# Characterization and Comparison of a High Performance CL-20 Explosive

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## ABSTRACT

CL-20 is a high performance nitramine that has been evaluated for use in a wide range of energetic formulations including pressed explosives, cast cure explosives, booster explosives, and high performance rocket propellants. Some formulations containing CL-20 have been found to be more sensitive than their counterparts that utilize HMX or RDX. However, other formulations containing CL-20 have demonstrated very respectable sensitivity. One of these compositions is a cast cure explosive identified as DLE-C038. Because of its excellent properties, researchers at ATK Aerospace Systems and the U.S. Army ARDEC have begun an extensive characterization study that will culminate in its qualification as a main charge explosive. This paper discusses the results of these characterization tests and compares the results with comparable HMX based explosives.

## INTRODUCTION

CL-20 is a high performance nitramine that was discovered and initially synthesized by researchers at the then Naval Weapons Center (now the Naval Air Warfare Center Weapons Division). The excellent performance of CL-20 is a result of several factors including high density, favorable oxygen balance, and a cage structure. CL-20 has higher density and energy than either HMX or RDX as illustrated in Figure 1.

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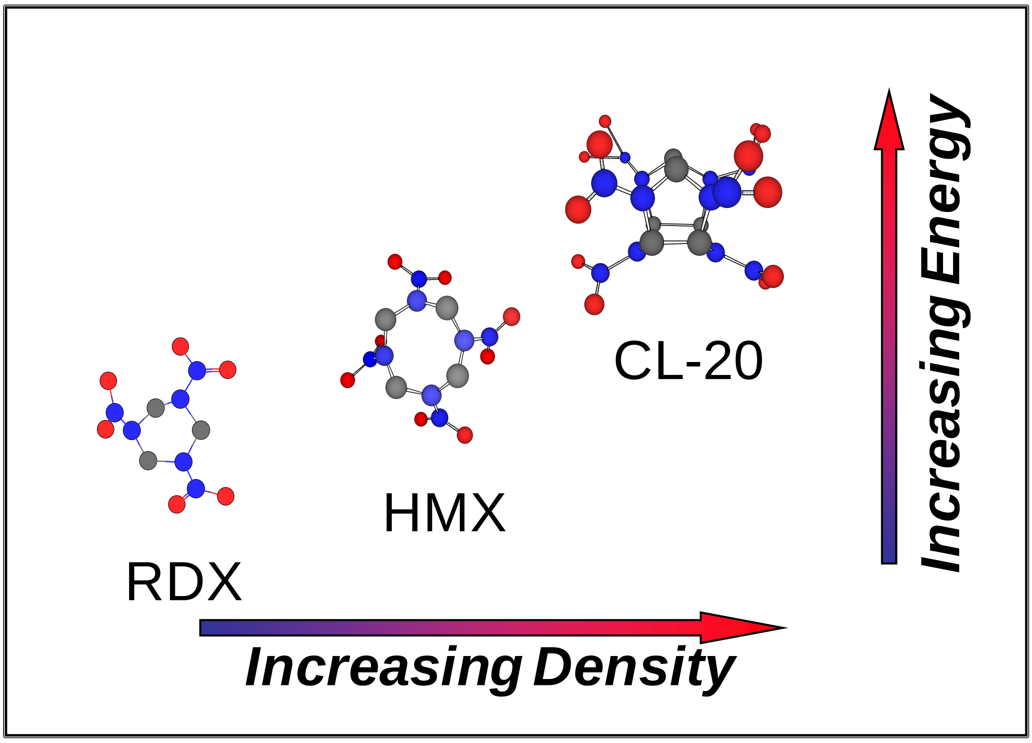


**Figure 1. Relationship Between Density and Energy for Three Common Nitramines**

When new high performance energetic materials, such as CL-20, are initially synthesized they are invariably considered for use in a wide range for formulations. For example, CL-20 has been evaluated for use in high performance rocket propellants, advanced gun propellants, pressed explosives, cast cure explosives, and so forth. While formulations using new energetic materials are developed many factors must be considered including the compatibility of the new material with other formulation ingredients, physical interaction between formulation components, and the basic safety and handling properties of the new ingredient. Theoretical studies and small scale formulation efforts indicated that CL-20 would be well suited for use in cast cure explosives, if a high solids level could be achieved in the formulation. One of the promising CL-20 based castable explosives developed during these early efforts was identified as DLE-C038.

A major challenge in the development of any high-solids castable explosive is devising a formulation and mix procedure that allow the formulation to be mixed and cast with low viscosity. The low viscosity is critical to casting articles within a reasonable time and with low void content. Early studies with DLE-C038 focused on understanding its processing characteristics and mechanical properties. Data generated in these studies show that this composition has excellent processing characteristics and mechanical properties. Tests on the explosive from these early mixes also indicated it was surprisingly insensitive to initiation via standard laboratory friction, impact, and electrostatic discharge (ESD) stimuli. In more recent testing, bullet impact and slow cook-off tests have been performed on 3.2-inch generic shaped charges loaded with this explosive. Further, plans have been developed to scale-up the manufacturing process for this explosive and qualify it for use as a main charge explosive.

This paper is organized as follows. First, the formulation and processing characteristics of DLE-C038 are summarized. The theoretical performance of DLE-C038 is compared to other formulations of interest. Insensitive munitions (IM) testing of DLE-C038 is presented and includes a description of shock sensitivity, variable confinement cook-off testing (VCCT), and bullet impact and slow cook-off testing of 3.2-inch generic shaped charge devices. Next, the plans for scale-up and qualification testing are summarized. We present our summary and conclusions in the final section.

## FORMULATION AND PROCESSING SUMMARY

DLE-C038 consists of 90 percent CL-20 in a bimodal blend of coarse and fine particle sizes. Both coarse and fine grades of CL-20 are made at ATK Aerospace Systems. The coarse CL-20 is made directly in the synthesis process and the fine CL-20 is ground in a fluid energy mill. The binder system consists of a plasticized HTPB binder system, which is cured using standard isocyanate curatives.

The processing of DLE-C038 has been excellent with end-of-mix viscosities generally ranging from less than 2 kilopoise (kP) to around 5 kP depending on the lots of CL-20 used. The robust relationship between viscosity and raw materials has been demonstrated during the development of DLE-C038. In this development, mixes were made using several different grinds and unground lots of CL-20 and all mixes had good processing characteristics.

## THEORETICAL PERFORMANCE

Thermochemical calculations have been performed to compare the expected performance of DLE-C038 to the castable HMX formulation PBXN-110 and to the high-solids pressed HMX explosive LX-14 (Table 1). Measured

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detonation velocities are also included in this table. At a volume expansion of $V/V_0$=6.5, the theoretical cylinder expansion energy of DLE-C038 is 22 percent greater than PBXN-110 and within 2 percent of LX-14. The CJ pressure of DLE-C038 is 32 percent greater than PBXN-110.

**Table 1. Cheetah Predictions of Performance**

| Formulation | DLE-C038 (Castable) | PBXN-110 (Castable) | LX-14 (Pressed) |
|---|---|---|---|
| Nitramine/Percent | CL-20/90 | HMX/88 | HMX/95.5 |
| Total Solids (Percent) | 90 | 88 | 95.5 |
| Density (g/cc) | 1.821 | 1.677 | 1.834 |
| $P_{cj}$ (Kbar) | 330 | 249 | 344 |
| Measured $V_d$ (km/s) | 9.04 confined | 8.39 | 8.84 |
| CJ Temperature (°K) | 4168 | 3670 | 3928 |
| Energy at $V/V_o$ =6.5 (kJ/cc) | 8.41 | 6.88 | 8.58 |
| Total Mechanical Energy (kJ/cc) | 10.24 | 8.88 | 10.27 |

## EARLY CHARACTERIZATION TESTING

### Shock Sensitivity (Large Scale Gap Test)

The shock sensitivity of DLE-C038 has been measured using the large scale gap test (LSGT). The go/no-go point was 159/160 cards and was confirmed with duplicate card gap pipes. This is a very good result for an explosive of this energy and may be attributed to the relatively large percentage of 2$\mu$ particles in the DLE-C038 or the high quality of the CL-20 crystals. These card gap results compare favorably with those reported for PBXN-110, which range from 158 to 180 cards.

### Bullet Impact

Bullet impact testing of a generic 3.2-inch shaped charge loaded with DLE-C038 has been performed. In this testing, the article was placed horizontally on a witness plate and held in place by tape. A single 50-caliber bullet was targeted at the article 6 centimeters from the end opposite the copper liner, through the center of the maximum volume of explosive fill. Regular video, high-speed video at 12,500 frames per second, and blast overpressure transducers were used to assess the violence of the event. Figure 2 shows the article prior to the test with the blast overpressure gages in the background.

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**Figure 2. The 3.2-inch Generic Shaped Charge Prepared for Bullet Impact Test**

This 3.2-inch generic shaped charge design has some design limitations as an IM test, particularly with the ease that the end closure is dislodged from the main body. Indeed, a 50-caliber bullet impact test of the article with an inert fill will send the end closure to a distance greater than 50 feet. Nevertheless, damage to the test article or witness plate, distance to which fragments are thrown, and blast overpressure can be used to assess the relative IM response of different explosives.

The bullet impact test resulted in an ejection of the end closure from the main charge after which the explosive fill burned mildly, which is shown by the high speed video. The end closure traveled about 200 feet and the main body about 60 feet in the opposite direction. Most of the traveled distance involved rolling on the ground. There was no damage to the end closure, the copper liner, or the main body except for the bullet holes and a short crack from the enlarged exit hole to the edge of the case (Figure 3). There was no overpressure detected by the pressure transducers that were ranged to record a full detonation. The test would be classified by STANAG 4241 as a Type IV reaction because of the distance that test articles were thrown.


**Figure 3. Photographs Showing the Entrance and Exit Holes from the Bullet Impact Test**

These results compare favorably with earlier testing using the same 3.2-inch generic shaped charge warhead loaded with PBXN-110.[1] In this testing a burn response was reported.

<u>Cook-off Testing</u>

Multiple VCCTs with confinements up to 0.090 inches have been performed. Only mild burning and pressure rupture reactions were seen in these tests. No detonations, explosions, or deflagrations were produced. All the tests are summarized in Table 2 and a photograph of a test at 0.075-inch wall thickness is shown in Figure 4.

**Table 2. Summary of VCCT Testing of DLE-C038**

| VCCT (two tests except for 0.090-inch wall) | | |
|---|---|---|
| **Wall Thickness (inch)** | **Reaction Temperature (ºC)** | **Result** |
| 0.030 | 156/156 | Burn/Burn |
| 0.045 | 156/156 | Burn/Burn |
| 0.060 | 157/156 | Burn/Pressure Rupture |
| 0.075 | 156/158 | Burn/Pressure Rupture |
| 0.090 | 156 | Pressure Rupture |

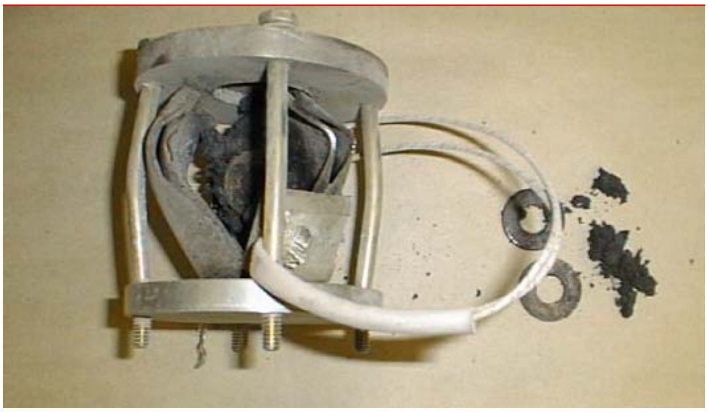

**Figure 4. VCCT Test Fixture at 0.075-inch Wall Thickness**

Larger scale slow cook-off testing was performed using a 3.2-inch generic shaped charge loaded with DLE-C038. The items were placed in an electric oven and heated at a rate of 3.3 °C per hour until the explosive reacted. Thermocouples recorded the temperature of the oven and the outside of the charge body. A trip wire was rigged to the end closure to initiate high-speed video and blast overpressure transducer recordings when ignition occurred. Regular video was also recorded. A witness plate was set up opposite the copper liner. Photographs of the oven before and after the test are shown in Figure 5.

Ignition occurred at an oven temperature of 317 °F (158 °C) and charge body temperature of 300 °F (149 °C). The end closure was separated from the main charge body during ignition. Both the end closure and the main charge body remained inside the oven. There was no damage to the end closure, main charge body, or copper liner as seen in photographs in Figure 6. There was no overpressure detected by the pressure transducers. The explosive was totally consumed in the fire. The reaction level of this test would be classified as a Type V (burning) reaction.

When these results are compared with testing performed by Collignon[1] using PBXN-110 in the same hardware, a burning response was also obtained. The reaction temperature of PBXN-110 in this test was approximately 17 °C higher than that of DLE-C038, which is to be expected because HMX is more thermally stable than CL-20.

**Figure 5. Pre- and Post-Test Pictures of the Slow Cook-off Oven**

**Figure 6. Photographs of the Shaped Charge After the Cook-off Test (No damage to the liner or body was evident)**

## PROCESS SCALE-UP AND QUALIFICATION PLAN

Based on the encouraging results of early performance, characterization, and IM screening tests, the U.S. Army ARDEC has funded a study to scale-up and qualify DLE-C038 as a main charge explosive. The first part of this program is the scale-up of the mixing process to five-gallon batch sizes. Explosives from these larger mixes will 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 3.

**Table 3. Explosive Qualification Test Matrix**

| General Test Classification | Specific Test |
|---|---|
| Stability Characterization | Vacuum Thermal Stability |
| | 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 |
| | Slow and Fast Cook-off |
| Electrostatic Sensitivity | Small Scale ESD Test |
| Impact Sensitivity | Explosive Research Laboratory (ERL)/Bruceton Impact Test |
| Friction Sensitivity | Bundesanstalt für Materialprüfung (BAM) Friction Test |
| Shock Sensitivity | Naval Ordnance Laboratory LSGT* |
| Other Sensitivity | Set-back Sensitivity |
| Chemical, Physical, and Mechanical Properties | Coefficient of Thermal Expansion |
| | Tensile Strength-Uniaxial Tensile* |

| | |
|---|---|
| | Density/Bulk Density |
| | Growth |
| | Exudation |
| | Glass Transition Temperature |
| | Compressive Strength |
| Performance Properties | Detonation Velocity |
| | Detonation Pressure |
| | Critical Diameter |
| Products of Combustion/Detonation | Cheetah Calculations |
| General Characterization | X-ray of Pressed Billets* |
| | Cube Cracking* |
| | Safe Life* |
| | CL-20 Polymorph* |
| | Antioxidant Content* |

*Tests completed on aged samples

The tests listed in Table 3 will be performed according to AOP-7 and/or the appropriate STANAG. Data from these tests will be summarized in a qualification report or presentation. In many cases, additional testing with an approved baseline material such as Class 5 RDX will also be performed. Based on the current program schedule it is planned to make the five-gallon mixes needed to support qualification testing in early September 2010. Based on favorable results from smaller scale mixes already made using the identical lots of materials, it is expected the larger mixes and qualification testing will be accomplished without difficulty.

## SUMMARY AND CONCLUSIONS

The DLE-C038 explosive offers significant improvements in energy over current state-of-the-art HMX-based castable explosives. The energy of DLE-C038 even rivals that of one of the most energetic HMX main charge pressed explosives, LX-14. The shock sensitivity of DLE-C038 is very low for a formulation of this energy. IM tests of slow cook-off and bullet impact suggest that it may function well against these threats. When insensitive munitions test data for DLE-C038 and PBXN-110 are compared, the results are remarkably similar despite the fact that DLE-C038 has much higher performance. The processing of the formulation has been very robust and excellent end-of-mix viscosities have been seen using a variety of CL-20 lots. DLE-C038 looks attractive for use in the next generation of high-value, high-lethality warheads given its ease of processing, performance, and potential for IM compliance.

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[1] : Collignon, S. L., Burgess, W.P., Wilson, W. H., Gibson, K.D. "Insensitive Munitions Program For The Development And Evaluation Of Metal-Accelerating Explosives," 1992 Insensitive Munitions Technology Symposium, Williamsburg, VA.