Although limited data was available, SCO test results depended on case material, with graphite composite cases performing better, especially when venting devices were employed to provide pressure relief prior to igniting the thermally damaged propellant. Furthermore, limited SCO tests with missile components and shipping containers indicated that insensitive motors can potentially produce hazardous fragments, leading to slightly more violent responses compared to bare motors.

Significant improvements were realized in this category of motors for response to FI, primarily by replacing or eliminating sensitive nitramines or other sensitive solids in the MS propellant while using composite cases. In fact, some examples of mild burning and no reactions have been observed at the extreme fragment velocity of 8,300 ft/s. However, confinement from missile components and shipping containers altered this insensitivity.

4.7 NEWER EFFORTS TO REDUCE MINIMUM SIGNATURE PROPELLANT SENSITIVITY

4.7.1 Nano-nitramines

As previously described, considerable work has been performed over the past 30+ years on reduced sensitivity minimum signature propellants for achieving IM characteristics in tactical motor applications. In many cases, mild responses to BI, FCO, SCO, SD, and low-velocity FI have been reported using a systems approach. However, in most approaches, eliminating violent reactions to high-velocity FI, as well as the violent SJC impact test, remained difficult. Success in reducing the shock sensitivity of minimum signature propellants was realized, in part, from reducing the particle size of sensitive materials such as nitramines like RDX, HMX, and CL-20 to 1–5 µm. Essel planned to continue with this approach by evaluating nanometer nitramines in propellant compositions [62, 63]. These materials can be prepared in the laboratory by two processes: (1) a bead-milling/spray-drying process developed by Patel et al. [64] at the U.S. Army Research Development and Engineering Center (ARDEC) and (2) a harvesting process developed at the U.S. Naval Air Weapons Center (NAWC). Essel's work is based on the relationship between nitramine particle size and reduced shock sensitivity as well as Victor's relationship between FI velocity and shock initiation pressure [65, 66]. This latter relationship is described by the equation in Figure 4-32, where V_e is the fragment velocity and P_e is the shock initiation pressure (shock sensitivity) of the energetic sample. As the shock initiation pressure becomes higher (lower sensitivity), the fragment velocity required for initiation becomes higher. (Note: for the equation in Figure 4-32, ρ_i is the density of the projectile, μ_{si} is the shock velocity of the unshocked material, and μ_{pe} is the particle velocity of the unshocked material.)

$$V_e = \mu_{pe} + \frac{P_e}{\rho_i \mu_{si}} .$$

Figure 4-32. Relationship Between Shock Sensitivity and FI Velocity [64, 66].

In the bead-milling process shown in Figure 4-33, a suspension of the unground energetic material (in an inert liquid) is agitated by rotating disks in the presence of a hard, milling media (beads). The process is monitored for particle size reduction until the desired product is achieved. The suspension is then directed through a filter to remove the milling media. The next step in the process involves simultaneous spray-drying the suspension and coating the submicron particles with inert polymers. An example of nano-CL-20 particles is shown in Figure 4-34.

The harvesting process involved three steps to yield nano-nitramines without further milling, as shown in Figure 4-35. A suspension of micron-sized nitramine is first treated with a polymer (which eventually becomes a coating) and then sonicated to "float" nano-particles to the surface of the suspension. After sonication, the suspension is processed through a centrifuge to separate

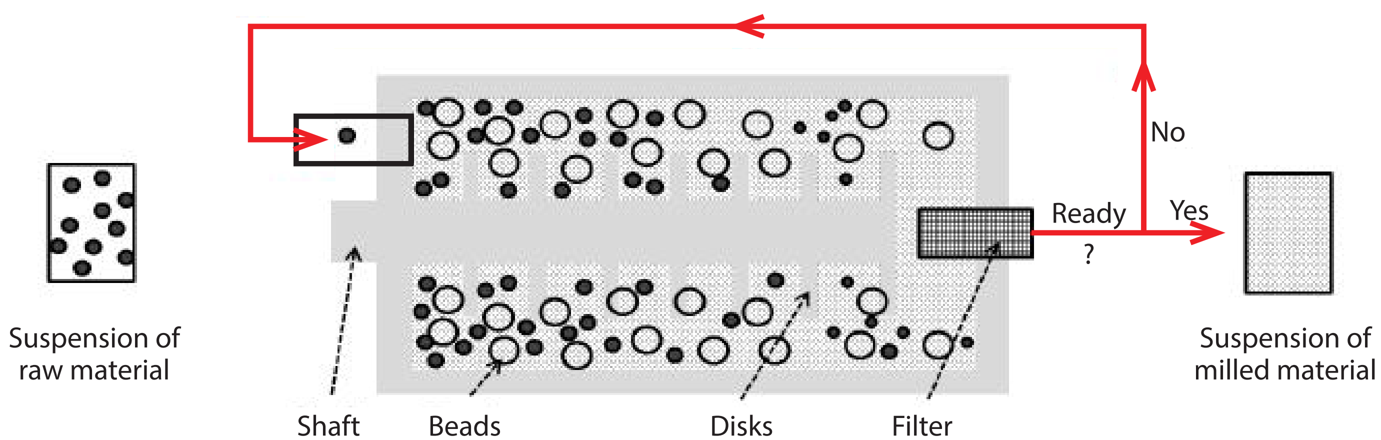

Figure 4-33. ARDEC Bead-Milling Process [62, 63].

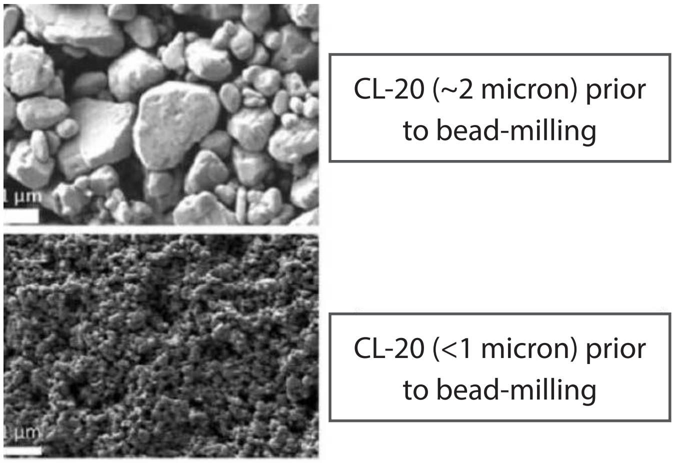

Figure 4-34. CL-20 Particles Prior to and After Bead Milling [62, 63].

nano-particles, which are easily decanted from the larger, suspended particles. This process can produce hundreds of grams of nano-particles in the laboratory. A pilot facility is in place at NAWC. However, since it does not involve further reduction in the size of the particles but rather extraction of available nano particles, the process is highly dependent on the nature of starting micron-nitramine. A significant fraction of nano-particles must be present in the micron-sized nitramine to allow this process to be viable.

Studies on materials from both processes have involved nano-particle solubility in binder materials, growth over time, evaluation of various inert polymer coatings for minimizing agglomeration, particle morphology changes, process scale-up capability, and initial propellant formulation work. In general, the studies have shown minimal particle size growth and agglomeration once the particles are coated. The four developmental propellants shown in Table 4-32 are planned for work with nano-nitramines under this study, which all give a volumetric impulse value of 15.3 lb_f-sin^3. Card gap values for these baseline propellants with high performance were not reported. Some difficulties have been experienced in processing these propellants with such high levels of nano-particles. Initial propellant processing needed to involve acoustic mixing due to very high viscosities and difficulty wetting the particles, while completing the mixing process could be accomplished in a conventional vertical mixer. Furthermore, inadequate cure was experienced, possibly due to the presence of water in the polymer coatings. Following successful processing, plans to cast and test card gap samples of each propellant are in place, along with samples for BVR testing.

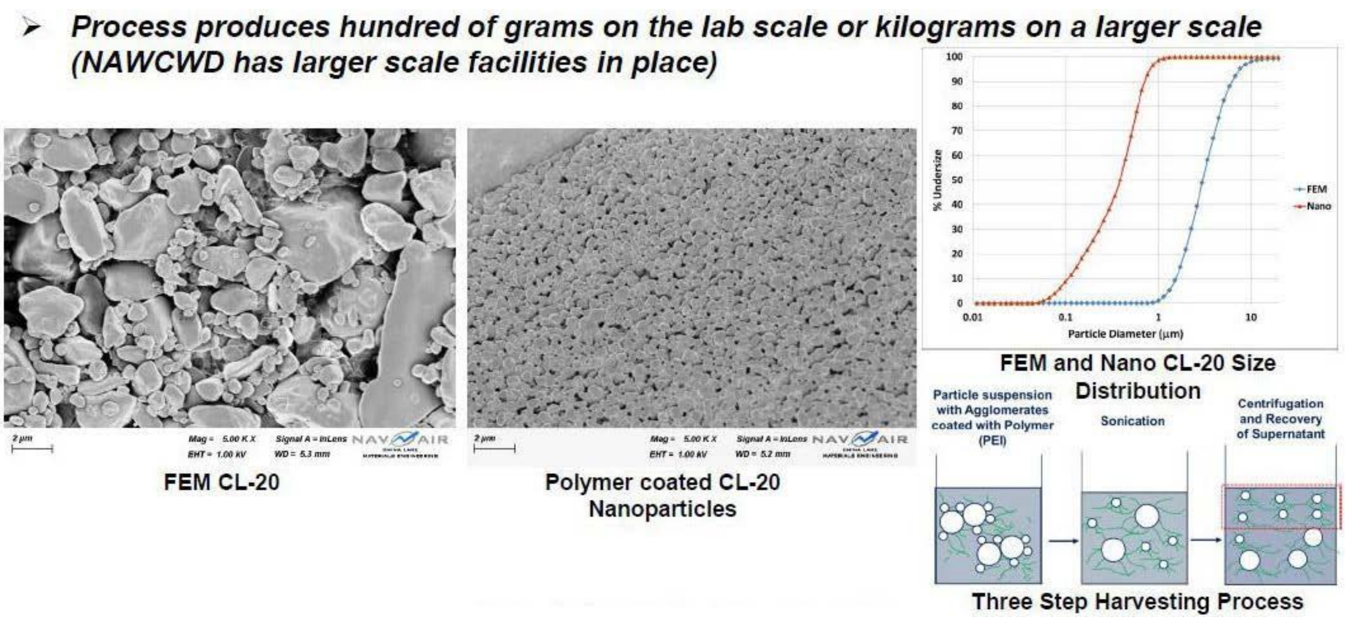

Figure 4-35. NAWC Harvesting Process for Nano-Nitramines [62, 63].

Table 4-32. Developmental Propellants for Evaluation of Nano-Nitramines [62, 63]

Ingredient	A-XLDB 1	A-XLDB 2	C-XLDB 1	C-XLDB 2
Source	Army	Army	Navy	Navy
Propellant Type	Castable Double-Base	Castable Double-Base	Castable Double-Base	Cast-Cure
Solid Filler Type	Nano-HMX	Nano-RDX	Fox-7/Nano-CL-20	FOX-7/Nano-CL-20
Solid Filler %	46	55	17/31	34/34
Polymer	PNC	PNC	PNC	Polyester
Plasticizer Type	Nitrate Ester	Nitrate Ester	Nitrate Ester	Nitrate Ester

4.7.2 InFuse NC

A novel material considered for castable double-base minimum signature propellants is a variation of nitrocellulose discovered by Orbital/ATK at the New River Energetics facility [67]. The material, labeled as InFuse NC, is the product from nitration of microcrystalline cellulose. This cellulose is used in the food and cosmetics industry and results from chemical breakdown of the amorphous structure of cellulose, leaving the crystalline segments [68]. InFuse NC is being considered as a replacement for PNC and standard NC in castable double-base formulations under development by Schiren and Drake [69]. The work is developing formulations with selected nitrate ester plasticizers that can be processed in conventional vertical mixers and can achieve a volumetric impulse goal of >15 lb_f-s/in^3. So far, work has shown that unlike standard NC, this new material is easily solvated in conventional energetic nitrate ester plasticizers and may be capable of moderately high content in a castable formulation. If so, opportunities for new castable propellants with tailorable ballistic and mechanical properties may be realized.

05 Conclusions

Since the development of cast-cure minimum signature propellants in the 1970s, researchers have investigated the shock sensitivity characteristics of these compositions. Correlations between propellant energy (impulse) and shock (card gap) sensitivity have been substantiated over time and used to guide new approaches for achieving high performance while reducing shock sensitivity. The need for IM throughout the DoD armed services, especially in minimum signature tactical rocket motors, has generated considerable interest over the past 30 years for this purpose. In general, newer approaches have sought to find ways to alter the established energy-sensitivity relationships by modifying existing ingredients, using less sensitive ingredients, and evaluating advanced insensitive materials. Existing materials with fine particle sizes have been, and continue to be, evaluated. Insensitive oxidizers, especially AN, have been used and tested extensively. New materials such as FOX-7, which have shown low-impact sensitivity, have been evaluated. Using materials common to less-sensitive extruded double base propellants to create new castable double-base compositions has also been considered. However, one single approach for generating new minimum signature propellants has not afforded solutions to all current IM issues or satisfied requirements for all future IM tactical rocket motors.

Newer propellants based on AN have shown promise for reducing impact and thermal sensitivities while meeting performance, chemical, and physical requirements for advanced IM rocket motors. They have not solved the more stringent high-velocity FI and SCJ IM tests. Castable double-base propellants have shown success in passing the high-velocity FI test while giving acceptable aging and performance but have so far suffered from poor physical properties at cold temperatures. These general conclusions can be made regarding MS propellant advancements.

- MS motors using Class 1.1 propellants tend to be sensitive to many IM tests, especially under confinement.
- MS motors up to 7 inches in diameter, using newly developed Class 1.3 reduced sensitivity propellants, tend to provide mild response to BI and FCO tests.
- Using venting devices provides reduced sensitivity to SCO in MS motors using Class 1.1 and newer Class 1.3 propellants.
- Obtaining compliance to the FI test is especially difficult, while results from low-velocity tests show reduced sensitivity for newer Class 1.3 propellants, compared to Class 1.1 compositions.
- Castable double-base propellants successfully pass high-velocity FI tests in some motor configurations, but further development needs to be conducted to afford practical compositions suitable for MS motor applications.

Using composite cases in advanced tactical rocket motors allowing high-pressure motor operation has compensated for some deficiencies, such as performance, while enhancing IM characteristics. These case designs have become an essential component in newer tactical MS motors. Other mechanical features, such as venting devices, have continued to show promise for surviving thermal IM tests. Combined, these successes have shown that a systems approach has been the best method for achieving IM characteristics for future tactical rocket motors. With a systems approach based on advanced minimum signature propellants and rocket motor components, future tactical missiles for JCM, IM Javelin, IM TOW, IM HELLFIRE, and IM AGMS are destined to become realities.

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APPENDIX

DESCRIPTION OF U.S. NAVAL ORDNANCE LABORATORY (NOL) CARD GAP TEST

The NOL card gap test for evaluating shock sensitivity of energetic material has been described in an early report by Price et al. The report provided the test method arrangement and calibration data for tetryl and pentolite boosters, as shown in Figures A-1 and A-2 and Table A-1. The calibration curves in Figure A-2 indicate the historic demarcation between Class 1.3 and Class 1.1 sensitivity at 70 cards and ~70 kBar pressure. This classic definition and test, which is conveniently sized for small-scale development work, is used throughout this report in lieu of more modern and less-convenient, larger scale tests. This classic NOL card gap test continues to be used today by many researchers in minimum signature propellants, especially for comparing historic data as described herein and for developing new formulations.

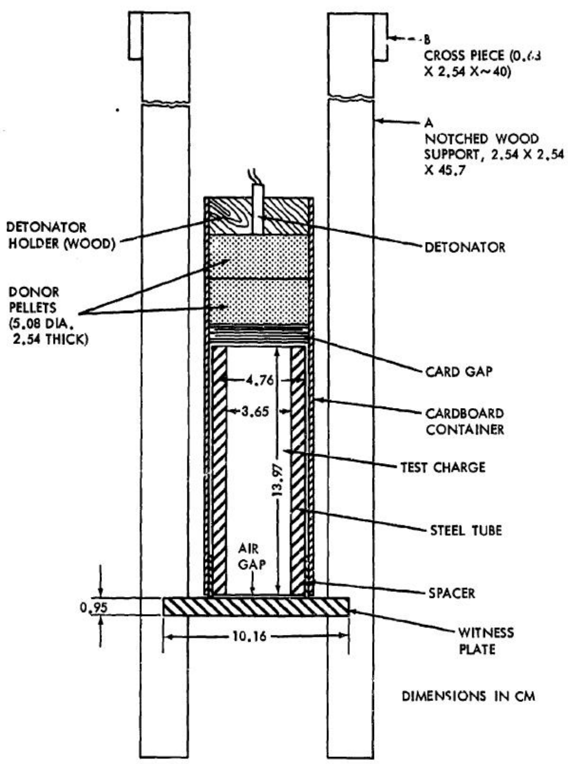

Figure A-1. Cross Section of NOL Card Gap Test Arrangement (All Dimensions Are in Millimeters).[1]

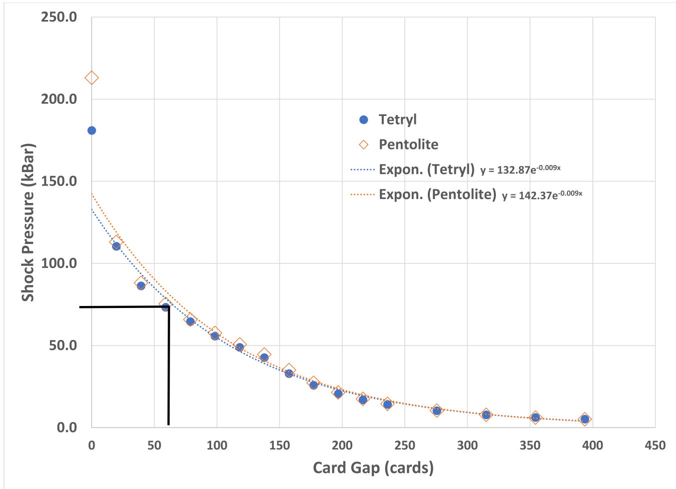

Figure A-2. Calibration Curves for Tetryl and Pentolite Boosters Used in the NOL Card Gap Test (Location of 70 Cards and ~70 kBar Pressure Indicated).[1]

Table A-1. Cards vs. Shock Pressure for Tetryl and Pentolite Boosters[1]

Cards	P (kBar)	
	Tetryl	Pentolite
0	181.0	213.1
20	110.4	113.0
39	86.3	88.2
59	73.3	75.4
79	64.6	65.8
98	55.7	57.7
118	48.9	50.7
138	42.6	44.6
157	32.9	35.1
177	25.8	27.3
197	20.6	21.5
217	16.9	17.5
236	14.1	14.5
276	10.3	10.4
315	7.8	7.8
354	6.2	6.1
394	5.2	5.1

[1] Price, D., A. R. Clairmont, and J. O. Erkman. "The NOL Large Scale Gap Test. III. Compilation of Unclassified Data and Supplementary Information for Interpretation of Results." NOLTR 74-40, 8 March 1974.

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ADVANCEMENTS IN MINIMUM SIGNATURE (MS) PROPELLANTS FOR INSENSITIVE MUNITIONS (IM) ROCKET MOTORS

By Dr. Albert DeFusco and Dr. Jamie Neidert

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