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Primary Explosive Processing in the Resonant Acoustic Mixer

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Abstract: Over the last decade, resonant acoustic mixing (RAM) technology has rapidly matured for use in the defense sector. Its ability to rapidly mix even highly viscous substances through application of acoustic energy while avoiding the use of traditional blades has provided substantial leaps forward in both safety and efficiency. To date, RAM has been applied by the energetics community to a variety of secondary explosive and propellant formulations with no reported incidents; however, the technology has never been rigorously evaluated with highly sensitive energetic materials, such as primary explosives. The work described in this report was performed to facilitate the establishment of safe operating procedures for the RAM mixing of primary explosives and primary explosive formulations. Through a Design of Experiments (DOE) approach, an analysis of mixing conditions that produce an initiation event was performed, which were used to set boundaries for the safe mixing of primary explosives and primary explosive formulations. For initial trials, uncoated copper (I) 5-nitrotetrazolate (DBX-1) was utilized, and boundaries were set for the results of this material only.

Keywords: Resonant Acoustic Mixing · Primary Explosives · DBX-1

1 Introduction

Resonant Acoustic Mixing (RAM) is a new bladeless mixing technology that operates through the use of resonant acoustic energy coupled to the formulation medium itself. Specifically, the RAM process is thought to be enabled by the production of Faraday Instabilities within the medium for rapid and efficient blending that does not generate any "dead zones" [1]. Recently, RAM technology has seen a tremendous amount of attention for the safe processing of energetic materials [2], with the majority of work being performed with secondary explosives, and propellants. Initial research has focused on the mixing of high viscosity cast-cure formulations [3–5], with end-of-mix (EOM) viscosities well exceeding that which can be accomplished through traditional bladed high shear mixers [6]. This cast-cure work was further progressed into mix-in-case (MIC) technology, where the raw ingredients are loaded into the end-item and the item itself acts as the mixing vessel on the RAM apparatus [7]. Additionally, research has focused on the use of RAM to generate small batches of energetic co-crystals with success [8]. However, very limited research has been performed to date beyond the extreme viscosity cast-cure formulations and co-crystal generation, and only minimal work has been performed with primary explosives or primary explosive formulations [9].

A primary explosive is an explosive chemical compound or formulation that can be triggered by a relatively small stimulus (impact, spark, heat, etc.) to initiate deflagration or detonation in another energetic material. These materials are essential components to almost all military and commercial munitions currently in use. In contrast to most secondary explosives, minute quantities (milligrams) of primary explosives are capable of undergoing detonation. Primary explosive formulations are used at the beginning of the explosive train, in which these materials are used to initiate booster or main fill secondary explosive formulations. Figure 1 shows a typical explosives train utilized for commercial and military munitions.

Table 1 provides a comparison of impact, friction, and electrostatic discharge (ESD) values that are required to initiate typical primary and secondary explosives.

Current primary explosive formulations utilize materials that contain the toxic material lead, such as lead azide and lead styphnate. There is a substantial effort to develop primary explosive materials and formulations that do not contain lead, for enhanced health and environmental considerations. One of the materials under development is copper(I) 5-nitro-

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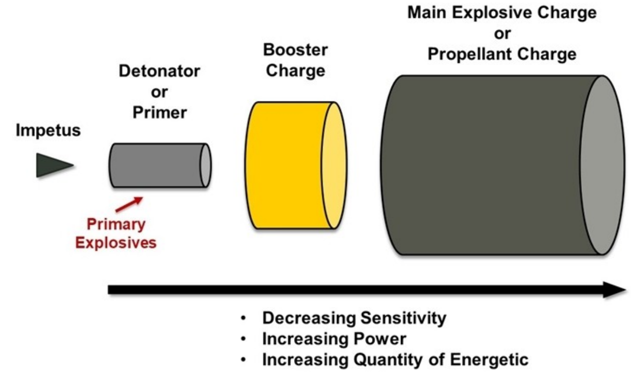


Figure 1. Illustration of a Typical Explosive Train.

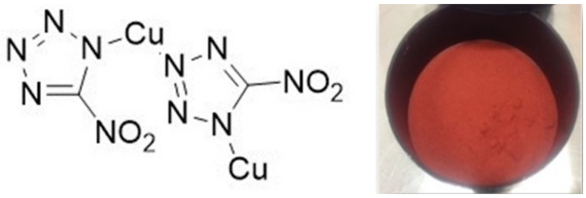


Figure 2. Chemical Structure (left) and Image (right) of DBX-1.

tetrazolate (DBX-1). DBX-1 was first reported by Pacific Scientific Energetic Materials Company (PSEMC) and US Navy, Naval Surface Warfare Center – Indian Head Explosives Ordnance Disposal Technology Division (NSWC-IHEODTD) and has sensitivity that is comparable to lead azide [10]. Presently, the synthesis process has been scaled to 100 gram levels and the material has been qualified by the US Navy and the US Army Energetic Materials Qualification Board (EMQB). US Army Combat Capabilities Development Command Armaments Center (DEVCOM AC) has worked to replace lead and mercury-based primary explosives with DBX-1 for much of the past decade by testing in several items (e.g. fuzes, blasting caps, primers, etc.). DEVCOM AC qualified this material at the 500 g lot scale, with approval granted by the EMQB in 2017. Currently, DEVCOM AC is working to scale-up the process for manufacturing DBX-1 at larger scales and qualify in different items. Figure 2 shows the structure of DBX-1 and a picture of the synthesized raw material and Table 2 provides an explosive property comparison between DBX-1 and common primary explosives lead azide and lead styphnate.

The existing formulation technique for primary explosives utilizes a bladed mixer and volatile liquid wetted materials (typically water). There are several safety and performance concerns regarding this mixing technique that include hand mixing small batches for research and development (R&D) purposes, settling due to density variations, and performance variations due to poor mixing. Hence, there is a need for an alternate in-line mixing process during primer loading, and RAM technology could provide this alternative method. The work described in this report was performed to facilitate the establishment of safe operating procedures for the RAM mixing of primary explosives and primary explosive formulations. Through Design of Experiments (DOE) approach, an analysis of mixing conditions that produce an initiation event were performed, which were used to set boundaries for the safe mixing of primary explosives and primary explosive formulations. For initial trials, uncoated DBX-1 was utilized, and boundaries were set for the results of this material only.

2 Experimental Section

The current processing and formulation methods for primary explosives present challenges both in terms of safety and effectiveness. Traditional bladed mixers can induce high shear forces and pinch points, leading to unintended initiation of the sensitive materials. Numerous incidents associated with the production of primary explosives have been reported over the last century, resulting in loss of life, serious injury, and/or significant property damage. Furthermore, primary explosive formulations, such as percussion primer mixes, can often suffer from inhomogeneity during and after the mixing process, leading to reliability is-

Table 1. Sensitivity Value Comparison for Typical Primary and Secondary Explosives.

Material	Impact (J)	Friction (N)	Electrostatic Discharge (J)
Primary Explosive	0.01–2.0	0.1–10.0	0.001–0.10
Secondary Explosive	>7	>120	>0.25

Table 2. Sensitivity and Explosive Properties of DBX-1, Lead Azide, and Lead Styphnate.

Material	Impact (J)	Friction (N)	Electrostatic Discharge (mJ)	Density (g/cm^3)	DSC Exo. (°C)	Detonation Velocity (km/s)
DBX-1	0.03	<0.1	3.1	2.58	333	~6.9
Lead Azide (RD-1333)	0.05–0.08	<0.1	4.7	4.80	315	5.3
Lead Styphnate (Basic)	0.04	<0.1	2.0	3.00	282	4.9

Table 3. Design of Experiment Input Factors.

	DOE Level 1	2	3	4	5	6
LabRAM Variable:						
Acceleration (G-force)	40	70	100			
Sample Variable:						
Liquid Content (wt% IPA)	50	40	30	20	10	0
Container Volume Fill (%)	50	70	90			
Container Size (mL)	0.13	1.65	3.73			

sues for the items they are loaded into. This is often the result of the mixes containing multiple components possessing wide variations in density, which can lead to mix settling.

To address these safety and effectiveness issues, new mixing methodologies for primary explosives and their formulations are needed. RAM technology presents a promising means to solving both problems based on its relatively low energy, blade-less mixing as well as its track record for homogenous mixing of high-solids, highly viscous materials.

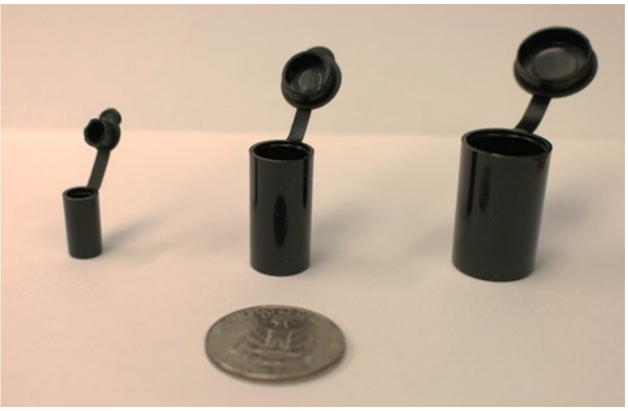


Figure 3. Conductive Sample Vials: 0.13 mL (left), 1.65 mL (center), and 3.73 mL (right). The coin shown is a standard US quarter dollar.

2.1 Design of Experiments (DOE)

Initial studies focused on DBX-1, a developmental lead-free primary explosive, which is highly sensitive to impact, friction, and electrostatic discharge (ESD). This material is desensitized by wetting or immersing in a liquid such as isopropyl alcohol (IPA). A modified Design of Experiment (DOE) was established to set the testing protocol for the trials. The input factors for the DOE were degrees of liquid wetting (0–50 weight %), filling conditions (50, 70, and 90% full), container size (small, medium, and large), and acceleration (40, 70, and 100 G). Table 3 provides the input factors and separates these factors into a single LabRAM variable and three sample variables. Figure 3 shows a picture of the three conductive sample vials used in these trials; the selected sizes were 0.13 mL, 1.65 mL, and 3.73 mL which could hold approximately 0.15 g, 1.00 g, and 2.60 g of DBX-1, respectively (for point of comparison, typical military detonators and blasting caps contain between 0.020 and 0.500 g of primary explosive).

The modification to the DOE was that the container size was not systematically varied throughout the trials, but rather the smallest container was used in the first trial, the intermediate size container was used for the second trial, and the largest container was used in the final trial. The rationale for not systematically varying the container size is that the initiation potential was not known a priori, and it was desired to limit the amount of material in the initial trials for safety purposes. The outcomes evaluated were initiation (Go/No–Go) and sample temperature at the end of the mixing cycle. For this testing, a "Go" was any chemical or physical change or reaction of the material. This included, but was not limited to: crystal breaking, charring, smoking, deflagration, explosion, or detonation. To ensure that the wetting liquid did not undergo significant evaporation during the trial, the mix times were limited to 5 minutes maximum. A full factorial DOE was developed with the aforementioned input factors, which produced a total trial size of greater than 550 runs. Since the available amount of DBX-1 was limited for these trials, the trials were pared down to the highest risk runs that were considered potential initiation capable events. As such, all liquid wetting concentrations above 30 wt% and the fill level of 50% were not examined in this research.

2.2 RAM Mixing

A LabRAM unit was donated to DEVCOM AC by Resodyn Acoustic Mixers for these trials under a Cooperative Research and Development Agreement (CRADA) [11]. The LabRAM has a maximum sample capacity of approximately 500 grams. Due to the small footprint and thin walls of the sample vials, the standard sample holder supplied by Resodyn Acoustic Mixers could not be used with single vials, as the vials were crushed under the required force to hold the sample in place without moving with high accelerations. As such, custom sample holders were fabricated for each sample vial. The custom sample holders were fabricated from $^1/_2$-inch thick rounds of high-density polyethylene. Top and bottom plates were fabricated with four to eight countersunk holes around the edge (eight holes for the 0.13 mL vials, six holes for the 1.65 mL vials, and four holes for the 3.75 mL vials) and one countersunk hole in the middle of the plates, in which sample vials are placed. The empty vials around the edge are designed to distribute the clamp-down forces over a wider area, such that the sample vial in the middle of the fixture is not crushed. By countersinking the holes, there was no possibility that the vials would "walk out of the fixture" during the mixing process. Finally, four alignment rods were installed into the fixture to enable ease of assembly. Figure 4 illustrates the custom fixture for the 0.13 mL vials.

To perform the testing, the requisite amount of DBX-1 and liquid (if needed) was loaded into the sample vial, the sample vial was placed into the middle of the custom sample holder, and the top plate was installed to complete the assembly of the sample holder. The sample holder was clamped into the RAM, the mixing room was secured, and the sample was subjected to the requisite acceleration per the DOE for five minutes duration. After the sample was recovered from the LabRAM, a small portion of select no-go samples were collected for scanning electron microscopy (SEM) analysis, to observe possible changes in particle size or morphology as well as to evaluate any signs of reaction at the micron to sub-micron level. Typically, samples that were deemed the highest risk for initiation were selected for SEM analysis. Sample recovery protocol is described below in "Safety Considerations."

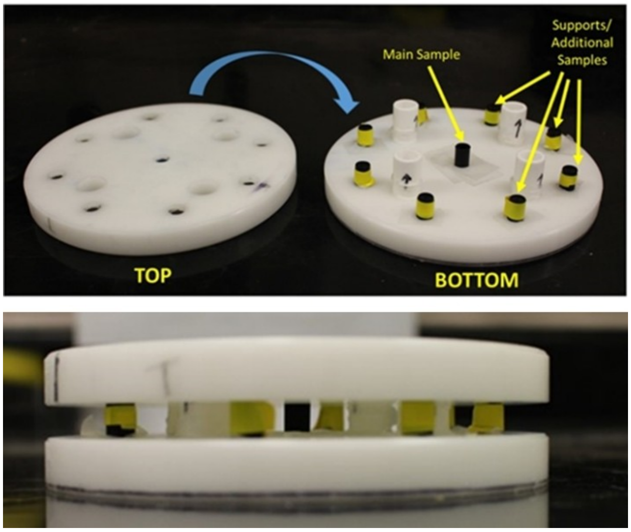


Figure 4. Custom Sample Holder for 0.13 mL Vials: (Top) Unassembled, and (Bottom) Side View of Assembled Holder.

2.3 Safety Considerations

Numerous safety considerations were observed in the testing protocol. First, a safety enclosure was built around the LabRAM unit, which was open on the top and had 2" thick Lexan (polycarbonate) walls around the perimeter, as shown in Figure 5.

The safety enclosure was designed such that in the event of the high-order reaction, the blast wave was directed upward to the ceiling, and all debris would be contained inside the enclosure. This precaution was needed for two reasons: first, personnel entering the lab would be protected in the case of the delayed reaction, and second, all other equipment located in the laboratory would be protected from the high order reaction event. The next safety precaution was the time to enter the mixing room after an apparent "No-go". For all wetted samples, a wait period of five (5) minutes was required prior to entry into the mixing room. For all dry samples, a wait period of overnight was required prior to entry into the mixing room. Finally, for wetted samples, upon entry of the room, a FLIR camera was used to assess the state of the sample. If the sample had a measured temperature of greater than 75 °C, or if the temperature was increasing independent of the initial measured temperature, the operator was to immediately vacate the mixing room and wait another five minutes before reentry. The two conditions just described were an indication of a reaction that had occurred or was occurring, meaning that sample recovery could not be completed safely. Once

Figure 5. Safety Enclosure for LabRAM.

the temperature fell below 75 °C or the sample temperature ceased rising, the operator could open the front door to the enclosure and retrieve the sample. For dry samples, it was assumed that if no reaction had occurred overnight, the sample was safe to recover first thing in the morning the subsequent day. In order to enter the mixing room, the operator was required to wear personal protective equipment (PPE) appropriate for the handling of dry primary explosives, including conductive shoes, safety glasses, face shield, cut-resistant neck guard, and cut-resistant gloves/ sleeves.

3 Results and Discussion

3.1 DBX-1 Mixing Studies

3.1.1 Trial Set #1 (Small Sample Containers)

To minimize the amount of material utilized for the first trial, the 0.13 mL conductive vial was utilized. This vial was able to be loaded with a maximum of 157 mg of DBX-1, which would not create a significant blast wave if a high order reaction were to occur during mixing. Table 4 (Runs 1–6) provides the individual input variables and result summar for Trial Set #1. None of the runs showed any signs of a "Go" reaction. Specifically, there was very little temperature increase for any run, and the material visually looked intact after the run was completed, even under dry conditions. For the runs that were initially set to have an acceleration of 100 G, the machine was only able to reach approximately 94 to 96 G. This reduced acceleration from the desired set point was due to the weight of the sample holder. The mass of the sample holder exceeded 500 grams, such that the total mass of the sample and sample holder exceeded the weight limitations of the LabRAM and the LabRAM was only able to reach the aforementioned acceleration levels. Nonetheless, the accelerations reached are within reason of the desired setpoint, and the runs were considered valid. Additionally, due to the small amount of material that was used in these runs, it was difficult to exactly reach 90 % fill volume. Prior to any runs, material masses were calculated to reach the desired fill volumes, based on known bulk densities of DBX-1. Unfortunately, it appears that the bulk density used for the calculation was slightly higher than the actual bulk density, and the total fill volume was closer to 95 %. Again, the actual volume was within reason of the desired volume and the runs were considered valid.

3.1.2 Trial Set #2 (Medium Sample Containers)

For the second trial set, the 1.65 mL conductive vial was used, which allowed for a maximum load of approximately

Table 4. Summary of LabRAM Mixing Trials with DBX-1.

	Run #	DBX-1 Vol %	DBX-1 Mass (g)	Liquid (Isopropanol) wt %	Liquid (Isopropanol) mL	Temperature Change (°C)	LabRAM Acceleration Setting (G) Attempted	LabRAM Acceleration Setting (G) Achieved	Result (Go/No–Go)
Trial Set #1	1	70	0.122	30	0.066	<2	40	40	No-Go
	2	70	0.122	30	0.066	<2	100	94–96	No-Go
	3	95	0.157	20	0.050	<2	40	40	No-Go
	4	95	0.157	20	0.050	<2	100	94–96	No-Go
	5	95	0.157	0	0.000	<2	40	40	No-Go
	6	95	0.157	0	0.000	<2	100	94–96	No-Go
Trial Set #2	7	70	0.750	40	0.636	<2	100	94 – 97	No-Go
	8	70	0.750	40	0.636	<2	100	94–97	No-Go
	9	70	0.750	30	0.409	<2	100	94–97	No-Go
	10	90	0.964	30	0.526	<2	100	94–97	No-Go
	11	90	0.964	20	0.307	<2	70	70	No-Go
	12	70	0.750	10	0.106	<2	100	94–97	No-Go
	13	90	0.964	10	0.136	<2	70	70	No-Go
	14	90	0.964	10	0.136	<2	100	94–97	No-Go
	15	70	0.750	0	0.000	<2	70	70	No-Go
	16	90	0.964	0	0.000	<2	70	70	No-Go
	17	90	0.964	0	0.000	<2	100	94–97	No-Go
Trial Set #3	18	70	2.032	10	0.287	<2	70	70	No-Go
	19	90	2.612	10	0.287	<2	100	94–97	No-Go
	20	70	2.032	0	0.000	<2	70	70	No-Go
	21	70	2.032	0	0.000	<2	100	94–97	No-Go
	22	90	2.612	0	0.000	<2	70	70	No-Go
	23	90	2.612	0	0.000	<2	100	94–97	No-Go

1 g of DBX-1. Table 4 (Runs 7–17) provides the individual input variables and the results of the runs for Trial Set #2. As with the first trial, none of the runs showed any signs of a "Go" reaction. All of the runs showed minimal temperature rises, and there were no visible signs of reaction after the run was completed, even under dry conditions. Again, as with the previous Trial Set, the maximum G-force was approximately 94–97 G due to the weight of the sample holder.

3.1.3 Trial Set #3 (Large Sample Containers)

For the third trial set, the 3.73 mL conductive vial was used, which allowed for a maximum load of approximately 2.6 g of DBX-1. Based on the results from Trial Set #2, the number of runs in Trial Set #3 was reduced to what was considered the extreme cases for probable reaction. Table 4 (Runs 18–23) provides the individual input variables and the results of the runs for Trial Set #3. None of the runs again showed any signs of a "Go" reaction. All of the runs showed minimal temperature rises, and there were no visible signs of reaction after the run was completed, even under dry conditions. Again, as with the previous Trial Set, the maximum G-force was approximately 94–97 G due to the weight of the sample holder. Based on the lack of temperature rise seen in any of the trials conducted, there was concern that the material was not mixing, and was simply stuck to the bottom of the mixing vessel during the entire mixing process. Since only a single material was used for all of the trials sets thus far, it was impossible to discern if mixing was occurring. Thus, to test for mixing, a second material of a different color was identified and a mixing run with the two materials was proposed.

3.1.4 Mixing Validation Study

Cobalt Aluminate Blue was identified as a candidate for the mixing validation studies. This material is used as a pigment in various applications and is known to have a bright blue color. Before any mixing activities, the Cobalt Aluminate Blue was tested for compatibility with the DBX-1 using the Differential Scanning Calorimetry (DSC) method. In this method, the two materials are mixed and a small amount of the mixture is placed in a sealed DSC pan. The sample is heated at 5 °C per minute until an exotherm is noted, which correlates to the degradation temperature of the energetic material. The materials are deemed compatible as long as the exotherm on-set is not more than 4 °C depressed from that of the virgin material. The exotherm on-set for virgin DBX-1 is approximately 313.8 °C, and the exotherm on-set for the DBX-1 with Cobalt Aluminate Blue was approximately 314.4 °C. As such, these two materials were deemed compatible. For the mixing validation study, equal amounts of Cobalt Aluminate Blue and DBX-1 were added to a 3.73 mL mixing vessel to a fill volume of 90 %, with the Cobalt Aluminate Blue being added first to the bottom of the mixing vessel and the DBX-1 being added second on top of the Cobalt Aluminate Blue. The sample was mixed at 100 G for five minutes, and the resultant material was analyzed for color. Figure 6C shows a picture of the resultant material post-mixing compared to the neat ingredients (Figure 6A and 6B).

From Figure 6, it is evident that the two materials are homogenously mixed after the mixing cycle. The material is a single color, of slightly purplish tint, indicative of a red and blue material being mixed. There are no streaks of red or blue throughout the material, and examination of the mixing container showed that there was no material stuck to the bottom of the cup after the material was poured out. This result validated that mixing is occurring and the material is not simply stuck to the bottom of the mixing vessel during the mixing process. A lack of temperature rise indicates that the material is being fluidized during the mixing process, leading to a low occurrence of particle-particle impacts and hence limited frictional heating. Nonetheless, there is still significant mixing action occurring to homogenously blend materials.

3.1.5 Scanning Electron Microscopy (SEM)

In order to investigate any effects of the mixing process on the integrity of the DBX-1 crystals themselves, samples from some of the "worst-case" mixing runs (i.e. highest filled, highest intensity, largest-scale, un-wetted mixes) were retained and sent for scanning electron microscope (SEM) imaging. Figure 7 shows images of the baseline, pro-

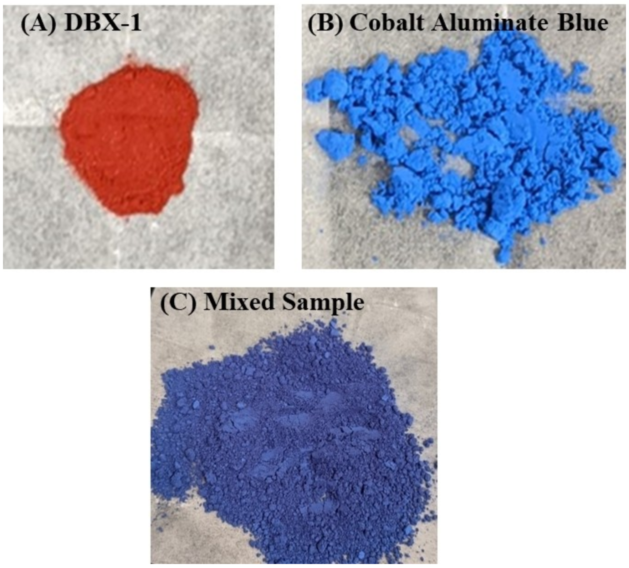
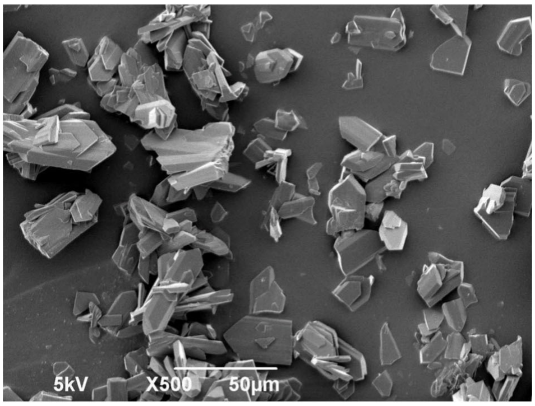
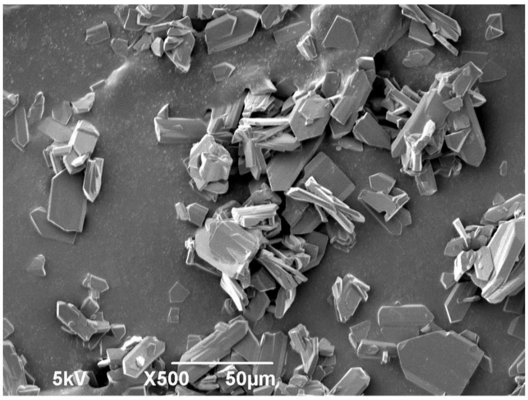


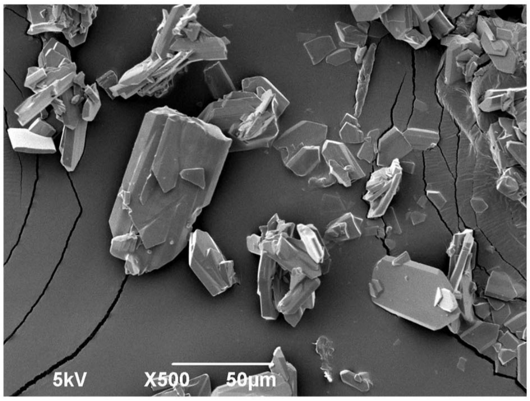
Figure 6. (A) Baseline DBX-1, (B) Baseline Cobalt Aluminate Blue, and (C) LabRAM-Mixed Cobalt Aluminate Blue and DBX-1.



A. Baseline DBX-1



B. Run 21: 70% fill, 100 G



C. Run 23: 90% fill, 100 G

Figure 7. SEM Images of DBX-1 Baseline and Post-Mix RAM Samples.

duction-batch DBX-1 compared to two such mixes, specifically Runs 21 (70 % fill volume, 100 G acceleration) and 23 (90 % fill volume, 100 G acceleration) from Trial Set #3.

Analysis of these images indicates no significant differences between the three samples; the particle size and morphology of the two runs are comparable to the baseline material that did not undergo any mixing process, affirming that obvious macroscopic crystal damage does not appear to be occurring during RAM mixing of DBX-1. Furthermore, no indication of any chemical reactions taking place (e.g. sample charring) was observed. The lack of crystal damage is a further indication that the material is fluidized during the mixing process and particle-particle impacts are minimized.

3.1.6 Potential Energy and Kinetic Energy Calculations

To provide a validity check of the experimental results, the potential energy required for the reaction of a single particle can be calculated and compared to the maximum kinetic energy of a single particle in the RAM at maximum acceleration. If the potential energy required for the reaction exceeds the maximum kinetic energy, the lack of reaction of the DBX-1 in the LabRAM can be further validated. To calculate the potential energy required for the reaction of a single particle, the impact sensitivity results from Table 2 will be used with the average particle size and density of DBX-1. DBX-1 has an average particle size of approximately 100 μm and a density of 2.58 g/cm^3 or 2580 kg/m^3. Assuming a spherical shape of the individual particles, the volume of a single particle can be calculated via the standard volume of a sphere equation, in which the volume of a single DBX-1 particle calculates to approximately 5.23×10^{-13} m^3. From the volume and density values, the approximate mass of a single DBX-1 particle calculates to 1.35×10^{-9} kg. For the impact sensitivity test, approximately 30 mg of material is used, which calculates to approximately 22,222 particles per trial. Thus, the potential energy required to react to a single DBX-1 particle is approximately 1.35×10^{-6} J.

To determine the kinetic energy of a single particle in the RAM at maximum acceleration, Equation 1 is utilized to determine the velocity of a single particle, in which ν is the velocity, A is the acceleration, g is the force of gravity (9.8 m/s^2), and f is frequency.

$$\nu = \frac{Ag}{2\pi f} \tag{1}$$

This equation makes several simplification assumptions that include, but are not limited to, the particle only moving as fast as the vessel it is impacting, and elastic collisions. These assumptions may not be completely accurate but will allow for a first approximation calculation. For the maximum acceleration, A is equal to 100, and f is equal to 60 Hz. From this equation, the maximum velocity of a particle calculates to approximately 2.6 m/s. To calculate the maximum kinetic energy, the maximum change in velocity is used and that value is equal to twice the maximum velocity, which equals 5.2 m/s. Using the kinetic energy equation, and the mass of a single particle as calculated prior, the maximum kinetic energy of a single particle at maximum acceleration calculates to approximately 1.83×10^{-8} J. From the potential energy and kinetic energy calculations, it is evident that the potential energy required for a reaction is approximately two orders of magnitude greater than the maximum kinetic energy experienced during maximum acceleration. As mentioned, the kinetic energy equation makes several simplification assumptions, but the calculations help to validate the lack of DBX-1 reaction during mixing.

4 Conclusion

The primary explosive DBX-1 was analyzed for potential initiation events while being processed via RAM technology. To conduct the study, a Design of Experiments was established that evaluated differing quantities of DBX-1, volumetric fill percentages, wetting liquid concentrations, and mixing accelerations in a LabRAM. The results of the trials indicated that DBX-1 did not react under any of the conditions examined. Most significantly, fully dry DBX-1 was shown to be unreactive even at the highest accelerations (100 G) that are capable with the RAM. In all trials, minimal temperature increases were seen after the mixing was completed. This lack of temperature rise suggests that the RAM is effectively generating a fluidized bed, in which particle-particle interactions (and therefore frictional heating) are minimized, but still allows for efficient mixing. To provide further support, a brief visual-based multi-material mixing study was also conducted to ensure that effective mixing was occurring with DBX-1, and this trial successfully resulted in an apparent homogenous mixture of DBX-1 with an inorganic salt. Finally, theoretical calculations were performed, which indicated that the maximum velocity of a single particle is about two orders of magnitude below the critical impact velocity required for the reaction. It should be emphasized, however, that these results are only valid for DBX-1, and the behavior of each primary explosive should be individually verified before being processed in the RAM at any scale. Nonetheless, the results of these trials are an early indication that the RAM environment is potentially safe for processing and formulating primary explosives.

In the future, various other primary explosives should be evaluated to gain a better understanding of the phenomenological relationships of sensitive material reactivity and high G-force acceleration mixing conditions. Materials such as lead azide, lead styphnate, silver azide, and their formulations (e.g. percussion primer or stab initiation mixes) should be evaluated to provide a more thorough safety analysis of the RAM for primary explosive mixing and formulation.

Symbols and Abbreviations

RAM	resonant acoustic mixing
DBX-1	copper (I) 5-nitrotetrazolate

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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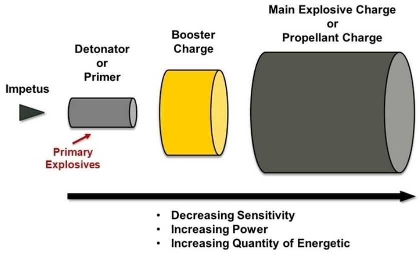

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1 – 9

Primary Explosive Processing in the Resonant Acoustic Mixer