# PAX-11, A High Performance Booster For Insensitive Munitions Applications

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## ABSTRACT

An approach often used to improve the insensitive munitions (IM) characteristics of main charge explosives is to add ingredients such as nitrotriazolone (NTO) or ammonium perchlorate (AP), which have large critical diameters to the formulations. Use of these ingredients increases the formulations' critical diameter and often results in improvements in sympathetic detonation and bullet and fragment impact response. However, explosives with large critical diameters are often difficult to initiate using conventional boosters such as PBXN-5 or PBXN-7. To ensure reliable detonation of new IM fills with conventional booster explosives, the booster size is often increased. Increasing the booster size can offset the IM gains achieved by using a new IM main charge. To address this deficiency, researchers at Research Development and Engineering Command - Armament Research, Development, and Engineering Center (RDECOM-ARDEC) and ATK Aerospace Systems are qualifying the very high-performance CL-20-based explosive PAX-11. This paper presents key results of qualification tests and analyses showing the benefits of PAX-11 as a means of reliably initiating insensitive main charge explosives.

## INTRODUCTION

Energetic solids such as cyclotrimethylenetrinitramine (RDX), cyclotetramethylene tetranitramine (HMX), and triaminotrinitrobenzene (TATB) have been used for many years in a variety of different castable, melt pour, and pressed explosives. More recently, CL-20 has been investigated as a major component in explosives that are targeted for high-performance applications such as precision shaped charges and boosters. A comparison of basic properties of CL-20 and other common high explosives at 100 percent of theoretical density is shown in Table I, illustrating CL-20's excellent performance potential.

**Table I.  Comparison of CL-20 and Other Common High Explosives**

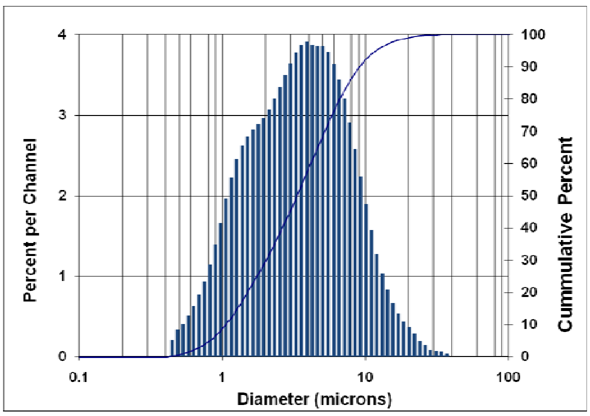
| | CL-20 | RDX | TATB | HMX |
|---|---|---|---|---|
| Chemical Formula | $C_6H_6N_{12}O_{12}$ | $C_3H_6N_6O_6$ | $C_6H_6N_6O_6$ | $C4H_8N_8O_8$ |
| Density (g/cc) | 2.04 | 1.82 | 1.94 | 1.91 |
| Heat of Formation (kJ/mol) | 377 | 70 | -140 | 75 |
| Calculated $P_{cj}$ (GPa) | 48.0 | 35.2 | 31.1 | 39.4 |
| Calculated $V_d$ (km/s) | 10.05 | 8.98 | 8.11 | 9.30 |

CL-20 is synthesized and crystallized at ATK Aerospace Systems. The unground CL-20 may be ground to smaller particle sizes or used in formulations as is. Through careful crystallization studies conducted over a number of years, the crystal shape of unground CL-20 has been steadily improved. A typical set of unground CL-20 crystals is shown in Figure 1. These crystals are well shaped and do not have multi-faceted characteristics found in early lots of unground material.

**Figure 1.  Light Microscope Photograph of Unground CL-20 at 100X Magnification**

Nominal ground and unground CL-20 particle size distributions are shown in Figure 2. In this qualification study, PAX-11 used both ground and unground material in the formulation.

PAX-11 is made using a standard water slurry manufacturing process. The first step in this process is to form a lacquer solution by dissolving a polymer and plasticizer in a solvent. Once the lacquer solution is prepared, CL-20 is added to a jacketed vessel containing water and the water/nitramine mixture is stirred until the CL-20 is thoroughly wetted. The lacquer solution is then added to the stirred mixture in the jacketed reactor where it coats the CL-20 and small molding powder granules form. The mixture is stirred under mild heat, airsweep, and/or vacuum to consolidate and harden the granules and remove the solvent. After the solvent is removed, the coated granules are collected on a screen and dried.



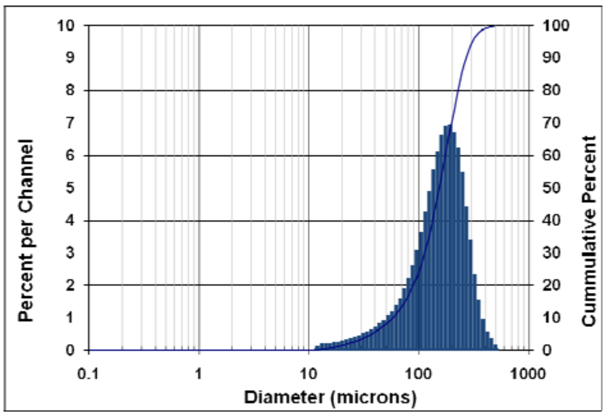




**Figure 2.  Ground (l) and Unground (r) Particle Sizes of CL-20 Similar to Those Used in This Study**

## QUALIFICATION PLAN

Based on the encouraging performance calculations and early characterization testing, the U.S. Army ARDEC is funding a study to scale-up and qualify PAX-11. The qualification program is designed to provide data needed to qualify this explosive as a booster explosive and as a main charge fill. To support these qualification tests, an 80-pound lot of PAX-11 was produced using the water slurry process described previously. The qualification plan specifies that explosives from this lot be tested over a one-year period that includes high-temperature and high-humidity conditions. Primary characterization tests to be completed during the qualification process are summarized in Table II.

**Table II. Explosive Qualification Test Matrix**

| General Test Classification | Specific Test |
|---|---|
| Stability Characterization | Vacuum Thermal Stability (VTS)<br>Thermal Stability at 75 °C |
| Thermal Characterization | Differential Scanning Calorimetry (DSC)* |
| Compatibility with Common Materials | DSC |
| Ignition Temperature | Critical Temperature Calculation |
| Explosive Response | Small-Scale Burn Test<br>Slow and Fast Cook-off |
| Electrostatic Sensitivity | Small-Scale Electrostatic Discharge (ESD) Test |
| Impact Sensitivity | Explosive Research Laboratory (ERL)/<br>Bruceton Impact Test |
| Friction Sensitivity | Bundesanstalt für Materialprüfung (BAM)<br>Friction Test |
| Shock Sensitivity | Naval Ordnance Laboratory (NOL)<br>Small-Scale Gap Test (SSGT)*<br>NOL Large-Scale Gap Test (LSGT)* |
| Other Sensitivity | Explosivity of Dust<br>Set-back Sensitivity |
| Chemical, Physical, and Mechanical Properties | Coefficient of Thermal Expansion<br>Density/Bulk Density<br>Growth<br>Exudation<br>Compressive Strength |
| Performance Properties | Detonation Velocity<br>Detonation Pressure<br>Critical Diameter |
| Products of Combustion/Detonation | Cheetah Calculations |
| General Characterization | X-ray of Pressed Billets*<br>Cube Cracking*<br>CL-20 Polymorph* |

*Tests completed on aged samples

## CHARACTERIZATION TESTING

Thermal Characterization

*Vacuum Thermal Stability*

VTS was completed for 5-gram samples of PAX-11 and reference materials LX-14 and Class 5 RDX according to MIL-STD-1751A (Method 1061). The samples were held at 100 °C for

48 hours, resulting in all explosives meeting the requirement of less than 2.0 mL/g gas evolution. The results are shown in Table III.

**Table III. VTS Gas Evolution**

| Material | 5-gram Samples (mL/g) |
|---|---|
| PAX-11 | 0.018 |
| RDX (Class 5) | 0.036 |
| LX-14 | 0.023 |

*Thermal Stability*

A thermal stability test was performed according to TB 700-2 in the UN Orange Book. The sample was placed in the oven for 48 hours at 75 °C. There was no evidence of a reaction and the overall weight loss was 0.06 percent. The weights before and after testing are listed in Table IV.

**Table IV. Sample Weights Before and After Thermal Stability Test**

| Material | Sample Weight (g) | |
|---|---|---|
| | Before Oven Test | After Oven Test |
| PAX-11 | 50.01 | 49.95 |

*Differential Scanning Calorimetry*

DSC analysis was conducted according to MIL-STD-1751A (Method 1072) using a heating rate of 5 °C/min on PAX-11 along with RDX and LX-14 for reference. The onset temperatures are listed in Table V. Aged samples of PAX-11 did not show any significant changes in the DSC. Additional testing will be performed after twelve months for material stored at 50 °C.

**Table V. DSC Onset Temperatures**

| Material | DSC Onset Temp. (°C) 0 Time | 50 °C | | | | 60 °C | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 mo | 3 mo | 6 mo | 9 mo | 1 mo | 2 mo | 4 mo | 6 mo | 8 mo |
| PAX-11 | 233 | 234 | 231 | 236 | 237 | 229 | 231 | 221 | 233 | 228 |
| LX-14 | 270 | 270 | 270 | 270 | 280 | 270 | 270 | 270 | 270 | 268 |
| RDX (Class 5) | 208 | 208 | 208 | 208 | 231 | 208 | 208 | 208 | 208 | 211 |

The compatibility of PAX-11 with common materials used in munitions was also tested using DSC. The same method was followed with the results shown in Table VI. All materials were found to be compatible with PAX-11.

**Table VI. Compatibility Results of PAX-11 Using DSC**

| Material | DSC Onset Temperature (°C) |
|---|---|
| PAX-11 | 233 |
| PAX-11/Aluminum | 233 |
| PAX-11/4340 Steel | 229 |
| PAX-11/Red Oxide Primer | 230 |
| PAX-11/Anodized Aluminum | 217 |

## Explosive Response

### *Small-Scale Burn Test*

The small-scale burn test was completed according to TB 700-2 in the UN Orange Book with all samples resulting in a rapid burn, a desirable result. Table VII shows the results for each sample.

**Table VII. Small-Scale Burn Test Results**

| Sample | Weight (g) | Time to Burn (s) | Length of Burn (s) | Event Description |
|---|---|---|---|---|
| 1 | 100.49 | 16.74 | 6.095 | Rapid Burn |
| 2 | 100.11 | 6.00 | 5.445 | Rapid Burn |
| 3 | 10.05 | 20.0 | 3.385 | Rapid Burn |
| 4 | 10.0 | 20.0 | 2.755 | Rapid Burn |

### *Variable Confinement Cook-off Testing*

Variable confinement cook-off testing (VCCT) was conducted according to STANAG 4491, starting with a confinement (wall thickness) of 0.03 inch. Slow cook-off test articles were heated at a rate of 3 °C/hr, while fast cook-off tests were heated at approximately 20 °C/min. These samples exploded or partially detonated at this level of confinement at 161 and 214 °C, respectively. Figure 3 shows post-test photographs of the test articles.


**Figure 3. Slow Cook-off (l) and Fast Cook-off (r) Tests at 0.03-inch Confinement**

## Chemical, Physical, and Mechanical Properties

The average density of the molding powder granules was determined according to MIL-STD-286C (510.3.1), which uses a gas pycnometer. The density of PAX-11 was determined to be 1.9735 g/cm$^3$. The thermal coefficient of linear expansion (TCLE) of PAX-11 was measured from -80 to 155 °C. The results are reported in Table VIII. The samples for TCLE were pellets measuring 0.25 inch in diameter and 0.25 inch in length. Figure 4 shows a chart with the plot of the growth versus temperature for one of the runs.

**Table VIII. TCLE of PAX-11**

| PAX-11 | Expansion Coefficient (mm/mm/°C) | | | |
|---|---|---|---|---|
| | -60 to 25 °C | 25 to 50 °C | 50 to 80 °C | 145 to 153 °C |
| Average | 53.69 e-6 | 49.34 e-6 | 28.51 e-6 | 2775.72 e-6 |

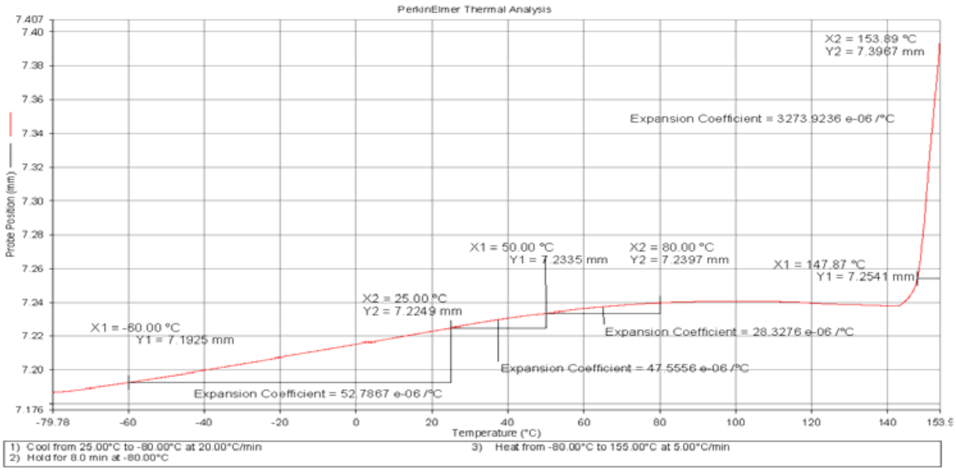



**Figure 4. Plot of Growth Versus Temperature for PAX-11**

Compressive strength samples were tested according to STANAG 4443. Testing was conducted at -45 °C, ambient, and 65 °C at a crosshead speed of 0.5 in/min. The results are shown in Table IX.

**Table IX. Compressive Strength Properties of PAX-11**

| Test Temperature (°C) | Strain at Max Stress (%) | Maximum Stress (ksi) |
|---|---|---|
| -45 | 2.93 | 7.12 |
| 23 | 3.0 | 2.22 |
| 65 | 3.18 | 1.03 |

Irreversible growth was determined using three 1-inch diameter by 1-inch long samples as specified in MIL-STD-1741A (Method 1162). Temperature cycling between -54 and 71 °C was conducted for a total of 30 cycles. The percent volume change was calculated by using measured dimensions and is shown in Table X with the average percent volume change being 0.28 percent.

**Table X. Irreversible Growth of PAX-11**

| Sample ID | Initial Volume (cc) | Final Volume (cc) | Volume Change (%) |
|---|---|---|---|
| 1 | 13.0377 | 12.9982 | -0.3 |
| 2 | 13.0176 | 12.9982 | -0.15 |
| 3 | 13.0504 | 12.9982 | -0.4 |

Exudation testing was performed on three samples as specified in MIL-STD-1751A (Method 1161). The samples were loaded into aluminum sleeves, placed in a conditioning oven set to 71 °C, and removed after 320 hours. The amount of plasticizer lost was determined by weight loss of the sample and is shown in Table XI.

**Table XI. Exudation of PAX-11**

| Sample ID | Initial Weight (g) | Final Weight (g) | Weight Loss (g) | Weight Loss (%) |
|---|---|---|---|---|
| 1 | 123.8086 | 123.7777 | 0.0309 | 0.0250 |
| 2 | 123.7582 | 123.7270 | 0.0312 | 0.0252 |
| 3 | 123.7816 | 123.7505 | 0.0311 | 0.0251 |
| Average | | | 0.0311 | 0.0251 |

*Polymorph Analysis*

Analysis by Fourier transform infrared spectroscopy (FTIR) shows that the CL-20 polymorph in PAX-11 is epsilon. Samples from the aging study indicate that a phase change does not occur when samples are exposed to high temperatures and humidity for extended lengths of time.

*Theoretical Performance*

The predicted performance of PAX-11 and currently fielded booster explosives PBXN-5 and PBXN-7 is shown in Table XII. All calculations shown in Table II were performed at 98 percent of theoretical density. These calculations predict that PAX-11 will markedly outperform these legacy formulations for all performance parameters considered. Of particular interest is the comparison between PAX-11 and PBXN-7. PBXN-7 was developed as an IM replacement for PBXN-5. However, because PBNX-7's performance is so low it will likely require a much larger booster to reliably initiate the new IM compliant main charge explosives. On the other hand, the superior performance of PAX-11 allows the use of a smaller booster to produce the shock input needed for reliable initiation of even the most insensitive main charge fills.

**Table XII. Performance Predictions**

| Formulation | PAX-11 | PBXN-5 | PBXN-7 |
|---|---|---|---|
| Primary Nitramine | CL-20 | HMX | TATB/RDX |
| Density (g/cc) | 1.94 | 1.86 | 1.85 |
| $P_{cj}$ (GPa) | 41.66 | 35.00 | 28.69 |
| $V_d$ (km/s) | 9.47 | 8.86 | 8.04 |
| CJ Temperature (°K) | 4597 | 4027 | 3525 |
| Energy at $V/V_o$ = 6.5 (kJ/cc) | 10.16 | 8.94 | 7.20 |

Measured Performance Properties

The detonation velocity and detonation pressure were determined according to MIL-STD-1751A. The detonation velocity was measured using confined and unconfined samples. The confined test used LSGT pipes with predrilled holes for sensors, while the unconfined samples consisted of nine pellets measuring 1.415 inch in diameter and 1.83 inch long with sensors placed between pellets. The test article and a plot of distance versus time for both test methods are shown in Figures 5 and 6, respectively. Table XIII shows the average velocity for each test.

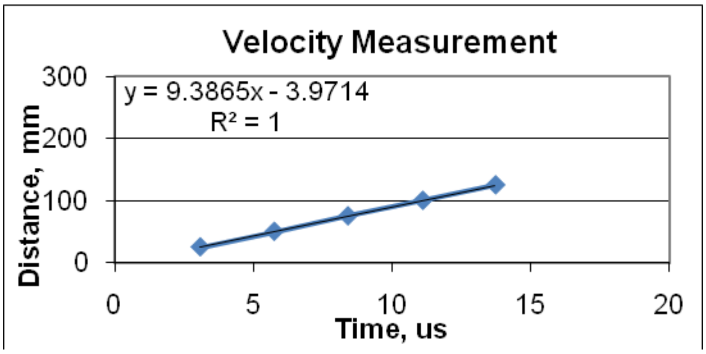
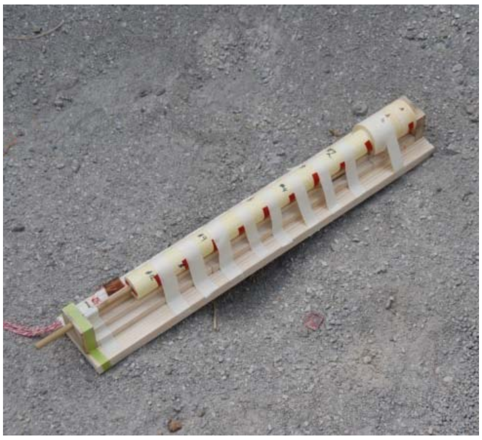



**Figure 5. Confined Detonation Velocity Setup and Measurement**



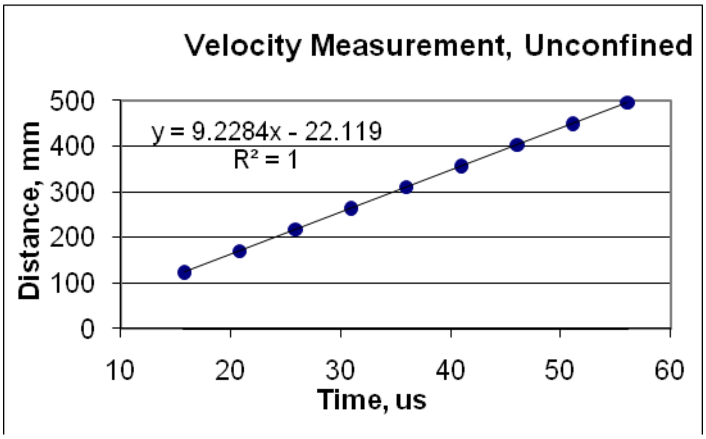



**Figure 6. Unconfined Detonation Velocity Setup and Measurement**

**Table XIII. Detonation Velocity of PAX-11**

| Test Type | Velocity (mm/µs) |
|---|---|
| Confined | 9.36 |
| Unconfined | 9.24 |

The detonation pressure was calculated from a dent test using an NOL LSGT pipe filled with PAX-11. The witness plate was 2.0-inch thick mild steel with hardness RB88. The dent depth was measured as 0.56 inches. The CJ pressure follows a rough linear relationship with dent depth. A plot of the CJ pressure versus dent depth for the calibrated materials is shown in Figure 7 and predicts the CJ pressure of PAX-11 to be 39.05 GPa.

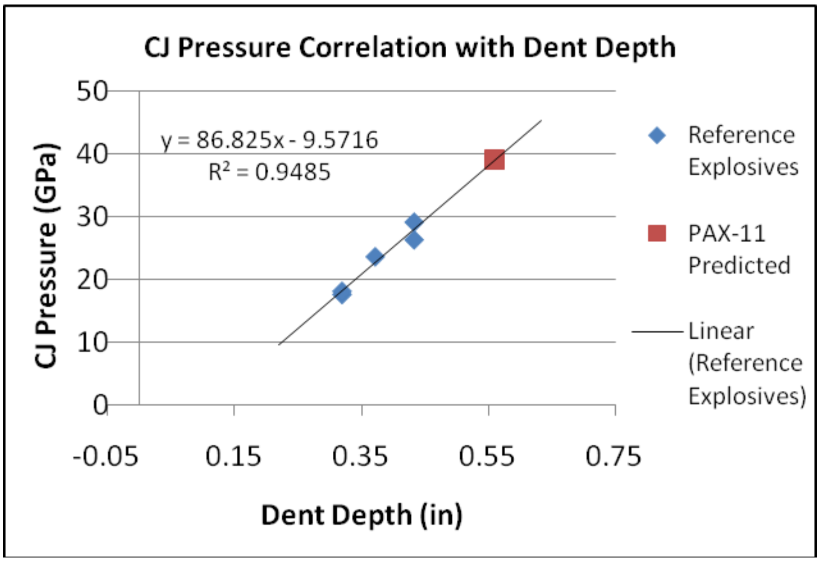



**Figure 7. Correlation of Dent Depth to CJ Pressure**

The critical diameter of PAX-11 was determined using the specifications listed in MIL-STD-1751A (Method 1091, stepped cylinder method). The smallest diameter tested was 0.2 inches. All samples detonated, showing that the critical diameter of PAX-11 is less than 0.2 inches. The witness plate after the test is shown in Figure 8. The average detonation velocities across the samples for the various diameters are shown in Table XIV.

**Table XIV. Critical Diameter of PAX-11**

| Diameter (in) | Length (in) | Average Velocity (km/s) |
|---|---|---|
| 0.2 | 0.812 | 9.103 |
| 0.25 | 1.0045 | 9.009 |
| 0.5 | 2.061 | 9.056 |

**Figure 8. Witness Plate After Critical Diameter Test Showing Detonation of All Samples of PAX-11 (smallest dent was made by 0.2-inch diameter charge)**

## SUMMARY AND CONCLUSIONS

PAX-11 is a high-performance, CL-20-based explosive which was developed to outperform legacy pressed explosives such as Comp A-4 and LX-14 with the best possible IM properties. The qualification and aging of PAX-11 completed to date has demonstrated acceptable results. Additional testing is ongoing and will be completed according to the approved qualification plan. In terms of performance, PAX-11 has been found to highly outperform legacy explosives, making it an ideal candidate for small, high-value items requiring high output.