SMALL-SCALE SAFETY AND PERFORMANCE CHARACTERIZATION OF NEW PLASTIC BONDED EXPLOSIVES CONTAINING LLM-105

T. D. Tran, P. F. Pagoria, D. M. Hoffman, B. Cunningham, R. L. Simpson, R. S. Lee and J. L. Cutting
Lawrence Livermore National Laboratory
Livermore, CA 94551

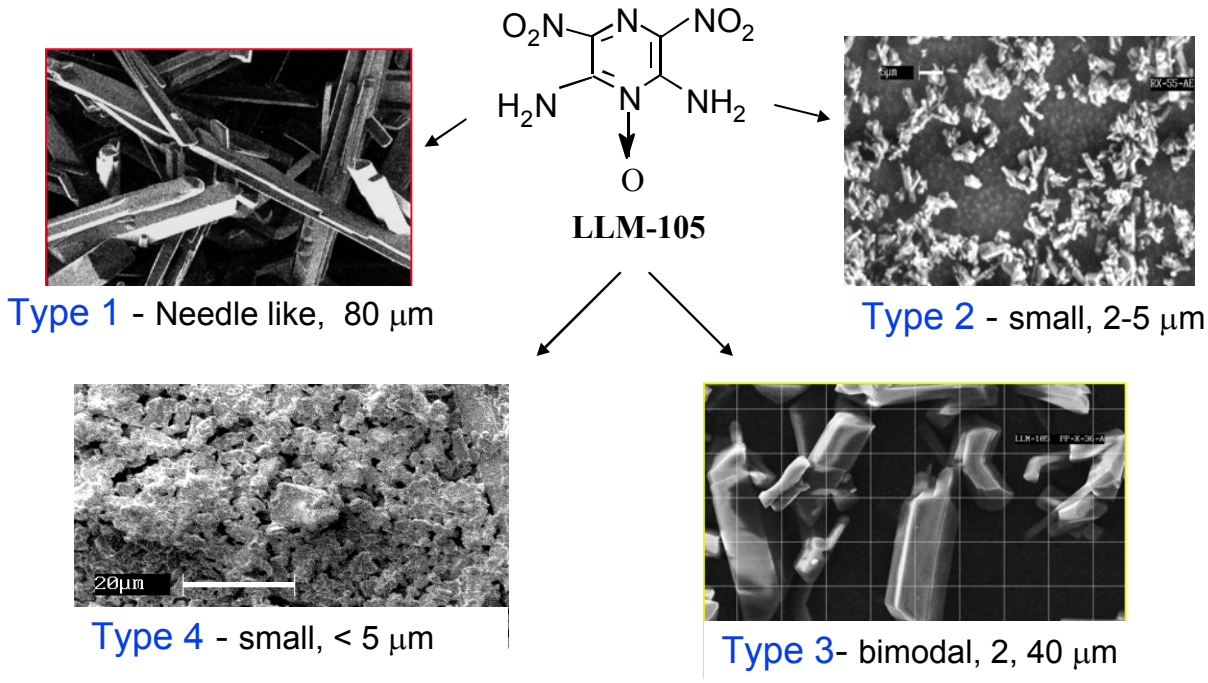
LLM-105 (2,6-diamino-3,5-dinitropyrazine-1-oxide) is a new molecule with performance and insensitivity between HMX and TATB. Its calculated energy content is about 85% that of HMX and 20% more than that of TATB. It is very thermally stable and fairly insensitive to shock, spark and friction. These combined properties make it attractive for applications that require moderate performance, thermal and chemical stability and insensitivity. One such application is as new booster materials that approach HMX in performance. Towards this effort we have formulated several plastic-bonded explosives of LLM-105 with a Viton A or Kel-F binder and compared their physical properties and detonation spreading characteristics to ultrafine TATB (UF-TATB). A series of recrystallization methods produced different particle sizes and morphologies.

Detonation spreading spot-size tests (Floret experiments) were used to measure the divergence characteristics of these LLM-105 formulations and showed higher energy output and superior divergence behavior than UF-TATB. The compressive properties of one prototype LLM-105 formulation (RX-55-AE2) containing 2.5 wt% Viton A binder showed much larger maximum yield stress at higher yield strain. The scale-scale safety data and results from Floret experiments and mechanical compression studies will be summarized.

INTRODUCTION

LLM-105 (2,6-diamino-3,5-dinitropyrazine-1-oxide), first synthesized at Lawrence Livermore National Laboratory[1], is a dense molecule (ρ = 1.913 g/cm^3) with excellent physical properties, good safety characteristics and 20% more energy than TATB. Its molecular structure and several different morphologies are shown in Figure 1. Differential scanning calorimetric traces (peak of exotherm = 354°C) indicated that it is more thermally stable than most HEs and is nearly identical to TATB. It is insensitive to spark and friction and has impact insensitivity (ΔH_{50} = 117 cm) approaching that of TATB (> 177cm). Different LLM-105 morphologies, obtained from various recrystallization methods, have shown a range of impact insensitivity values (ΔH_{50}) between 40 and 117 cm. Synthetic conditions clearly affect the material safety characteristics and this offer a means for controlling their properties. Tiny plate experiments[2], One-Dimensional, Time-to-Explosion (ODTX) measurements[2], shock-loading tests[3], and cylinder studies[3] have shown its insensitivity to shock, thermal stability and predicted performance explosive power. These combined properties make LLM-105 attractive high-performance insensitive high explosive (IHE). Preliminary characterization results were published earlier.[4]

The LLM-105 particle morphology and chemical purity are dependent on its synthetic and processing history. Collaborative synthetic and chemical processing efforts have yielded several materials with a range of particle sizes and morphologies. Pure LLM-105 and plastic bonded composites have been found to possess a range of safety and processing



characteristics. Several of these IHEs were formulated for further characterization in this study.

FIGURE 1: LLM-105 (2,6-DIAMINO-3,5-DINITROPYRAZINE-1-OXIDE) AND SCANNING ELECTRON MICROGRAPHS OF SEVERAL TYPES OF LLM-105 PARTICLES. MICROGRAPHS HAVE APPROXIMATELY THE SAME SCALE (SEE TYPE 4 MICROGRAPH).

Current interest has been on alternative IHE booster materials with detonation divergence properties approaching that of HMX. Booster explosives require small particle sizes and other morphological features for easier initiability. In support of this development, a series of recrystallization methods was developed to yield different particle sizes and morphologies. This approach allows the LLM-105 physical properties to be tailored. One type of LLM-105, for example, most resembling that of ultra-fine TATB (UF-TATB) morphology, i.e., granular shapes with low aspect ratio and some fines, could be prepared directly from synthesis. The impact height (drop hammer results) for this material, however, was lower than other batches. The effects of LLM-105 morphology on physical properties, safety characteristics and, eventually, performance have to be addressed in this initial phase of development.

The detonation-spreading (divergence), spot-size (Floret) test, developed by Kennedy and co-workers[5,6], was selected as the primary screening test for initiability and divergence behavior. The test has no dynamic diagnostics and requires only small amounts of materials, which makes it ideal for rapid performance screening studies. The Floret test enables quick feedback to synthetic chemists and processing engineers so that particle morphologies and formulations can be tailored for a specific application.

With higher energy output and significant initiation performance improvement, a small amount of binder can be introduced. An LLM-105-based plastic bonded explosive can facilitate processing (i.e., handling and pressing) and provide more mechanically robust pressed boosters (as compared to UF-TATB boosters without binder). Pressing tests have demonstrated higher pressed densities in

formulations with binder. Stress-strain measurements in compression at slow and fast strain rates on one formulation were conducted to characterize its mechanical properties.

EXPERIMENTAL

SYNTHESIS AND RECRYSTALLIZATION

LLM-105 may be synthesized by the oxidation of 2,6-diamino-3,5-dinitropyrazine (ANPZ), first reported by DuPont[7] in 1974. The DuPont synthesis of ANPZ was determined by us to be too difficult for scale-up so a Russian[8] procedure was initially employed. This involved reacting commercially available 2,6-dichloropyrazine with sodium methoxide in MeOH to yield 2-methoxy-6-chloropyrazine which was nitrated with nitric acid at 70°C, then treated with NH_4OH in CH_3CN at 60°C to yield 2,6-diamino-3,5-dinitropyrazine (ANPZ). Oxidation of ANPZ with a mixture of trifluoroacetic acid (TFA) and 30% H_2O_2 yielded LLM-105 in 36% overall yield from 2,6-dichloropyrazine. We have made significant improvements during our research and development stage of the scale-up process to the yields and ease of work-up of the Russian procedure. The final oxidation step involved treatment of 2,6-diamino-3,5-dintropyrazine with a mixture of TFA and 30% hydrogen peroxide at room temperature overnight. Approximately 1.2 kg of LLM-105 was synthesized using this procedure, in a series of 95 g batches.

A series of recrystallizations of LLM-105 were performed in an effort to optimize purity and crystal morphology. Table 1 summarizes several of these preparation methods, morphology and drop hammer values. Scanning electron micrographs of selected morphologies are included in Figure 1. Our initial recrystallizations were from DMSO (10% solution, heated to <120°C and slowly cooled - LLM-105 Type 1 in table 1) or crash-precipitated from warm DMSO with cold water (Type 2). These initial recrystallizations gave a product comprised of fine yellow needles that had good drop hammer (ΔH_{50}) values but had a slightly broad Differential Scanning Calorimetry (DSC) curve. The needles had a high aspect ratio and did not press well when formulated with Kel-F. Recrystallization from boiling γ-butyrolactone (BL) (10% solution) or from L/ xylenes yielded "cubic" crystals with a lower aspect ratio (resulting in Type 3 material). A DSC of the L-recrystallized material also had a higher decomposition point of 354°C, suggesting higher purity. The ΔH_{50} values for the BL-recrystallized material ranged from 50-70 cm, a significant drop that cannot as yet be explained. A standard ball mill was also used to prepare particles with smaller size and more fractured morphology (Type 4).

All morphologies are thermally stable and are insensitive to spark and friction (data not included here). The impact sensitivities, however, depended on the particle size and morphology, with ΔH_{50} values ranging from 40 to 117 cm. The relationship between particle morphology and safety characteristics is not well understood and is the subject of an on-going investigation. The factors we are investigating include purity, crystal morphology, impurities and method of synthesis. Several other recrystallization solvents including DMF, DMF/water, NMP, NMP/water all yielded fine needles with similar sensitivity characteristics to the L-recrystallized material. Heating of LLM-105 in polar, aprotic solvents above 100°C for prolonged periods caused the solvent to darken and reduced the recovery of the LLM-105. Some of the work will be reported later.

Recently we developed a new synthesis route for LLM-105 from 2,6-dichloropyrazine (with an overall yield of 50%). Our new procedure involved reacting 2,6-dichloropyrazine with excess NaOMe to yield 2,6-dimethoxypyrazine which was nitrated at room temperature with 100% H_2SO_4 and 98% HNO_3 to yield 2,6-dimethoxy-3,5-dinitropyrazine (DMDP). DMDP was reacted with NH_4OH in CH_3CN to give ANPZ in 80% yield, and subsequently oxidized with 30% H_2O_2/ TFA to give LLM-105 as yellow cubes. This synthesis was scaled-up to produce 1.2 kg of LLM-105 as yellow cubes[9]. Safety and performance characterization of this material is not yet available.

ANPZ, an intermediate in the LLM-105 synthesis process (described above), is another interesting energetic material because it is very insensitive to impact (off-scale on LLNL drop hammer test) and has a DSC exotherm onset temperature of 356°C (at a sweep rate of 10°C/min). It has a lower density than LLM-105, 1.84 g/cm^3, resulting in significantly less power (equivalent to TNT in performance). ANPZ has similar solubility characteristics to LLM-105 and may be recrystallized

from BL/xylenes to give yellow plates. ANPZ is also being investigated as a booster material.

FORMULATION

Several 25g quantities of plastic-bonded explosives containing LLM-105 and a binder (Viton-A or Kel-F) were formulated using a vertical, high shear Cramer mixer. Typically, an acetone solution containing 10% Viton A was prepared in a mixer bowl. An appropriate amount of LLM-105 material was added to this solution. The composite was mixed initially by hand and then remotely under vacuum in the mixer. The slurry was continually mixed with heating until most of the solvent was removed (~ 30 minutes). The powder was recovered into a petri dish and dried under vacuum at 55 ± 5°C for 2 days or until a constant weight was observed. Table 2 lists many RX-55 formulations that were prepared under this work.

Table 1. Summary of several LLM-105 preparative methods, morphology and impact sensitivity

LLM-105 type	Preparation method	Morphology (Average size, micron)	Drop hammer ΔH_{50}, cm
0	Unrecrystallized (from small 95 g batches)	(80)	115-120
1	Slow recrystallization from warm DMSO with hot water	Sharp needles (60)	105
2	Crash precipitated from warm DMSO with cold water	Small particles (2)	60
3	Crash precipitated from γ-Buturylactone with xylene	Rounded granules and small fines (40 + 2)	55-70
4	Type 1 materials subjected to milling for 22 hrs	Fractured granules (2)	80
5	Unrecrystallized (from 1.2 kg large scale batch)	Granular (40-50)	40-90

Table 2. List of formulations containing UF-TATB, LLM-105 and a binder evaluated in this work

Formulation	LLM-105 type	Weight percent, %				TMD, g/cm^3	Drop hammer ΔH_{50}, cm
		UF-TATB	LLM-105	Viton A	Kel-F		
UF-TATB		100				1.938	> 177
LLM-105	0		100			1.913	117
RX-55-AB	1		92.4		7.6	1.921	129
RX-55-AD	2	25	74	1		1.918	
RX-55-AE	2		97.5	2.5		1.911	55
RX-55-AE2	3		97.5	2.5		1.911	69
RX-55-AE3	4		97.5	2.5		1.911	102
RX-55-AE4	0		97.5	2.5		1.911	90
RX-55-AF	2	75	22.5	2.5		1.929	
ANPZ						1.84	> 177

Small cylindrical pellets for Floret experiments and mechanical properties measurements were ram pressed (in a die) at 200 MPa and 105°C for 3 cycles with a 5-minute dwell per cycle under vacuum (400 mtorr or less). Specimens at different densities were prepared by varying the amount of pre-weight powder and pressing to volume.

FLORET TESTS

A modified Floret test, adapted from an original test developed by Kennedy and co-workers[5,6], was used to screen and rank the performance of these materials and other common explosives. This test measures the dent produced on a copper witness plate as a result of the detonating sample. The cavity depth and its shape are useful semi-quantitative measures of the pellet energy and its detonation-spreading

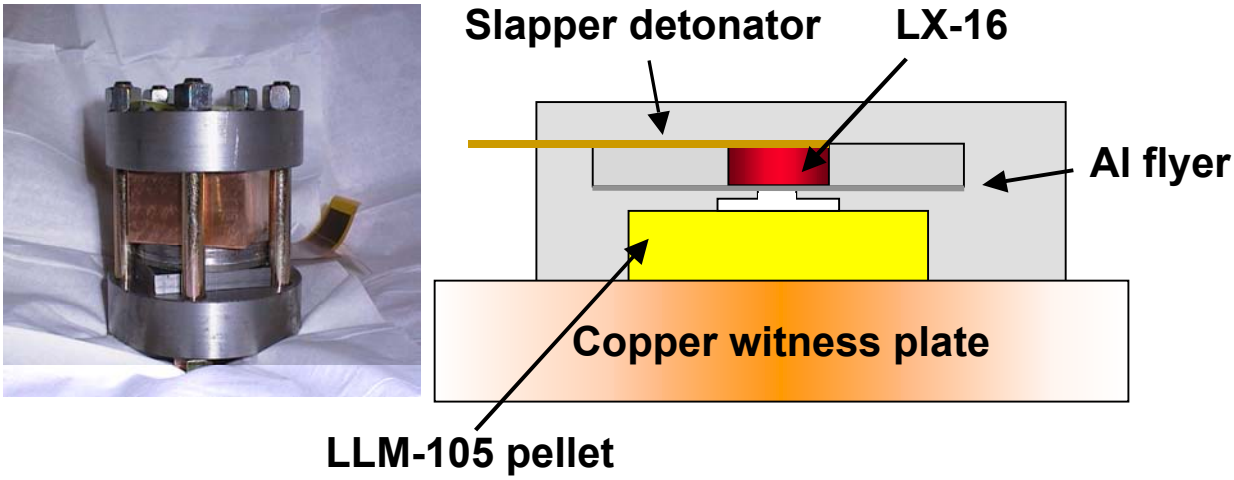


FIGURE 2: THE MODIFIED FLORET TEST ASSEMBLY AND ITS SCHEMATIC

(divergence) characteristics, respectively. Figure 4 shows a schematic of the Floret assembly. This set-up uses the assembly from Cutting's et al. Tiny Plate experiment[2] and contained several modifications to that from Kennedy's design. The two main differences were the use of an Al flyer plate in this work (versus a stainless steel one in Kennedy et al.'s experiment) and steel spacer/housing components held together by thick plates with nuts and bolts. The latter introduces additional confinement to the system.

The test involves initiating a 12.7-mm diameter x 4-mm thick IHE pellet using a 5.1-mm diameter x 0.125-mm thick Aluminum flyer plate. A LX-16 pellet (density = 1.70 ± 0.01 g/cm^3) drives the flyer across a 1.83 mm gap before impacting the acceptor specimen. The LX-16 pellet was detonated with an exploding foil initiator. A copper witness plate (50.8 mm x 50.8 mm square x 25.4 mm thick) placed on the opposite surface, records the output of the detonating pellet. The various components were stacked together with 50.8 mm steel discs as spacer or housing components. The stacks were held together with five 10 mm-diameter nut and bolts. Tests were done at ambient temperature and at -54°C.

The dent shape profile across the center was read using a profilometer (Cordax 1808-MZ DCC MEA, Sheffield Measurement) that was programmed to take reading every 25.4 μm along the horizontal scan through the center of the dent. Minor corrections were made to account for the small tilt and slight offset in the cavity profile record associated with each test. The volumes of the cavities were determined by numerical integration.

RESULTS AND DISCUSSION

The energy output and divergence of formulations containing LLM-105 and a binder were primarily evaluated using the Floret experiments. The dent geometry associated with each material was compared to a series of UF-TATB tests at different densities. The latter results yield different dent sizes, which are useful as a qualitative performance scale.

UF-TATB PERFORMANCE

A series of Floret experiments with UF-TATB at densities between 1.69 and 1.83 g/cm^3 established a baseline of the dent profiles. A blank test was also conducted where a Teflon pellet replaced the UF-TATB sample.

The profiles through the center of the cavities formed from the detonating pellets are shown in Figure 3. The cavities are symmetric as suggested from the profiles shown. The sharp tips in the profiles are artifacts due to the 10-fold compression of the x-axis relative to the y-axis. When the axes are scaled geometrically, the tip of the cavity is fairly spherical in shape. Dent diameters in region in

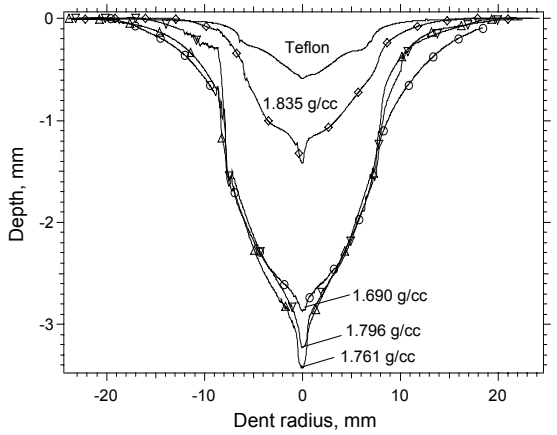


FIGURE 3. CU WITNESS PLATE DENT PROFILES FOR 4 mm-THICK UF-TATB PELLETS AT VARIOUS DENSITIES.

contact with the pellet are generally found to be larger than the diameter of the sample (12.7 mm).

The dent depths and widths reflect a strong dependence of density on the energy output and divergence behavior. While the density range (1.690-1.835 g/cm^3) for these specimens represents only a 10% difference in chemical energy content, the resulting cavity volumes varies by as much as 350%, suggesting a significant difference in energy release. UF-TATB at 1.761 g/cm^3 yielded the deepest dent. The pellet at this density appears to be completely reacted as no residue was found after the test. The 1.83 g/cm^3 pellet showed a much smaller cavity. Yellow TATB powder was observed after the experiment, indicative of a partial reaction. The difference in the cavity sizes is attributed to the different divergence behavior in these samples. Good divergence in lower density materials (e.g., 1.761 g/cm^3) facilitated lateral spreading of the detonation wave and allowed most or all of the pellet to react. On the contrary, poor divergence in the densest pellet (1.835 g/cm^3) resulted in less lateral spreading, produced less energy and, therefore, a smaller dent. Comparing to the dent size from a blank (Teflon), the larger dent for this (highest density) pellet indicated that at least some of the UF-TATB materials reacted.

This semi-quantitative relationship between the cavity volumes and density provides a useful scale for ranking the relative divergence behavior of new formulations. Such information can provide quick feedback on the effects of experimental variables on the material performance.

The results on density effects here are consistent with the trend observed by Lee and co-workers[6] for UF-TATB. However, the cavities in these tests are about twice as deep. The larger dent sizes are attributed to higher confinement in our experiments as well as other experimental factors (different flyer material and a larger gap). Also, the UF-TATB materials are different.

The reproducibility of the dent depth and shapes was evaluated in three Floret tests with RX-55-AE2 conducted under identical conditions. The results are shown elsewhere[4]. The shape and general features of the cavity are very reproducible. The integrated volumes are reproducible to about 5%.

BINDER EFFECTS

Figure 4 compares the performance of four formulations containing various LLM-105 concentrations and particle morphologies with that of UF-TATB. All composites containing LLM-105 show profiles that are deeper and wider than that of the optimum UF-TATB pellet (at 1.796 g/cm^3). RX-55-AB (92.5 wt% LLM-105, 7.5 wt% Kel-F, see Table 2), formulated like LX-17, was pressed to high density and still produced more energy output than that of UF-TATB. RX-55-AE with 97.5 wt% LLM-105 (type 2) and 2.5 wt% Viton A binder showed the largest profile. RX-55-AE2 formulation, consisting of another type of LLM-105 (type 3) with the same amount of binder, showed slightly less energy than the formulation containing the type 2 particles but

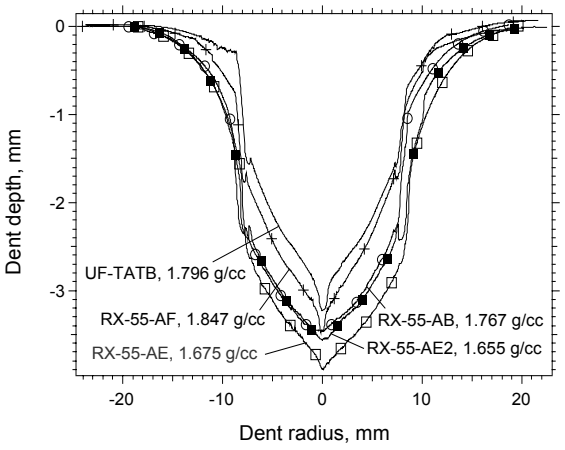


FIGURE 4. DENT PROFILES COMPARING SEVERAL FORMULATIONS OF LLM-105 (SEE TABLE 2) AND UF-TATB AT 1.796 g/cm^3.

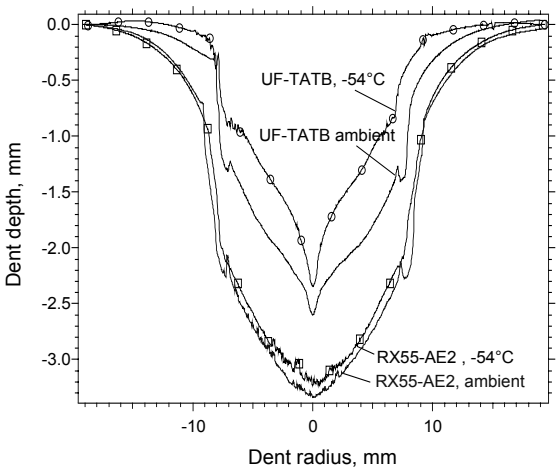


FIGURE 5. COMPARISON OF DENT PROFILES OF UF-TATB AND RX-55-AE2 AT AMBIENT CONDITIONS AND AT - 54°C.

was still superior to UF-TATB. RX-55-AF (75 wt% UF-TATB, 22.5 wt% LLM-105, 2.5 wt% Viton A) showed UF-TATB-like profile but higher energy output. The results represent a large range of composites containing different variables that can be manipulated to tailor the properties of LLM-105-containing formulations. Such parametric studies to optimize the binder type and composition and type of LLM-105 morphologies can be extensive and have not been started. RX-55-AE formulation containing 97.5 wt% LLM-105 and 2.5 wt% Viton A binder was selected as a prototype formulation for further characterizations.

EFFECTS OF TEMPERATURE

A comparison of the performance between UF-TATB and LLM-105 formulations at ambient conditions and at - 54°C is shown in Figure 5. A 3.8-mm diameter aluminum flyer plate was used to initiate the RX-55-AE2 pellets in the cold tests. Under similar conditions, UF-TATB would not be initiated. The profile for cold RX-55-AE2 is deeper and broader than that for UF-TATB. Also, the temperature effect on RX-55-AE2 is much less pronounced than that seen for UF-TATB. While the better cold temperature performance with LLM-105 samples could be anticipated, the weak temperature dependence was indeed significant. The results clearly demonstrate that the detonation-spreading behavior of this LLM-105 formulation was superior to that of UF-TATB at cold temperature.

EFFECTS OF FLYER SIZE

In light of the superior divergence of RX-55-AE2 formulations, it was of interest to study the use a smaller flyer plate for initiation. The results are illustrated in Figure 6 for aluminum flyer plates with diameters between 2 to 5.1 mm. RX-55-AE2 pellets at similar densities (1.660 ± 0.005 g/cm^3) were used in these tests. Full detonation was observed for all tests. The profiles for all tests are deeper and broader than that for UF-TATB. Divergence in these RX-55-AE2 pellets is good and the resulting lateral spreading consumes most or all of the pellets since no yellow LLM-105 residue was observed. The relationship of the dent depth and volume and the flyer diameter is not easily discerned from the Figure. The results, nevertheless, demonstrated that a much smaller flyer could be used to initiate formulations containing LLM-105. The failure diameter of this formulation is clearly less than 2 mm.

RANKING OF LLM-105 PERFORMANCE

A series of Floret experiments were conducted to rank LLM-105 formulations against other high explosives (LX-04, PBX 9501, TNT, Composition B) as well as LX-17 and PBX 9502. The Floret cavity profiles are compared in Figure 7. As expected, both LX-17 and PBX 9502 failed to initiate because the flyer size is well below their failure diameters.[10] The profile for RX-55-AE2 ranks

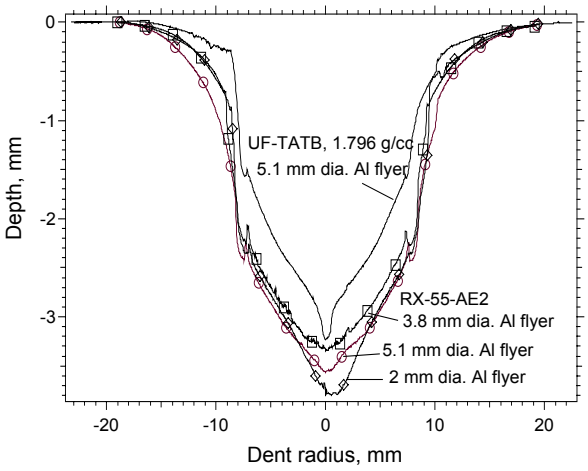


FIGURE 6. EFFECTS OF FLYER PLATE DIAMETER ON DENT PROFILES OF RX-55-AE2. TESTS CONDUCTED AT AMBIENT CONDITIONS.

only below HMX-based LX-04 and PBX 9501 in terms of volumes. The results clearly show the superior performance of LLM-105.

The volumes of the Floret dents were integrated numerically using an Excel spreadsheet. The energy of the Floret sample was calculated from the theoretical heat of detonation and the actual mass of the pellet energetic component. The total energy yield discussed here also includes the energy content from the LX-16 initiating pellet. Figure 8 plots the integrated volumes versus the theoretical detonation energy. This relationship is meant here to obtain insights onto relationship between LLM-105 energy and their dent sizes and how they compared to both UF-TATB and other common explosives. Lee et al.[6] have correlated the Floret energy to the dent profile using the Johnson-Cook model to treat the material strength of the copper. We have not attempted to model how the initiating pellet affects the Cu witness plate. The relationship obtained here only serves as a semi-quantitative guide to explore the utility of this test.

The dent volume-detonation energy relationship for UF-TATB for a series of 4 mm specimens (Fig. 8) is parabolic and reflects an expected dependence of both energy density and divergence characteristics. The volumes are largest in the intermediate density range where divergence in UF-TATB is best. Divergence is poor for the high density resulting in less material consumed and a smaller volume. Energy

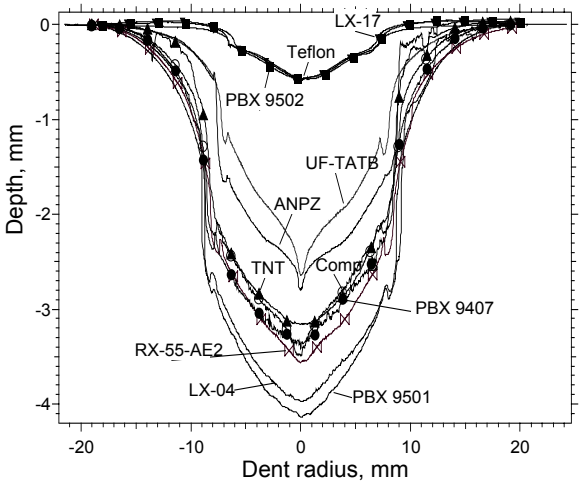


FIGURE 7. DENT PROFILES FOR 4 mm THICK SAMPLES OF RX-55-AE2 AND OTHER EXPLOSIVES.

contents are reduced at the lowest densities where the dents are proportionally smaller. The sensitivity of the dent depths and volumes to various LLM-105 formulations, on the other hand, is not quite as great. Although all values showed larger volumes (compared to UF-TATB), they appear to be insensitive to factors such as density effects (unpublished results) or flyer size effects (see Figure 6). The dent profiles for LLM-105 composites are comparable to those for many common HEs, suggesting that the Floret samples were fully reacted under these conditions. Perhaps the current test would not be useful to discern small divergence differences associated with particle size differences in LLM-105 formulations. A number of means can be considered to modify the Floret test to enhance its sensitivity to divergence. These include cold temperature operation, larger diameter acceptor pellet at same flyer size for more lateral wave spreading or thinner acceptor pellet.

A series of experiments with thinner pellets (at 2 mm thick) were conducted to evaluate the test sensitivity to LLM-105 particle morphology and density effects in three RX-55-AE formulations, RX-55-AE2, RX-55-AE3 and RX-55-AE4 (see Table 2). Also, several thinner UF-TATB samples were initiated for comparison. The volumes are included in Figure 8. The dent volumes for the thinner pellets

were reduced by approximately one-half. The test sensitivity appears greatly enhanced, as the volume changes associated with different formulation are

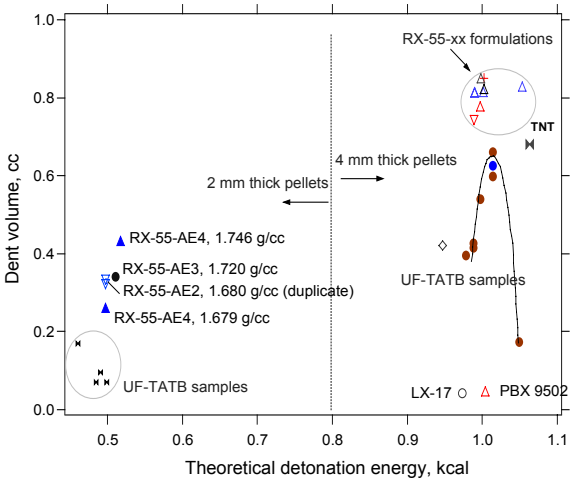
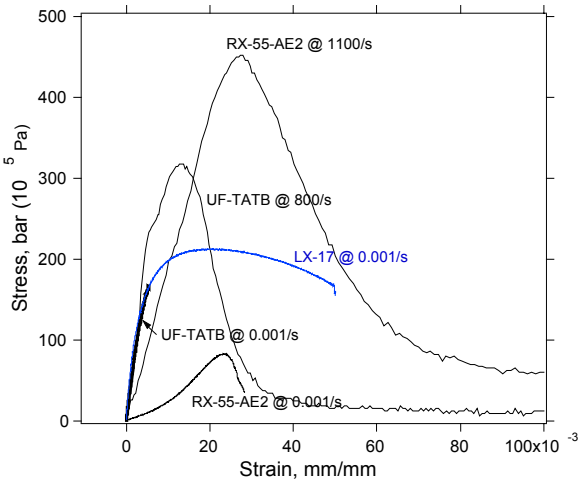


FIGURE 8. PLOT OF INTEGRATED DENT VOLUMES VERSUS PELLET HEATS OF DETONATION.

expanded than that observed in 4 mm specimens. The reproducibility is good and the dent volumes suggest that divergence is better with Type 2 particle than that associated with Type 0. The smaller particles observed in type 2 support this trend. The effect of density is also substantial in thin pellets. More work, however, is needed to calibrate and discern this effect. The initial results demonstrate that the modified Floret experiments appear to have enough sensitivity to screen for divergence changes associated with particle morphology difference, density and other parameters in LLM-105 formulations.

ANPZ is an intermediate in the production of



LLM-105. It has about 20% less energy per unit volume but provides advantages in simpler synthesis route and less sensitivity. The impact sensitivity (shown in Table 2) is comparable to that of UF-TATB. The dent profile of ANPZ with fine particle sizes (similar to those typical of UF-TATB) is included in Figure 7, showing higher energy and better divergence characteristics than UF-TATB.

COMPRESSION STUDIES

Intermediate and high rate compressive tests at room temperature were performed using a hydraulically-actuated tensile/compressive test set-up

FIGURE 9. COMPRESSIVE BEHAVIOR OF UF-TATB AND RX-55-A2 AT INTERMEDIATE AND FAST STRAIN RATES. INTERMEDIATE RATE SAMPLES, 12.7 mm DIAMETER BY 25.4 mm LONG. FAST RATE SAMPLES, 7.62 mm DIAMETER BY 3.81 mm LONG. TESTS DONE AT AMBIENT CONDITIONS.

and a split Hopkinson Bar. The data is shown in Figure 9. For reference, a typical stress-strain curve for LX-17-1 at room temperature and 10^{-3} s^{-1} strain rate is also shown. At high rates (on the order of 1 x 10^{3} s^{-1}), RX-55-AE2 shows a peak strength of about 450 bar. Engineering strain at peak strength is about 2.5%. By contrast, UF-TATB shows less peak strength (310 bar) with the peak occurring at only 1.2% (0.012 mm/mm) strain. After achieving its peak

strength, the UF-TATB stress curve falls off quickly, which is indicative of relatively poor mechanical integrity in this binderless material. To assure ourselves that these results were not specimen size dependent, we generated additional data using specimens of a somewhat different geometry. The results from these tests are not included, but were consistent with previous data and so we believe specimen geometry was not a factor. At low strain rates ($10^{-3}s^{-1}$), UF-TATB shows considerable peak mechanical strength but fail catastrophically at very low strain (< 1%). While the strengh of RX-55-AE2 at this slower strain is less than that for UF-TATB, it fails in a far less brittle manner, with strain at peak stress in excess of 2%.

SUMMARY

Small-scale safety tests, pressing studies, Floret experiments and mechanical properties measurements were conducted to characterize several formulations containing LLM-105 and another binder. The properties are compared to those for UF-TATB. The results demonstrate that LLM-105 is a promising high-performance insensitive high explosive. Several LLM-105 formulations developed as booster materials show higher energy, superior divergence characteristics and better mechanical strength than UF-TATB. Even-higher performance can be expected with improved LLM-105 particle morphology and a selection of a higher density formulation.

ACKNOWLEDGEMENT

S. Weber, L. Lauderbach and R. Weese helps with the small-scale safety analysis and pressing. G. Lee helps with the synthesis. R. Hanks and P. Wilkins assisted with data analysis. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

REFERENCES

1. Pagoria P., A. Mitchell, R. Schmidt and L. Fried, Munitions Technology Development Program, UCRL-ID-103483-99, p. II-5, (1999).

2. Cutting J., H. Chau, R. Hodgin, D. Hoffman, F. Garcia, R. Lee, E. McGuire, A. Mitchell, P. Pagoria, R. Schmidt, R. Simpson, P. Souers and R. Swansinger. *Proceedings of the 11th International Detonation Symposium*, Office of Naval Research, ONR 33300-5, p. 828. (1998).

3. Forbes, J. and Souers, C. personal communication, LLNL.

4. Tran T., P. Pagoria, D. Hoffman, J. Cutting, R. S. Lee and R. L. Simpson. *Proceedings of the 33rd International Annual Conference of ICT*, Karlsruhe, Germany, June 25-28, (2002).

5. Kennedy J., K. Lee, T. Spontarelli and J. Stine. *Proceedings of the 24th International Pyrotechnics Seminar*, p. 743-748, Monterey, CA, July (1998).

6. Lee K., J. Kennedy, L. Hill, T. Spontarelli, J. R. Stine and G. Kerley. *Proceedings of the 11th International Detonation Symposium*, Office of Naval Research, ONR 33300-5, p. 362. (1998).

7. Donald D. S., U.S. Patent 3,808,209, Apr. 30, (1974).

8. Russian Patent SU 1703645A1.

9. Schmidt R., G. Lee, P. Pagoria and P. Hsu, personal communication, LLNL.

10. Campbell A., and R. Engelke. *Proceedings of the Sixth International Detonation Symposium*, Office of Naval Research, Department of Navy, ACR-221, p. 642, (1977).