Development and Performance of High Energy High Performance Co-Layered ETPE Gun Propellant for Future Large Caliber System

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ABSTRACT

The objective of this program is to develop a high energy, high density energetic thermoplastic elastomer (ETPE) propellant that can be processed without solvents. Gun propellants were prepared using ETPE binders that can be processed without the use of solvents. The hazard characteristics of the ETPE-based gun propellants were tested, and samples of propellant and the ETPE based molding powder were delivered to ARDEC for processing.

Technical work on the program began in June 1998, with the preparation of oxetane monomers, and the subsequent synthesis of ETPE polymers by cationic polymerization. Polymer synthesis was conducted on a laboratory-scale initially. Poly-BAMO/NMMO (BN7) was prepared as an ETPE for the first time, and its properties appear to be similar to those of poly-BAMO/AMMO. The BN7 was prepared by the systematic addition of BAMO and NMMO to give a tri- block copolymer of ABA architecture. Several gun propellant formulations consisting of the BN7 were incorporated with RDX and nitroguanidine plasticized with BDNPA/F. The formulations consist of the slow burning and the fast burning with a burn rate differential of 1.72:1. The formulations were developed as a spiral technology for Future Combat System applications. A co-layered radial strip configuration was manufactured at ARDEC for 60 mm ETC test fixture gun firings to be conducted by United Defense, Limited Partnership (UDLP). This paper is limited to a characterization of the various properties of the propellants.

INTRODUCTION AND APPROACH

The objective of this program was to develop a gun propellant[1, 2, 5] (GEN2) with an impetus greater than or equal to 1250 J/g for a “fast” burning formulation and 1075 J/g for a “slow” burning formulation, a flame temperature less than or equal to 3450K, vulnerability and sensitivity characteristics the same as or better than those for JA2 and acceptable mechanical properties from -32^0 C to 63^0 C. A layered ETPE propellant consisting of an inner fast burning propellant and an outer slower burning propellant was developed to meet the above requirements.

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Slow Burning Formulation Candidates

Three slow burning propellant candidates were selected for processing based on the results of thermochemical calculations, formulation development work and characterization. After reviewing the results of characterization test and thermochemical data, formulation downselection was narrowed down to two formulations. These were lots PAP-8287 and PAP- 8288. The thermochemical properties are listed in Table 1 below. The slowest burn rate and the highest burn rate differential obtainable lead to the final downselection of PAP-8288. PAP-8288 was selected for characterization, scaled-up manufacturing and gun firing in a radial strip configuration in 60 mm ETC gun test fixture

The same particle size distribution of RDX was used in the three propellants except for PAP-8287 where a 4 micron size RDX was used as a blend.

Table 1: JA2, Fast and Slow Burning Formulations

Ingredients	**JA2**	**Fast Burning PAP-8194J**	**Fast Burning PAP-8194AA**	**Fast Burning PAP-8194BB**	**Fast Burning PAP-8289**	**Slow Burning PAP-8233D**	**Slow Burning PAP-8287**	**Slow Burning PAP-8288**
Impetus , J/g	1164	1276.17	1276.17	1276.17	1276.17	1050.92	1050.92	1022.45
Flame Temp, K	3475	3252	3252	3252	3252	2543	2543	2473
Density, g/cc	1.580	1.6675	1.6675	1.6675	1.6675	1.6159	1.5945	1.5923

The slow burning propellant PAP-8288, consisting of RDX, NQ and BAMO-NMMO, has a remarkably low flame temperature and a slightly lower impetus than PAP-8287. These thermochemical properties based on previous experience with co-layered ETPE formulations were signs used in predicting an acceptable burn rate differential between the slow and the fast burning formulations.

The slow burning formulations PAP-8287 and PAP-8288 were processed through ARDEC's horizontal sigma blade mixer and then roll milled to the desired dimensions. The synthesis of the BAMO NMMO ETPE and the preparation of the initial propellant molding powder were made at GENCORP AEROJET's Sacramento facility. Samples of each propellant were characterized at ARDEC, and some small quantities were shipped to ARL for additional testing and evaluation.

A summary of the burning rate data for these propellants as well as fast burning candidates is found in Table 2. As shown by these data, the three slow burning propellants had burning rates near 4.6 and 5.1 inches per second at 40,000 psi. Testing was conducted at ambient temperature and the burning rates of the three propellants followed the expected trend of slower burning rates. These slow burning rates were well within the prime target range for outer layer propellants.

Table 2: Slow and Fast Burning Formulation Burn Rates

Ingredients	JA2	Fast Burning 8194J	Fast Burning 8194AA	Fast Burning 8194BB	Fast Burning 8289	Slow Burning 8233D	Slow Burning 8287	Slow Burning 8288 (
Burn rate@40ksi		7.226		7.863	8.006	5.021	5.069	4.571
Coefficient		0.240736E-03		0.569389E-03	0.373879E-02	0.543665E-03	0.617472E-03	0.552724E-03
Exponent		.972903		.899642	.723735	0.861661	.850561	.851256

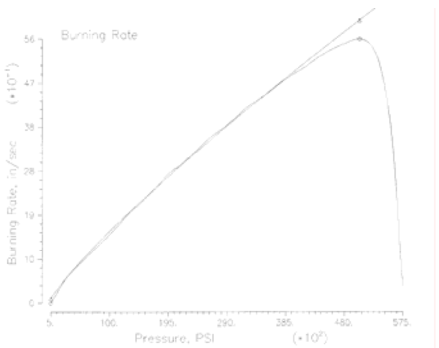


Figure 1. Burning rate of PAP-8288 propellant at cold temperature.

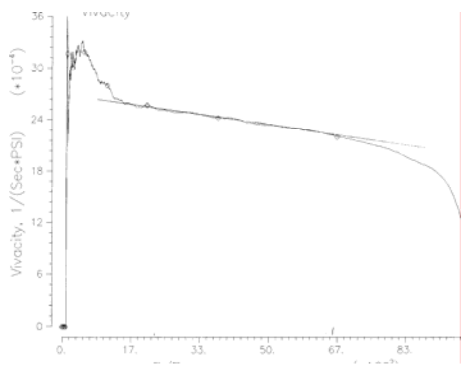


Figure 2: Vivacity curve for PAP-8288 propellant at cold temperature.

Burning rates and vivacity plots at cold for the downselected formulation PAP-8288 propellant are shown in Figures 1 and 2, respectively. For PAP-8288 propellant, the general shape of the burning rate is linear and the vivacity plots follow the expected form function.

Additional closed bomb testing was conducted on the slow burning formulation PAP-8288 that was re-processed. PAP-8288R1 represents a propellant lot that was re-processed for the first time. PAP-8288R4 represents a propellant that was re-processed for the fourth time. Finally, PAP-8288R5 represents a propelllant lot that was re-processed for the fifth time. As shown in Figure 3, the burn rates for Lot 8288R1, R4 and R5 samples did not show any change in the burn rates. The burn rates were the highest at hot and lowest at cold temperature. This behavior shows that the propellant burn rates were not affected by the re-processing of the propellants.

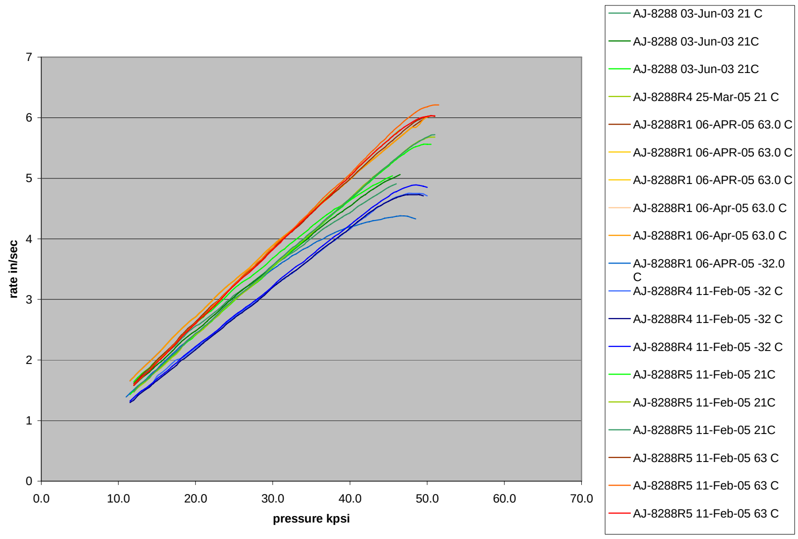


Figure 3: Burn rates for Lot 8288 at 63^0 C, 21 ^{0} C and -32 ^{0} C originally processed (PAP-8288), re-processed PAP-8288R1 and PAP-8288R5.

Mechanical property testing was conducted by Dr. Robert Lieb and Michael Leadore (ARL) on these slow burning formulation candidates[8]. The results of the compression testing are shown in Table 3 and are plotted on Figures 4, 5 and 6.

Table 3[8]: Mechanical Properties of lots PAP-8287, PAP-8288 and JA2 propellants at 63^0 C, 21^0 C, and -32 ^{0}C.

Lot #	Stress@ Failure (MPa)	Strain @Failure (%)	Modulus (GPa)	Failure Modulus (GPa)	IED (MPa)	FAV
63 ^{0} C						
JA2 HCL93J014001	**7.02**	**6.57**	**0.244**	**0.0290**	**2.37**	**0B**
PAP-8287	**7.65**	**7.65**	**0.110**	**0.013**	**1.81**	**1AB**
PAP-8288	**8.80**	**7.33**	**0.192**	**0.015**	**2.31**	**1AB**
21 ^{0} C						
JA2 HCL93J014001	**17.22**	**6.37**	**0.281**	**0.005**	**3.70**	**0B**
PAP-8287	**17.68**	**8.20**	**0.270**	**0.036**	**4.52**	**1AB**
PAP-8288	**18.65**	**8.57**	**0.302**	**0.037**	**4.68**	**1AB**
-32 ^{0} C						
JA2 HCL93J014001	**54.8**	**7.67**	**1.01**	**0.067**	**13.82**	**5AS**
PAP-8287	**88.64**	**7.80**	**1.56**	**-0.210**	**17.02**	**2AS**
PAP-8288	**76.67**	**7.89**	**1.63**	**-0.550**	**10.52**	**3AS**

Note: The Failure Modulus is the slope of the curve after failure. Generally, the lower the value the worse the material (negative value indicates the material unable to sustain load).A positive value indicates a positive failure slope (material better able to support load).The IED (energy density) value reported is the amount of energy absorbed at 25% strain, this includes a portion of the area located under the stress/strain curve. The tested specimens were assigned a Fracture Assessment Value (FAV). The values will range from 0 (no fractures) through 9 (severe fracturing). The type of fracture were characterized using the following: A = axial fracture, S = shear fracture, B = barreling,R = radial splitting. (i.e., 5AS would indicate the tested specimens suffered moderate amounts of axial and shear fracture).

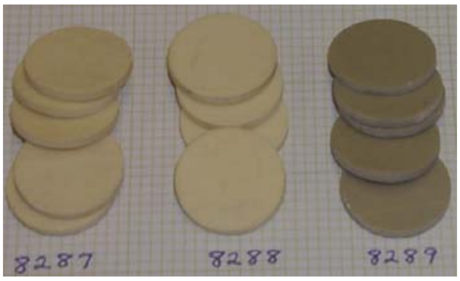


Figure 4a: Samples at room temperature prior to mechanical property testing.

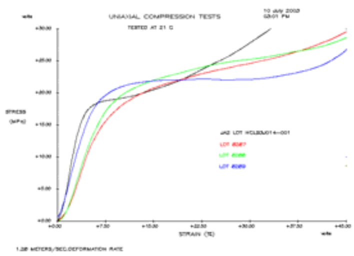


Figure 4b. Stress vs. Strain of JA2,
Lots PAP-8287, 8288, and 8289 at 21^0 C.

Figure 4c: Specimen from
Propellant Lots PAP-8287,
8288 and 8289 that were tested at 21^0C.

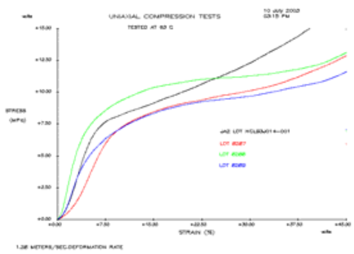


Figure 5a: Stress vs. Strain of JA2,
Lots PAP-8287, 8288, and 8289 at 63^0 C.

Figure 5b: Specimens from
Propellant Lots PAP- 8287, 8288
and 8289 that were tested at 63^0 C.

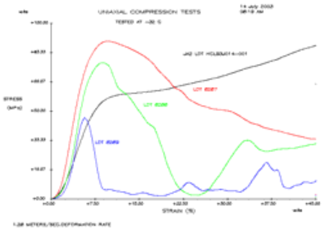


Figure 6a: Stress vs. Strain of JA2, Lots PAP-8287, and 8288 at -32 ^{0} C.

Figure 6b: Specimens from Propellant Lots PAP-8287, and 8288 Tested at -32 ^{0} C**.**

The cold temperature mechanical properties shown in Figure 6a shows that PAP-8288 have a similar structural strength with PAP-8287. However, the burn rate of PAP-8288 is much slower than PAP-8287 as shown in Table 2. The slower burn rate of PAP-8288 was much more preferrable when determining a higher burn rate differential with the fast burning formulation candidate. As a result, propellant PAP- 8288 was downselected as the slow burning propellant for scale up. During the scale up, Aerojet was tasked to make the molding powder[6]. The molding powder consisted of coating the RDX with the BAMO NMMO binder using a water slurry process. ARDEC was tasked to complete the processing of the propellant which include the mixing, ram extrusion, rolling, and laminating. The BDNPA/F plasticizer was added during the mixing of the molding powder[7]. The propellant was re-processed five times. The first and second reprocessing consisted of adding propellant scrap with virgin propellant during the mixing cycle. The fifth rework consisted of just re-mixing the remaining scrap to complete the required number of radial strips. The mechanical properties test results conducted at 63^{0} C, 21^{0} C and -32^{0}C of PAP-8288 are shown in Figure 4,5 and 6.

Figure 7: Remains of JA2 Specimens Tested at 21 ^{0}C, 63 ^{0}C, and -32 ^{0}C

Mechanical Testing Results:

The three slow burning propellants and a lot of JA2 high-energy gun propellant (Figure 7) were tested for mechanical response evaluation at ambient pressure while temperature conditioned at 21 C, 63 C, and -32 C. The materials were tested in uniaxial compression to ~50 percent end strain using a deformation rate of 1.28 meters per second.

At 21 C, the two slow burning propellants and JA2 lots showed good response to uniaxial compression. The positive failure modulus values achieved by ARDEC lots PAP-8287, PAP-8288, and the JA2 lots at 21C indicate these materials ability to sustain load. Also note the stress vs. strain plot (Figure4b) shows the ARDEC and JA2 lots work hardening beyond 45 percent strain. The tested specimens (Figure 4c) for ARDEC lots PAP-8287, and PAP-8288 at 21 C suffered only permanent deformation with very minimal fracturing, while the JA2 lot showed permanent deformation and barreling (Figure 7).

At 63 C, the three slow burning propellants and JA2 lots were quite good. The Young's compressive modulus values at 63 C indicated some "material-softening" when comparing the 21 C values. This was a result of the higher testing temperature and was expected. The stress/strain plot (Figure 5a) shows all the lots ability to sustain load. The tested specimens (Figure 5b) for the ARDEC lots showed permanent deformation and minimal fracturing. The JA2 lot showed some barreling and permanent deformation at 63 C (Figure 7).

At -32 C, the JA2 lot showed the superior mechanical properties followed by lots PAP-8287 and then PAP-8288. The tested specimens from lot 8287 (Figure 6a) suffered only minimal amounts of axial and shear fracture and the core area of the tested specimens remained intact. Lot PAP- 8288 tested specimens showed minimal to moderate amounts of axial and shear fracture damage. Note the stress/strain plot at -32 C (Figure 6b) clearly shows the JA2 lot as the superior performer followed by lot PAP-8287. Any propellant with a failure modulus value of less than –1.0 GPa is showing significant fracture failure. JA2 showed moderate amounts of axial and shear fracture (Figure 7).

In summary, ARDEC lots PAP-8287, PAP-8288, and JA2 mechanical response at 21 C and 63 C were quite good and also very similar. At -32 C however; the JA2 lot was clearly the superior material followed by ARDEC lot PAP- 8287.

PAP-8288 was selected as the slow burning candidate because of its low pressure exponent and mechanical properties, especially at hot and cold temperatures.

Fast Burning Formulation Candidates

As shown in Table 1, the fast burning propellant candidates considered were PAP-8194J, PAP-8194AA, PAP-8194BB and PAP-8289. These four fast burning formulations contains BAMO-NMMO, plasticizer and RDX. In order to achieve a high burn rate differential between the slow and the fast formulation candidates, the particle size of the RDX were varied. PAP-8194J has 4 microns RDX. PAP-8194AA has 4 microns and 10 microns RDX. PAP-8194BB has 4 microns and 10 microns RDX. Finally, PAP-8289 has 10 microns RDX.

Thermochemical calculation results for the performance parameters for all fast burning propellants are shown in Table 1. As shown by these data, all of these candidates have moderate flame temperature, higher impetus and higher density than JA2.

These fast burning GEN2 candidates were processed at ARDEC using a horizontal sigma blade mixer, ram extrusion press and then roll milled to the desired dimensions[7]. Samples of each propellant were characterized at ARDEC and ARL for additional testing and evaluation. A summary of the burning rate data for these propellants is found in Table 2. As shown by these data both PAP-8194BB and PAP- 8289 propellants had burning rates near 7.45 and 8.0 inches per second at 40,000 psi., respectively. Closed bomb testing of PAP-8194BB showed that the burning rate did follow the expected trend. However, PAP-8289 which had 73 % of the 10 micron RDX, did not follow the expected trend, and this was due to the large 10 micron RDX and the low density of the propellant obtained when compared to the theoretical maximum density (TMD). The low density is an indication of the presence of voids in the propellant interior and exterior surface, resulting in an anomalous burning behavior. As a result, the propellant was reprocessed until the density was approximately 99% of the TMD. The burning rates of the reprocessed propellants are well within the prime target range for inner layer propellants which is approximately 8 inches per second at 40 kpsi, but it still showed signs of burning in depth, and so was not selected.

Burning rates and vivacity plots for PAP-8194BB propellants are shown in Figures 8a and 8b, respectively. The burning rate curves for both propellant samples show a significant linear range and both vivacity curves follow the expected form function.

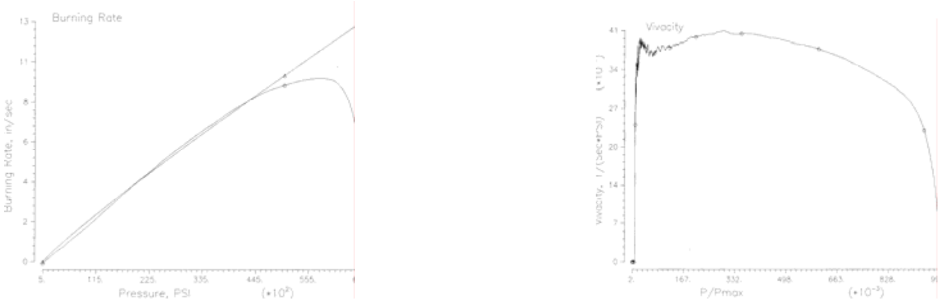


Figure 8: (a) Burn rate and (b) Vivacity curve for PAP-8194BB

Additional closed bomb testing was conducted by Dr. Barrie Homan (ARL) on the last re-processed fast burning propellant formulation, designated as PAP- 8194 R5. Results are shown in Figure 9a.

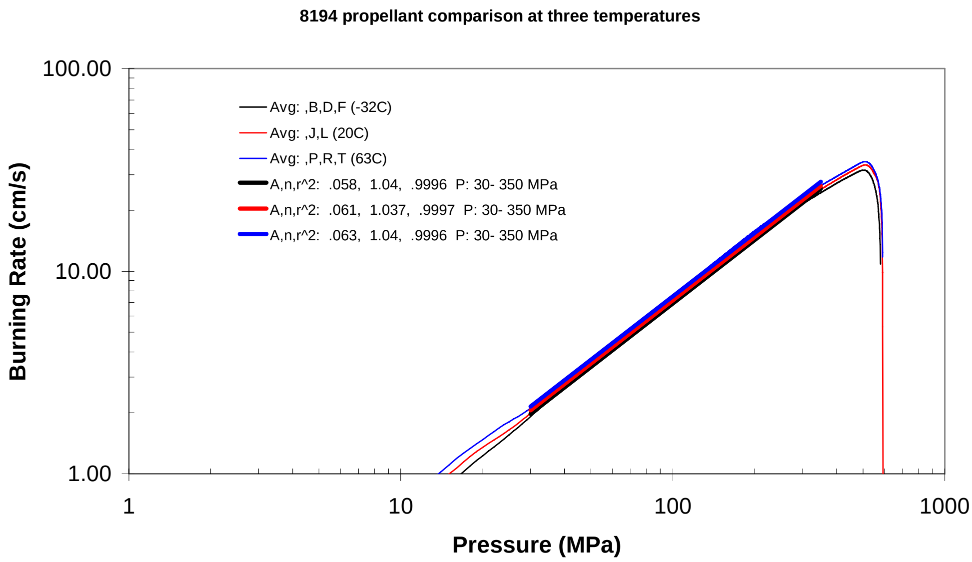


Figure 9a: Burn Rates for Lot 8194 R5 at 63^0 C, 21^0 C, and -32^0 C

As you can see, the propellant is still well behaved and the burn rates are highest at 63^{0}C and lowest at -32^{0}C. Figure 9b shows a plot summary of all the burn rates of all the fast burning formulations. Data is presented for the virgin propellant, first recycled (R1) and last recycled PAP-8194R5. As can be seen on the chart, all the burn rates shows the propellants are well behaved and follow the expected form function.

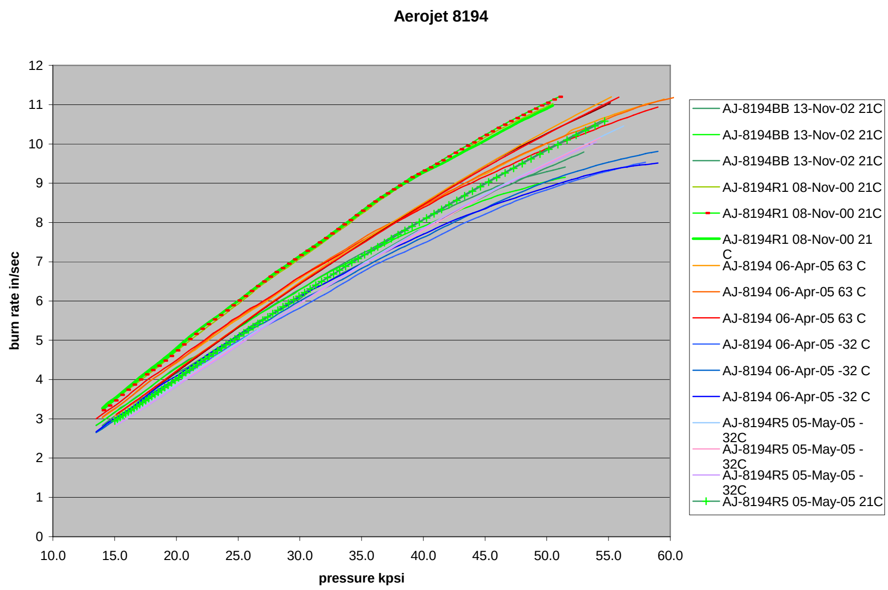


Figure 9b: Summary of Burn Rates for all the Fast Burning Propellants Processed (Lot 8288)

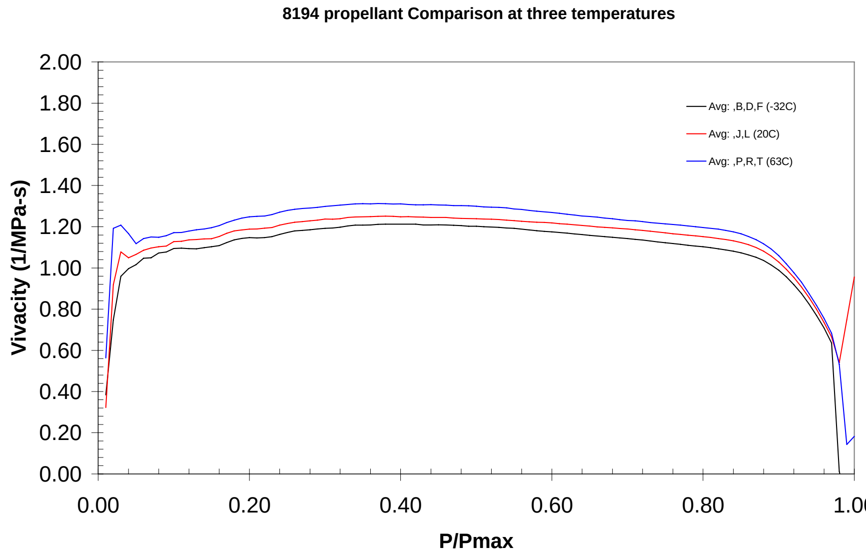


Figure 9c: Vivacity curves for Lot 8194 R5 at 63^0 C, 21^0 C, and -32^0 C

Figure 9b and 9c show the burn rates and vivacity curves are higher at hot, followed by ambient and then the lowest at cold temperatures.

Table 4: Summary of Burn Rates for Lot 8288R1/R5 and 8194R1/R5 and Burn Rate Differentials of Lot 8194 (Fast Burning) / Lot 8288 (Slow Burning)

LOT 8288R1	**63^0 C**	**21^0 C**	**-32^0 C**
Pressure Coefficient	0.478722E-03	0.552724E-03	0.873594E-03
Pressure Exponent	0.87300	0.851256	0.799747
20 kpsi, burn rate in/s	2.722	2.534	2.425
30 kpsi, burn rate in/s	3.8722	3.578	3.526
40 kpsi, burn rate in/s	4.985	4.571	4.19
Lot 8288R5			
Pressure Coefficient	.2069E-03	0.198347E-03	0.214117E-03
Pressure Exponent	0.953278	0.949800	0.932513
20 kpsi, burn rate in/s	2.6	2.413	2.195
30 kpsi, burn rate in/s	3.835	3.546	3.253
40 kpsi, burn rate in/s	5.046	4.661	4.238
Lot 8194R1			
Pressure Coefficient	0.7544E-03	0.374174E-03	0.723218E-03
Pressure Exponent	0.877512	0.954209	0.871697
20 kpsi, burn rate in/s	4.486	4.755	4.059
30 kpsi, burn rate in/s	6.403	7.001	5.780
40 kpsi, burn rate in/s	8.332	9.213	7.428
Lot 8194R5			
Pressure Coefficient	.6497E-03	0.518E-03	0.427E-03
Pressure Exponent	0.806	0.838	0.863
20 kpsi, burn rate in/s	4.082	3.973	3.83
30 kpsi, burn rate in/s	6.41	6.114	5.9
40 kpsi, burn rate in/s	8.44	8.051	7.81
Burn Rate Ratio			
8194R1/8288R1@40kpsi	**1.6931**	**2.0155**	**1.7727**
8194R5/8288R5@40kpsi	**1.6726**	**1.7273**	**1.8429**

Table 4 shows a tabulated summary of the burn rates for the slow burning formulation (Lot PAP-8288) and the fast burning formulation (Lot PAP-8194) plotted in Figures 1,2,3, and 9, respectively.

The burn rate differential for the fast and the slow burning formulations were calculated and the numbers are shown in Table 4. As you can see, the burn rate ratio was 1.6726 at 63^0 C, 1.7273 at at 21^0 C, and 1.8429 at -32^0 C. Although the initial goal for the burn rate ratio was 3, the values obtained were based on the optimized slow and fast burning formulations that can deliver the impetus required to meet the ballistics requirement of the 120mm FCS-system. Another decision factor that was considered in selecting the slow and the fast burning formulations was the processibility and mechanical properties of the propellant.

Mechanical property tests were conducted by Dr. Robert Lieb and Michael Leadore on lots PAP-8194BB and PAP-8289. These two fast burning formulations were selected for mechanical property testing because of the high burn rates obtained when compared with the other two fast formulation candidates listed in Table 2. The results of the compression testing were shown in Table 5. As shown, the slope of the failure modulus for PAP-8194BB was much smaller as compared to PAP-8289 at cold temperature. This value indicated that PAP-8194BB had a much better mechanical properties than PAP--8289. The stress versus strain diagrams at 63^0 C, 21^0 C, and -32 ^{0}C[10] for PAP-8194BB were plotted on Figures 10, 11, 12, and 13.

Table 5[10]: Tabulated Mechanical Properties of lots PAP-8194BB, PAP-8289 and JA2 propellants at 63^0 C, 21^0 C, and -32 ^{0}C.

Lot #	Stress@ Failure (MPa)	Strain @Failure (%)	Modulus (GPa)	Failure Modulus (GPa)	IED (MPa)	FAV
63 ^{0} C						
JA2 HCL93J014001	7.02	6.57	0.244	0.029	2.37	0B
PAP-8289	6.81	7.67	0.121	0.016	1.83	1AB
PAP-8194BB	7.74	11.05	0.094	0.0046	1.54	1AB
21 ^{0} C						
JA2 HCL93J014001	17.22	6.37	0.281	0.005	3.70	0B
PAP-8289	19.89	7.77	0.391	0.014	4.84	1AB
PAP-8194BB	17.60	13.32	0.251	0.0034	11.60	1AB
-32 ^{0} C						
JA2 HCL93J014001	54.08	7.67	1.01	0.067	13.82	5AS
PAP-8289	42.75	5.87	1.91	-1.76	2.80	8AS
PAP-8194BB	93.50	7.68	1.76	-0.250	16.80	5AS

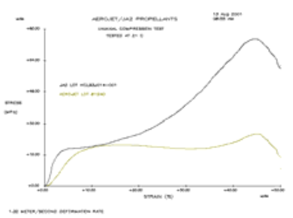


Figure 10: Stress vs. Strain of JA2 and PAP-8194BB at 21 C.

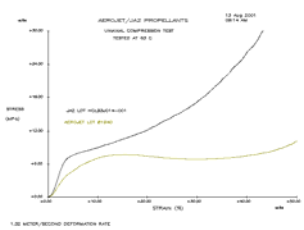


Figure 11: Stress vs. Strain of JA2 and PAP-8194BB at 63 C.

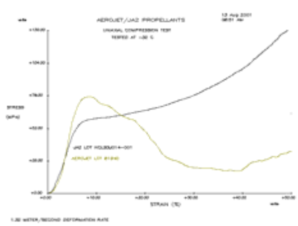


Figure 12: Stress vs. Strain of JA2 and PAP-8194BB at -32 C.

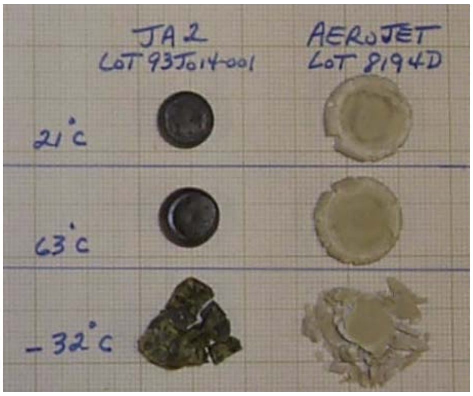


Figure 13: Remains of PAP-8194 and JA2 tested at 21C, 63C and -32C.

A lot of donwnselected PAP- 8194 and a production lot of JA2 were tested for mechanical response evaluation at ambient pressure while conditioned at 21 C, 63 C, and -32 C. The materials were tested in uniaxial compression to ~50 percent end strain using a deformation rate of 1.32 meters per second.

At 21 C, the downselected PAP-8194 lot and the JA2 lot all showed good response to uniaxial compression. The positive failure modulus values achieved indicated all of the lots abilities to sustain load beyond ~40 percent strain. Note the stress vs. strain plot (Fig.10) shows the JA2 lot work hardening beyond 40 percent strain. The tested specimens (Fig.16) suffered permanent deformation with very minimal fracturing.

At 63 C, again, the mechanical response of all the lots were quite good. The Young's modulus values showed some "softening" as a result of the higher testing temperature, this would be expected. The stress/strain plot (Fig.11) shows all the lots able at sustaining load. The tested specimens (Fig.13 again showed very minimal axial fracture and deformation.

At -32 C, the tested specimens (Fig.12) suffered moderate amounts of axial and shear fracture; however the core area of the tested specimens remained mostly whole. Note the stress/strain plot at -32 C (Fig.13) shows the JA2 lot able at sustaining load and work hardening up to 50% strain and thus, the only lot yielding a positive failure modulus value.

Overall, all the materials mechanical response at 21 C and 63 C were quite good. At -32 C, the JA2 lot was clearly the better material, followed by the PAP-8194BB. The propellant with lot number PAP-8194 was selected as the fast burning candidate because of the burning rate ratio (1.73:1) developed in combination with PAP-8288 and acceptable mechanical properties across the ballistic temperature range.

Co-layered propellant

Based on the test results discussed previously on the slow and the fast burning formulation candidates, PAP-8288 was selected as the slow burning formulation, and PAP-8194BB was selected as the fast burning formulation. PAP-8288 was selected because of its low pressure exponent and better mechanical properties, especially at hot and cold temperatures. The propellant PAP-8194 was selected as the fast burning candidate because of the burning rate ratio (1.73:1) developed in combination with PAP-8288 and acceptable mechanical properties across the ballistic temperature range. The downselected slow and fast burning formulations were laminated in a co-layered radial strip configuration shown in Figure 14. The fastcore geometry composed of the two outer layers consisting of the slow burning formulation, Lot 8288 and the inner layer consisting of the fast burning formulation, Lot 8194, Figures 14 (d, e) In order to achieve maximum performance, the thickness of the slow and the fast burning layer were calculated by Dr. James Luoma (BAE Systems) and Don Chiu (ARDEC). The ETC plasma igniter ("red picolo tube") is shown in Figure 14c.

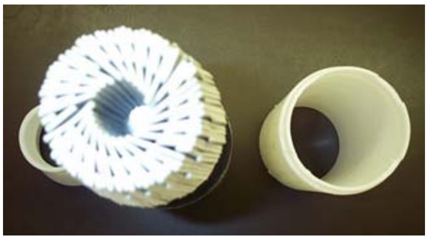
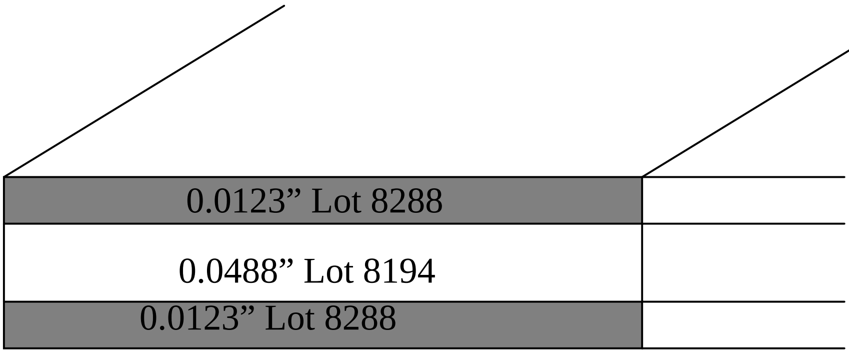
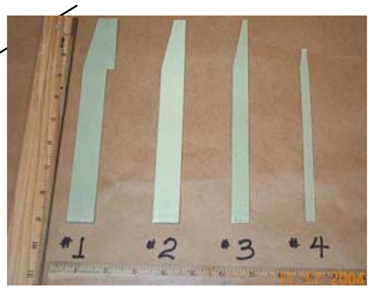


Figure 14: (a) Top View of Cartridge Assembly

(b) 60 mm ETC Cartridge Assembly

(c) Cartridge Assembly with Plasma Igniter





(e) Four Shapes of Radial Strips

Figure 15: (d) Co-layered configuration

Before the lamination process was initiated, the reprocessed slow layer and fast layer formulations were tested for mechanical properties in order to determine if reprocessing had deteriorated the mechanical properties and the burn rates of each formulations. The results of the uniaxial compression testing of the reprocessed propellants are shown in Table 6 and are plotted in Figures 16 to 20.

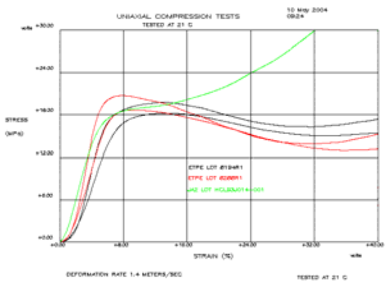


Figure 16. Stress vs. Strain of ETPE and JA2 Lots at 21º C.

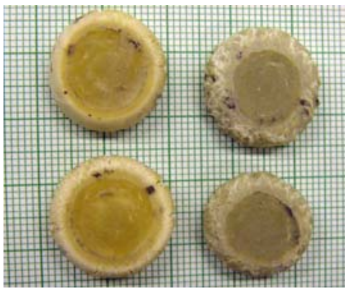


Figure 17. Specimens from Propellant Lots 8288R1 and 8194R1 Tested at 21º C.

Table 6[8]: Mechanical Properties of 8194, 8288, and JA2 Lots at 21º C.

Lot #	Stress@ Failure (MPa)	Strain@ Failure (%)	Modulus (GPa)	Failure Modulus (GPa)	IED (MPa)	FAV
@ 21º C						
Lot 8194R1	17.58	8.50	0.27	0.004	8.22	0B
Lot 8288R1	22.05	7.17	0.42	-0.027	5.18	1AB
JA2	18.12	7.58	0.78	0.055	4.70	0B
@ 63º C						
Lot 8194R1	4.55	5.87	0.14	0.006	2.44	1B
Lot 8288R1	5.20	7.90	0.10	0.004	1.14	1B
JA2	7.62	7.87	0.24	0.049	3.37	0B
@ -32º C						
Lot 8194R1	69.04	5.90	1.66	-0.25	24.52	4AS
Lot 8288R1	75.87	6.79	1.73	-0.53	23.08	5AS
JA2	58.08	9.37	1.49	0.067	13.22	5AS

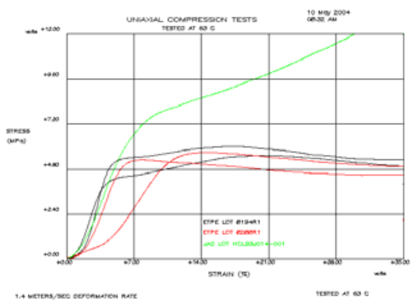


Figure 18. Stress vs. Strain of ETPE and JA2 Lots at 63º C.

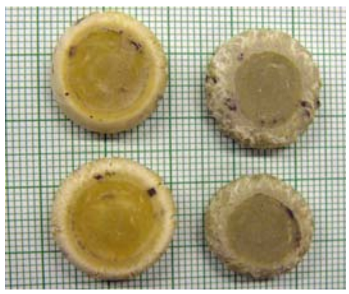


Figure 19. ETPE Lots 8288R1 and 8194R1 Specimens Tested at 63º C

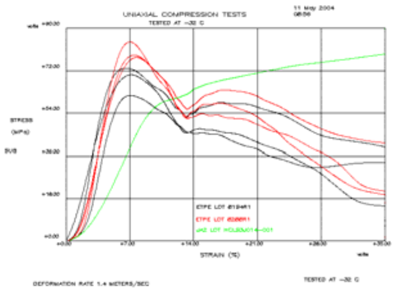


Figure 20. Stress vs. Strain of ETPE and JA2 Lots at -32º C.

Figure 21. ETPE Lots 8288RR1 and 8194R1 Specimens Tested at -32º C

At 21º C, the ETPE lots PAP-8194R1, PAP-8288R1, and the JA2 lot showed good response to uniaxial compression. The failure modulus values measured for the ETPE lots at 21º C indicates these materials slowly losing the ability to sustain load but are able to maintain mechanical integrity. Also, note the stress vs. strain plot (Figure 16) shows the JA2 lot work hardening beyond 35 percent strain. The tested specimens (Figure 17) for the ETPE lots at 21º C suffered permanent deformation and very minimal fracturing while the JA2 lot showed permanent deformation and barreling.

At 63º C, again, the mechanical response of the ETPE lots PAP-8194R1, PAP-8288R1, and JA2 lots were quite good. The Young's compressive modulus values at 63º C indicated some "material-softening" when compared with the 21º C values. This was a result of the higher test temperature and was expected. The stress/strain plot (Figure 18) shows the ETPE lots again slowly losing the ability to sustain load but able to maintain mechanical integrity. The JA2 lot continued to work harden beyond 30 percent strain. The 8194R1 and 8288R1 tested specimens showed similar damage in the form of some barreling of the materials due to the softening at 63º C. (Figure 19).

At -32º C, the ETPE lots PAP-8194R1 and PAP-8288R1 again, showed good response to mechanical compression testing. Lot 8288R1 achieved a higher stress at yield value than lot 8194R1. Note the stress/strain (Figure 20) plot at -32º C clearly shows the JA2 lot as the superior performer, followed by lots 8288R1 and 8194R1. The failure modulus values achieved for lots 8194R1 and 8288R1 indicated the materials losing the ability to sustain load. However, the stress vs. strain plot shows the materials able to recover with increasing stress at ~13 percent strain. The tested specimens (Figure 21) from lots 8194R1 and 8288R1 suffered minimal to moderate amounts of axial and shear fracture. The tested chards from the JA2 lot (Figure 22) showed moderate amounts of axial and shear fracture.

21º C **63º C** **-32º C**

Fig. 24. JA2 Specimens Tested at 21º C, 63º C, and -32º C.

In summary, the ETPE lots 8194R1, 8288R1, and JA2 mechanical response at 21º C, 63º C, and –32º C were quite good. However, the JA2 lot was clearly the better material at –32º C.

The fifth recycled propellant designated as lot PAP 8194R5 was tested for mechanical properties to assess whether the mechanical properties were degrading with increased processing. The results of the compression testing are shown in Table 7 and are plotted in Figures 22 to 28.

Table 7: Mechanical Properties of 8288R5SB, 8194R5FB and JA2 Lots at 21º C, 63º C and 32ºC.

Lot #	Stress@ Failure (MPa)	Strain@ Failure (%)	Modulus (GPa)	Failure Modulus (GPa)	IED (MPa)	FAV
@ 21º C						
Lot 8288R5	10.18	9.10	0.15	0.014	6.22	1B
Slow Burning						
Lot 8194R5	15.15	8.47	0.28	0.013	12.18	1B
Fast Burning						
JA2	18.12	7.58	0.38	0.065	14.70	0B
@ 63º C						
Lot 8288R5	4.55	8.77	0.045	0.006	3.24	1B
Slow Burning						
Lot 8194FB	5.20	7.90	0.10	0.003	4.19	1B
JA2	7.62	8.97	0.21	0.049	3.37	0B
@ -32º C						
Lot 8288R5	29.14	5.70	0.86	-0.65	2.52	8AS
Slow Burning						
Lot 8194R5	55.09	6.39	1.13	-0.70	7.18	7AS
Fast Burning						
JA2	56.06	12.37	0.79	0.067	13.22	5AS

Two lots of ETPE 8288R5 slow burning, 8194R5 fast burning propellants and a lot of JA2 granular high-energy gun propellant were tested for mechanical response evaluation at ambient pressure while temperature conditioned at 21º C, 63º C, and -32º C. The materials were tested in uniaxial compression to ~50 percent end strain using a deformation rate of 1.10 meters per second.

At 21º C, lots 8288R5, 8194R5, and the JA2 lot showed good response to uniaxial compression. The failure modulus values measured for the lots at 21º C indicated these materials ability to sustain load and also maintain mechanical integrity. Also, note the stress vs. strain plot (Figure 23) shows the JA2 lot workhardening beyond 50 percent strain. Lot 8194R5 consistently showed higher stress values than lot 8288R5. The tested specimens (Figure 24) for the ETPE lots at 21º C suffered permanent deformation and very minimal fracturing while the JA2 lot showed permanent deformation and barreling.

At 63º C, again, the mechanical response of the ETPE lots 8288R5, 8194R5, and JA2 lots were quite good. The Young's compressive modulus values at 63º C indicated some "material-softening" when compared with the 21º C values. This was a result of the higher test temperature and was expected. Note that lot 8194R5 again showed consistently higher stress values when compared with lot 8288R5. The stress/strain plot (Figure 25) shows the ETPE lots again able at sustaining load and also maintaining mechanical integrity. The JA2 lot continued to work harden beyond 50 percent strain. The 8288R5 and 8194R5 tested specimens showed similar damage in the form of some barreling and minimal fracture of the materials due to the softening at 63º C. (Figure 26).

At -32º C, the ETPE lots 8288R5 and 8194R5 showed a very poor response to mechanical compression testing. There was much scatter in the stress, strain, and modulus values. The poor mechanical response was indicative of numerous voids that were discovered (scanning electron microscopy) in the extruded material as received from ARDEC. Lot 8194R5 achieved higher stress at yield values than lot 8288R5. Note the stress/strain (Figure 27) plot at -32º C clearly shows the JA2 lot as the much superior material. The failure modulus values achieved for lots 8288R5 and 8194R5 indicate these materials rapidly lost the ability to sustain load, likely due to the voids in the material. The tested specimens (Figure 8) from lots 8288R5 and 8194R5 suffered moderate to severe of axial and shear fracture. The tested chards from the JA2 lot (Figure 22) showed moderate amounts of axial and shear fracture.

In summary, the ETPE lots 8288R5 and 8194R5 mechanical response at 21º C and 63º C were quite good. At –32º C however, the response was somewhat less than desired, a result of testing voided materials.

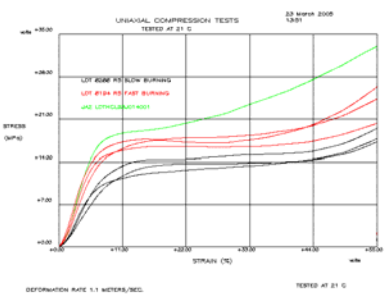


Figure 23. Stress vs. Strain of ETPE and JA2 Lots at 21º C.

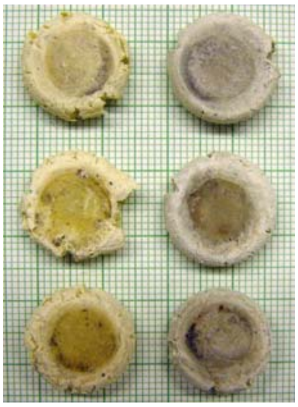
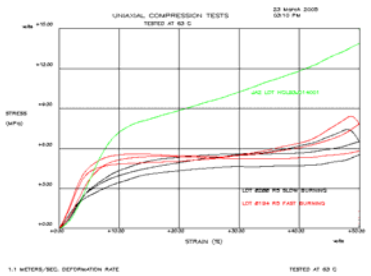


Figure 24. ETPE Lots 8288R5 and 8194R5 Specimens Tested at 21º C



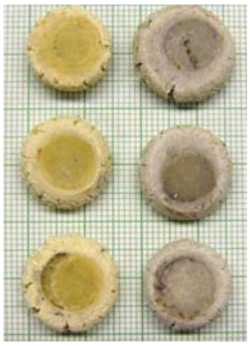


Figure 25. Stress vs. Strain of ETPE and JA2 Lots at 63 C.

Figure 26. ETPE Lots 8288R5 and 8194R5 Specimens Tested at 63º C

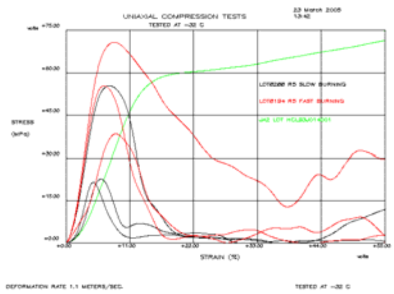


Figure 27. Stress vs. Strain of ETPE and JA2 Lots at -32º C.

Figure 28. ETPE Lots 8194R5 and 8288R5 Specimens Tested at -32º C

Tensile Bond Strength Test (similar to Peel Test)

The final configuration selected by the ARDEC/Aerojet IPT team was the co-layered radial strips. In order to determine if there will be a potential delamination during the gun firing across the ballistic temperature range, the co-layered radial strips were tested for tensile bond integrity test. An occurrence of delamination could result in a significant increase in surface area leading to gun overpressurization. Figure 29 shows the original specimen before testing. Figure 30 shows the specimen test set up prior to the tensile bond test. Dr. Robert Lieb and Mike Leadore (ARL) conducted the test and the results are shown in Figures 31, 32 and 33.

Figure 29: Co-layered Propellant Test Specimen

Figure 30: Specimen Test Set Up

At 21º C, at the seamed area, no failure was observed (Figure 31) between the layers. Average specimen failure occurred at ~400 newtons of force applied.

At 63º C, at the seamed area, no failure was observed (Figure 32) between the layers. However, one crack did develop in the second specimen tested at 63º C but the specimen ultimately failed away from the seam. Average specimen failure occurred at ~350 newtons of force applied.

At –32º C, at the seamed area, no failure was observed (Figure 33) between the layers. Average specimen failure occurred at ~600 newtons of applied force.

In summary, the lamination of the slow and the fast burning formulation in radial strip configuration should not delaminate at 63^{0}C, 21 ^{0} C, and -32^{0} C, because the bond between the two formulations is stronger than the propellant.

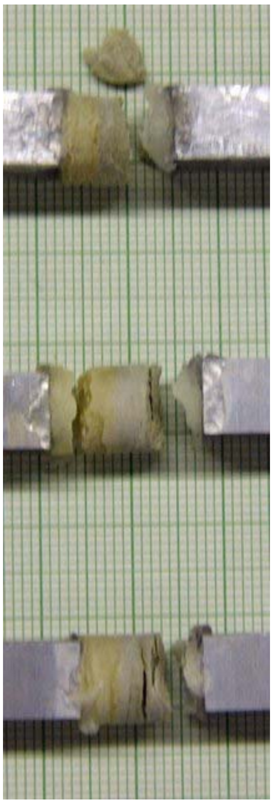


Figure 31. Tested Specimens of Co-Layered Material at 21º C. Failure did not occur at layered seam.

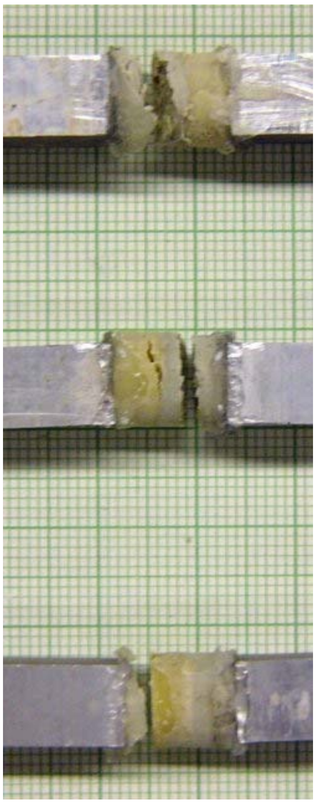


Figure 32. Tested Specimens of Co-Layered Material at 63º C. Failure did not occur at layered seam

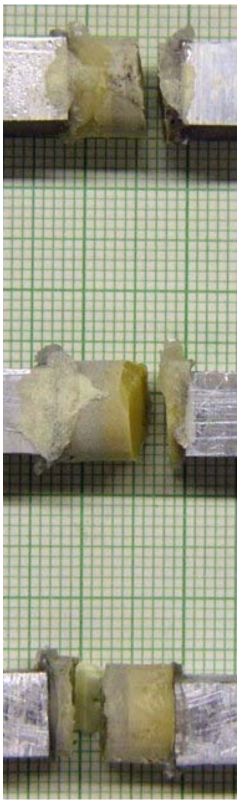


Figure 33. Tested Specimens of Co-Layered Material at -32º C. Failure did not occur at layered seam

Closed Bomb Test of Co-layered Propellant

The co-layered radial strip samples were closed bomb tested to determine the burn rates and vivacity curves. The results are shown in Figure 36 and 37, respectively. Tabulation of burn rates at pressures from 137 MPa to 276 MPa (20 kpsi to 40 kpsi) are shown in Table 8 and all the data plotted in Figures 34 and 35 for the burn rates and vivacity curves, respectively.

Table 8: Burn Rates for Co-Layered Radial Strips of Propellants from Lot 8194 (Fast) and Lot 8288 (Slow)

Pressure/Burn Rates(kpsi/in/s)	63^0C	21^0C	-32^0C
20(137MPa)	2.96	2.77	2.72
30(206MPa)	6.32	5.85	5.47
40(275MPa)	8.63	8.15	7.75

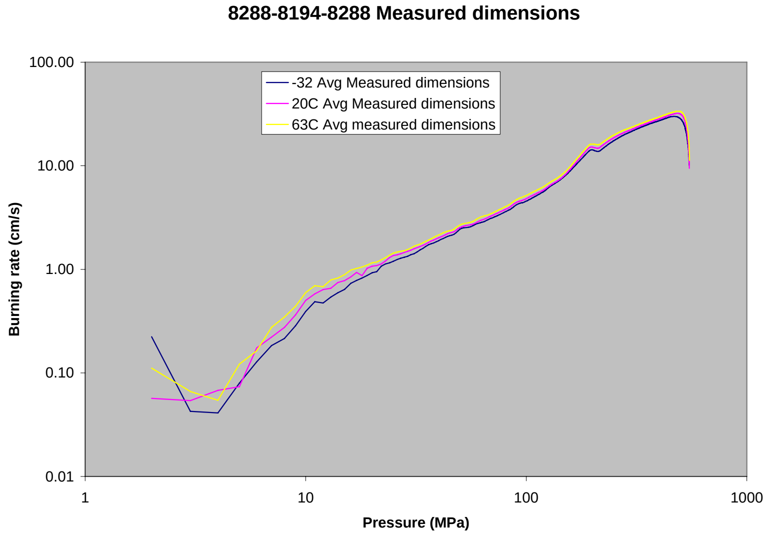


Figure 34: Burn Rates for Co-layered Radial Strips at 63^{0}C, 21^{0}C and -32^{0}C.

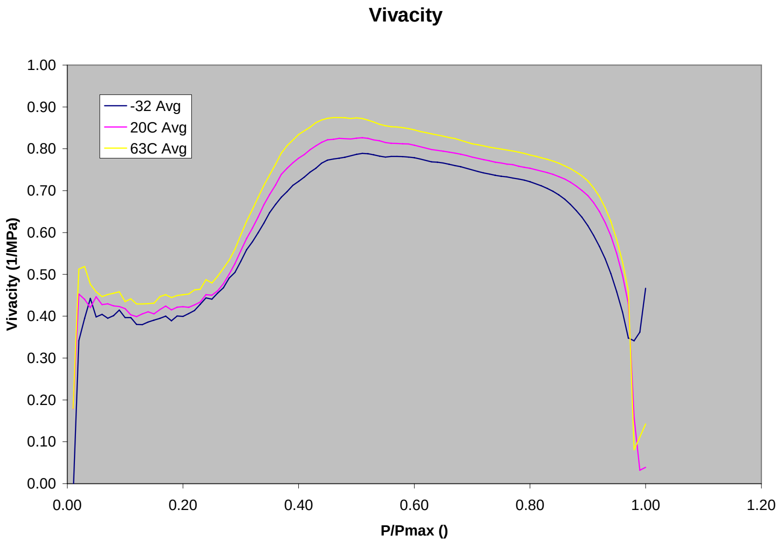


Figure 35: Vivacity Curves for Co-layered Radial Strips at 63^{0}C, 21^{0}C and -32^{0}C.

The burn rates and the vivacity curves for the co-layered radial strips of the slow and fast formulations showed that the propellants were well behaved and followed the form function. The burn rates and the vivacity curves are highest at hot temperature and lowest at cold temperature as shown in Figures 34 and 35. As shown in Figure 35, the slow burning propellant is progressive from 20 P/Pmax to 40 P/Pmax. It is then followed by the fast burning propellant degressively and ends at approximately 90 P/Pmax

Dr. James Luoma from UDLP made a full charge interior ballistics prediction of the slow and the fast burning formulation by using the worst case scenario in order to safely fire the co-layered propellants in the 60 mm ETC gun test fixture at Elk River, Minnesota. He had plotted all the burn rates of the Lot 8288 (slow) and Lot 8194 (fast) formulations and selected the highest burn rate as shown in Figure 36.

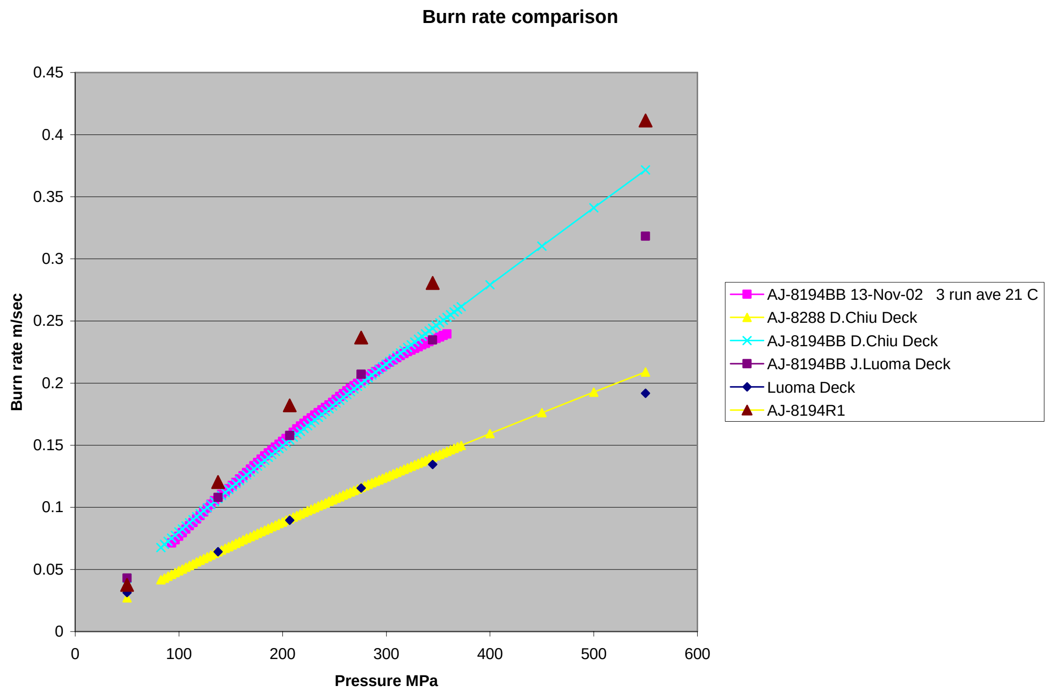


Figure 36: Summary of all burn rates of Lot 8288 (slow burning) and 8194 (Fast burning)

By selecting AJ- Lot 8194R1 burn rates as the worst case scenario, which is the highest burn rate and pressure, the predicted pressure, velocity versus time was determined using the IBHVG2 code. The predicted maximum pressures and velocity are shown in Figure 37.

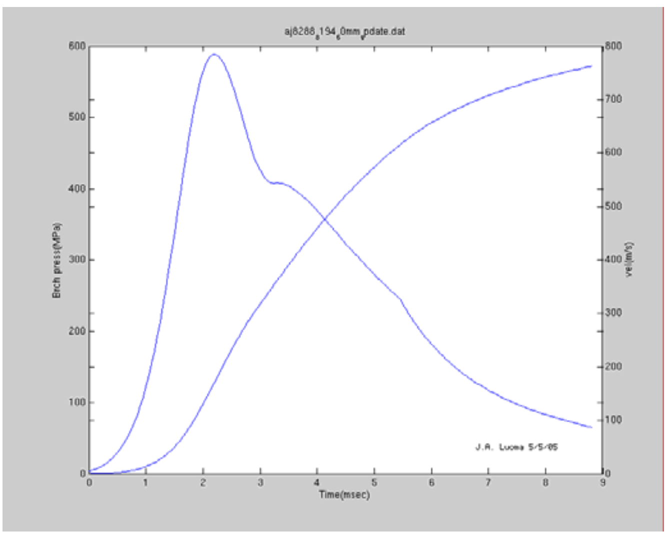


Figure 37: Predicted Pressure, Velocity, and Time Trace for the Co-layered ETPE propellant.

The maximum pressure shown in Figure 37 is within the maximum allowable pressure in the 60 mm ETC gun test fixture. These values were 590 MPa for the pressure and 762.45 meters per second for the velocity. The maximum pressure at 63 ^{0}C is 675 MPa in the 60 mm

ETC gun test fixture at UDLP. Thefore, it was recommended that the co-layered formulation was safe to fire in the 60 mm ETC gun test fixture.

Propellant Configuration and Geometry

A radial strip configuration was selected for the 60 mm gun firings (Figure 38). It was felt that in the 60 mm ETC gun system, this configuration would allow for the better flame spreading as compared to other sheet geometries such as disks. The schematic diagram of the 60 mm cartridge used in the gun firing is shown in Figure 39.

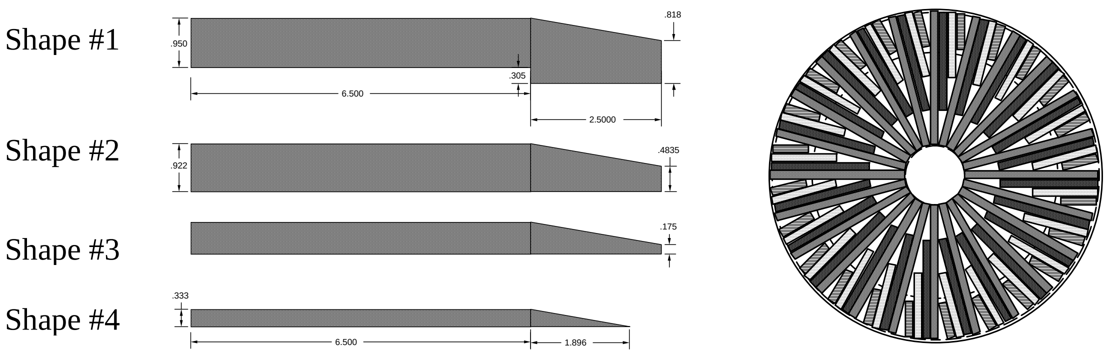


Figure 38 – Strip configuration for shots 1-15

It was decided not to emboss the strips believing the shape alone would provide adequate flame spreading. Radial strips also produced less scrap than disks when produced. Aerojet produced the BN7 along with the propellant molding powder at their Sacramento, CA facility. The molding powder was made by dissolving BN7 in a solvent and then adding that mixture to a RDX water slurry that is continually being mixed. The RDX coated with BN7 was dried to form a molding powder. The molding powder was shipped to Picatinny to be processed into a final propellant.

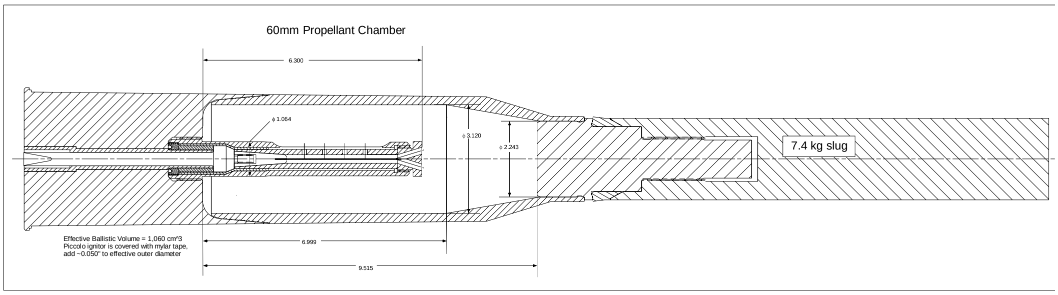


Figure 39: 60mm Cartridge with plasma ignitor

The molding powder at it's melt temperature was mixed with the addition of the BDNPA/F plasticizer in the horizontal sigma blade mixer. The mixed dough was then extruded using a slit die to form an extruded ribbon to be used as a feed stock in the roll mill. The pre-heated extruded ribbons were fed into the roll mill to form sheets of 0.0123 inch thickness for the slow burning layer and 0.0488 inch for the fast burning layer. Developing the rolling process proved to be a challenge that when resolved, left an effective, yet time consuming, operation. Following the roll mill operation, the rolled strips were trimmed using a press with inserts of the four different shapes shown in figure 38. The scrap propellant from trimming operation was used and re-mixed , re-extruded, and trimmed. The trimmed radial strips of shapes 1-4 were assembled into groups of three to form a “sandwich”. The pre-heated “sandwichs” were pressed together at experimentally determined temperature and pressure values. The co-layered strips were annealed to form the final propellant.

A total of 1440 strips in the four different shapes were produced. The propellant would be used in the assembly of (15) 60 mm propellant charges as shown in Figure 40.

Figure 40– Propellant load for shot #4

Testing

The following characterization testing were completed prior to ballistic testing: close bomb burning rate, Scanning Electron Microscope, Friction, Electrostatic Discharge, Impact, Chemical Analysis, Peel Test, Mechanical Properties, Particle size analysis and Rheology. After the suite of characterization testing and evaluation was completed and the data analyzed, it was decided to move forward with the 60 mm ETC firings.

A total of 15 rounds were fired, as shown in table 9.

Table 9: 60 mm ETC Gun Firing results

Round Number	Charge weight, grams	Temp, C	Pmax MPa	Max dP MPa	Vmuzzle m/s
1	947	20	159	-12.762	533
2	1023.9	20	257	-21.0853	635
3	1100	20	320	-49.3577	682

4	1144.10	20	429.8	-71.8651	720
5	1125.8	20	390	-55.6482	713
6	1123.80	20	381	-11.4971	709
7	1127.4	63	390	-50.5527	689
8	1124	63	418	-47.7186	705
9	11128.6	63	409	-34.6392	697
10	1125.4	0	375	-22.276	705
11	1128.8	-10	426	-15.7317	725
12	1123.8	-20	401	-20.0931	717
13	1124.4	-32	540	-72.0385	752
14	1125.9	-32	503	-86.191	744
15	1123.6	-32	538	-114.9868	752

Chamber pressures were lower than expected for any given charge weight, but on a positive note the muzzle velocities were near the predicted values. High pressures at cold and large negative pressures differentials marred the test results. The typical delta P cutoff for large caliber firings is -34.5dP. The test results at 63^0 C and 20^0 C yielded good results in matching ballistic predictions. Test results at -32^0 C yielded higher chamber pressures than predicted most likely due to flame spread difficulties on ignition which could be easily solved.

An IBHVG2 simulation was able to duplicate the ballistic cycle by delaying ignition of some of the propellant grains. This effect strongly suggests inadequate plasma flame spread in the propellant bed and possibly even the lack of hot particles from the plasma igniter due to the propellant strips packing too closely together. The pressure – time trace of Round 13 is shown in Figure 41.

On shots that did show large pressure excursions, there was evidence of poor plasma ignition as evidence by large differential pressures early in the ballistic cycle. This is observed on cold shot as shown in figure 42. Note the distinct difference in these pressure traces as compared to the ones shown in figure 43 obtained from firing a disk configuration that had disk fracture from previous testing of ATK/Thiokol propellant.

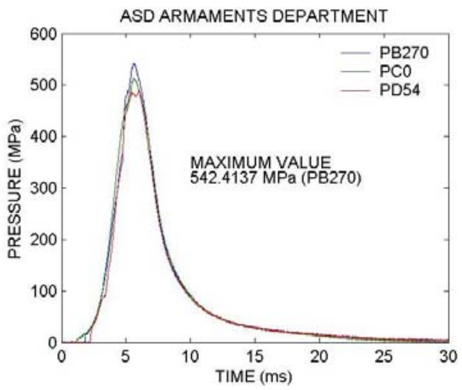


Figure 41: P-t trace from shot 13 at -32 C.

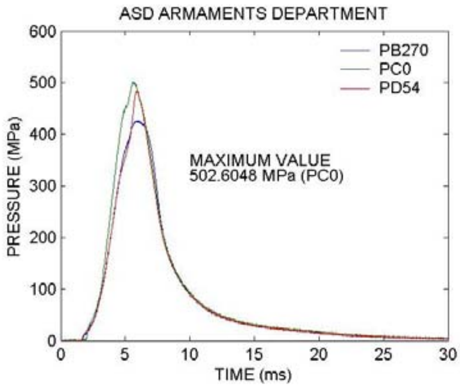


Figure 42. P-t traces of shot 14 at -32 C.

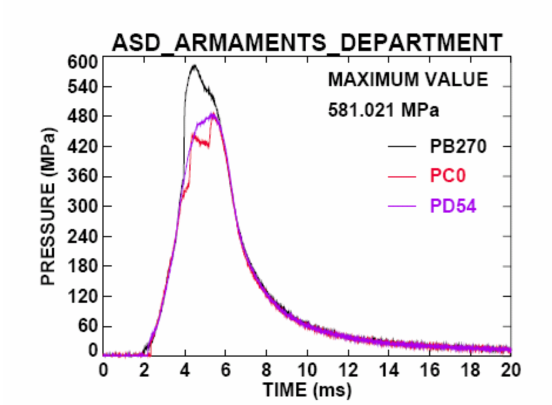


Figure 43. P-t traces of ATK./Thiokol
cold shot at -32 C.

Another possibility for high pressure at -32^0 C as simulated using the IBHVG2 code by Mr. Donald Chiu was that three of the number 1 strips were modeled as fracturing and delaminating, resulting in premature ignition shown in Figure 44.

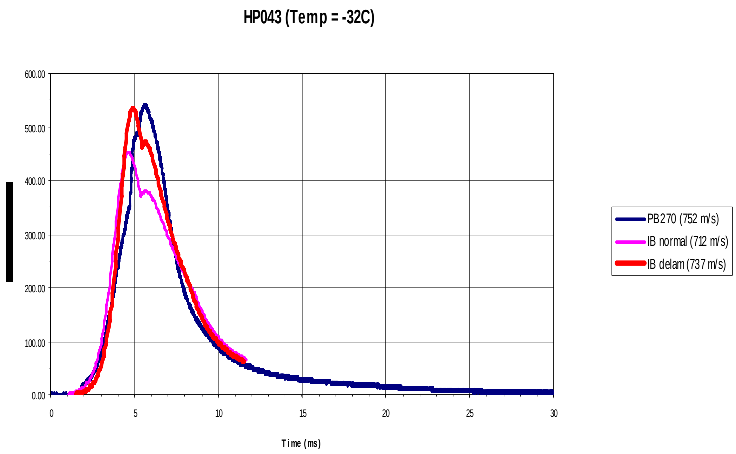


Figure 44. Pressure excursion from shot #13, at -32 C.

Small Scale Sensitivity Testing

The small scale sensitivity testing was conducted on the slow and fast formulations by Theodore Dolch (ARDEC) to determine the safety data of the propellants needed for safe processing and handling. The propellant processing consist of mixing with the horizontal sigma blade mixer, ram extrusion, rolling, trimming, laminating and finally, annealing. All of these processing steps require process equipment that can sometimes result in unsafe conditions without knowing the sensitivities of the slow and fast burning formulations. The ARDEC pilot plant standard operating procedures requires all the propellant sensitivity data to be obtained prior to using the process equipment.

The samples were cooled with dry ice then ground in the Wiley Mill and passed through a 20 mesh screen before testing for all tests listed below.

The ERL, Type 12 impact tester, utilizing a 2 ½ kg dropweight, was used to determine the impact sensitivity of the sample. The drop height corresponding to the 50% probability of initiation is used to measure impact sensitivity. The impact test is described in MIL-STD-1751A, dated 11 December 2001, Method 1012, "Impact Sensitivity Test -ERL(Explosives Research Laboratory)/Bruceton Apparatus". The results of the ERL Impact Test are shown in Table 10.

Table 10: Results of Small Scale Sensitivity Tests

Propellant	ERL Type 12 Impact 50% point (cm)	Electrostatic Discharge Test (ESD)	BAM Friction (N)
RDX Lot # 21-18	24.8± 1.2 25.1± 1.7	-	212N reacted 188N 10/10 no go
JA2 Lot # PD-065-5	32.0± 1.4	NR 20 trials @ 0.25 Joules	212N reacted 188N 10/10 no go

Fast Burning Lot 8194	**86±1.3**	**NR 20 trials @ 0.25 Joules**	**(R1)252N reacted (R1)360N 10/10 no go (R5)240N reacted (R5) 216N 10/10 no go**
Slow Burning Lot8288	***impact insensitive Reacted in 2 out of 10 trials @ 100 cm drop height.**	**NR 20 trials @0.25 Joules**	**(R1) 324N reacted (R1) 288N 10/10 no go (R5)252N reacted (R5) 240N 10/10 no go**
Co-layered	**64.8±1.2**	**NR 20 trials @0.25 Joules**	**240N reacted 216N 10/10 no go**

*This sample reacted in 2 out of 10 trials at 100 cm drop height. The drop height of 100 cm is the maximum for the test apparatus. Drop heights greater than 100 cm damages the test tooling. Lot 8288 is impact insensitive.

The Large BAM Friction Test Method is described in MIL-STD-1751A, dated 11 December 2001, Method 1024, "BAM Friction Test". A sample was placed on the porcelain plate. The porcelain pin was lowered onto the sample and a weight was placed on the arm to produce the desired load. The tester was activated and the porcelain plate was reciprocated once to and fro. The results are observed as either a reaction (i.e. flash, smoke, and/or audible report) or no reaction. Testing is begun at the maximum load of the apparatus (360 N) or lower if experience warrants it. If a reaction occurs in ten trials, the load is reduced until no reactions are observed in ten trials. The minimum load value at which reaction occurs is reported in Newtons. The summary of results are shown in Table 9. The Lot 8194R5 and laminated samples reacted at 240 N and did not react in 10 trials each at 216 N. The Lot 8288R5 sample reacted at 252N and did not react in 10 trials at 240N. The Lot 8194-R1 sample did not react in 10 trials at the maximum load of 360 N. The Lot 8288R1 sample reacted at 324 N and did not react in 10 trials at 288 N.

The Electrostatic Sensitivity Test is described in MIL-STD-1751A, dated 11 December 2001, Method 1032, "Electrostatic Discharge Sensitivity Test (ARDEC (Picatinny Arsenal) Method)". All three samples did not react in 20 trials each at 0.25 joule, as shown in Table 9 (the maximum energy level of the test apparatus).

Based on the results of the small scale sensitivity tests, the slow burning, fast burning and co-layered propellants have demonstrated much lower sensitivities to impact, ESD and friction than the JA2 propellant and the RDX ingredient.

Conclusion:

Based on the test results discussed previously, PAP-8288 was selected as the slow burning formulation, and PAP-8194BB was selected as the fast burning formulation. PAP-8288 was selected because of its low pressure exponent and mechanical properties, especially at hot and cold temperatures. The propellant PAP-8194 was selected as the fast burning candidate because of the burning rate ratio (1.73:1) developed in combination with PAP-8288 and acceptable mechanical properties across the ballistic temperature range. The reprocessing of the slow and the fast burning formulations did not show any deterioration on the mechanical properties and burn rates. However, the presence of porosities in the slow and fast burning propellant showed bad mechanical properties at cold temperature. The porosities can be eliminated with improved rolling process[7]. The chemical analysis has also shown that the chemical compositions of the re-processed propellants were within the propellant formulation thermochemical calculation values. Based on the results of the small scale sensitivity tests, the slow burning, fast burning and co-layered propellants have demonstrated much lower sensitivities to impact, ESD and friction than the JA2 propellant and the RDX ingredient. In addition, the tensile bond strength test shows that the laminated slow and fast burning formulations should not delaminate across the ballistic temperature range which is from +63 ^{0}C to -32 ^{0}C. Finally, the interior ballistic predictions by Dr. James Luoma (BAE Systems) have shown that the predicted maximum pressure will not exceed the maximum allowable pressure, 675 MPa, of the ETC gun test fixture. These downselected formulations have been fabricated at the ARDEC[7] pilot plant into a co-layered radial strip configuration by the ARDEC/AEROJET IPT Team for the 60 mm ETC gun firings.

While all (15) 60 mm rounds of the layered ETPE were fired, the results were mixed. It is recommended that for any future work with radial strips, the strips be embossed to aid in flame spread and an alternate ignition system be considered.

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