(U) One Step No Waste Composition C-4 Production

Project Number: WP-201508

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*** * ***
(formerly: Armament Research, Development & Engineering Center ARDEC)

Final Debrief
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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Eliminate the legacy Comp C-4 ten-step water slurry process that is time, energy, and labor intensive. Eliminate post-processing of Comp C-4 bulk “cake” into M112 demolition blocks at an off-site extrusion facility. Combine explosives formulation and M112 manufacture processes onto a single production platform. Replace inconsistent C4 lacquer coating system with silicone oil for efficient particle wetting without the need to use solvents and water. Replace energetic nitramine RDX with HMX to enhance energy release and reduce impact on environment. Use computer modeling to design the TSE mixing protocol, including an M112 forming die, for optimal solids loadings and product throughput. Demonstrate technology to compound PAX-52 formulation and extrude M112 demolition blocks.

15. SUBJECT TERMS
No Waste, Composition C-4 Production, C4, PAX-52, M112, Twin Screw Extrusion

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			John Centrella
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(U) Document Distribution Statement

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(U) Project Team

- John Centrella, Principal Investigator, Armaments Center (AC.)
- Dr. Dilhan Kalyon, Stevens Institute of Technology.
- Travis Swanson, Rocky Mountain Scientific Laboratories
- Michael Fair, Technical Lead, Armaments Center (AC.)
- Dr. Kelly Scanlon, Office of the Assistant Secretary of Defense (Sustainment)

Key Words

C4: Composition 4 is the US Army qualified demolition explosive developed in 1950 and currently produced only in bulk powder form.

PAX-52: Picatinny Arsenal Explosive. Hand-moldable explosive produced in block form.

M112: Demolition Charge made of C4 or PAX-52

TSE: Twin Screw Extrusion

ARDEC: Former name of armaments R&D center at Picatinny Arsenal. Now called: **Armaments Center**

(U) Technical Objectives

- (U) Eliminate the legacy Comp C-4 ten-step water slurry process that is time, energy, and labor intensive.
- (U) Eliminate post-processing of Comp C-4 bulk "cake" into M112 demolition blocks at an off-site extrusion facility.
- (U) Combine explosives formulation and M112 manufacture processes onto a single production platform. Twin-screw Extruder (TSE)
- (U) Replace inconsistent C4 lacquer coating system with silicone oil for efficient particle wetting without the need to use solvents and water.
- (U) Replace energetic nitramine RDX with HMX to enhance energy release and reduce impact on environment.
- (U) Use computer modeling to design the TSE mixing protocol, including an M112 forming die, for optimal solids loadings and product throughput.
- (U) Demonstrate (TSE) technology to compound PAX-52 formulation and extrude M112 demolition blocks.

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(U) Performance Objectives 1/5

Performance Objective	Data Requirements	Success Criteria	Success?
Quantitative Performance Objectives			
PAX-52 shall be produced continuously by a steady state process for at least three hours.	1. Time record. 2. Temperature and pressure records.	Recorded production run exceeding three hours. Recorded feedback data within three standard deviations for pressure, temperature, and torque.	Partial Success
PAX-52 consists of only two ingredients. Taggant not accounted for in the formulation.	Composition Analysis using High Performance Liquid Chromatography (HPLC)	Detection of HMX at 85 percent by weight.	Success
Demolition charge cross-section	MIL-DTL-50523B, drawing 9204248.	Measurement of 2"x1" with side concavity allowance.	Success
M112 Physical properties - Plasticity	Penetrometer MIL-DTL-50523B 3.2.1.1	Force resistance of not less than 2.0 pounds and not greater than 8.0 pounds	No Test

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(U) Performance Objectives 2/5

Performance Objective	Data Requirements	Success Criteria	Success?
Quantitative Performance Objectives			
M112 Specific Gravity	Archimedes' water method MIL-DTL-50523B 4.4.2	Specific gravity greater than 1.50	Success
Energy Output	Plate-cutting test MIL-DTL-50523B 4.4.3	Cut a steel witness plate completely into two separate sections.	Success
Physical Sensitivity	ESD (AOP-7201.03.001) BAM Friction (AOP-7 201.02.006) ERL Impact (AOP-7 201.01.001)	ESD: No Go < 0.25 Joules BAM Friction: 10 No Go greater than 200 Newtons ERL Impact: 50% reaction height greater than 75 cm	Success Success
Shock sensitivity	Cap Sensitivity (TB700-2 Para 5.6a). IHE Gap Test (AOP 201.04.005)	Sustained Detonation Response Attenuation Gap between 161-171 cards.	Success

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(U) Performance Objectives 3/5

Performance Objective	Data Requirements	Success Criteria	Success?
Quantitative Performance Objectives			
Detonation velocity Energetic performance	Detonation velocity test Plate dent test	Velocity greater than 7.5 km/sec At 99% TMD Pressure greater than 25.0 GPa at 99% TMD	Success
Product response to ignition	1. VCCT (AOP-7 202.01.002) 2. Small Scale Burning Test (TB700-2 Para. 5.4a)	1. Pass: No detonation response 2. Pass: No detonation response	Success
PAX-52 chemically stable	1. Vacuum Thermal Stability (40 h @ 100 ºC - AOP-7; US/202.01.022) 2. Thermal Stability (48 h @ 75 ºC - AOP-7; US/202.01.013). 3. Aging Study	1. Pass: no significant decomposition or off-gassing. 2. Pass: no exothermic reactions. 3. No accumulated exudation of oil.	Success

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(U) Performance Objectives 4/5

Performance Objective	Data Requirements	Success Criteria	Success?
Quantitative Performance Objectives			
Homogeneity	Composition analysis	Mixedness index greater than 0.99	Success
Environmental impact	Deposition rate test	Less than 1% by weight of RDX accumulation.	Success
HMX workplace exposure	1. ACGIH 2016 Threshold Limit Values & Biological Exposure Indices	1. (ACGIH-TLV) for HMX is 0.5 mg/m3	Success

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(U) Performance Objectives 4/5

Performance Objective	Data Requirements	Success Criteria	Success?
Qualitative Performance Objectives			
Packaging	Contractor Inspection Report	MIL-DTL-50523A, drawing 9204248.	Success
User evaluation	Color Manual Moldability Tackiness Surface oil transfer.	No noticeable change in the quality of the product during any field demonstration conditions.	Success

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(U) Site Description

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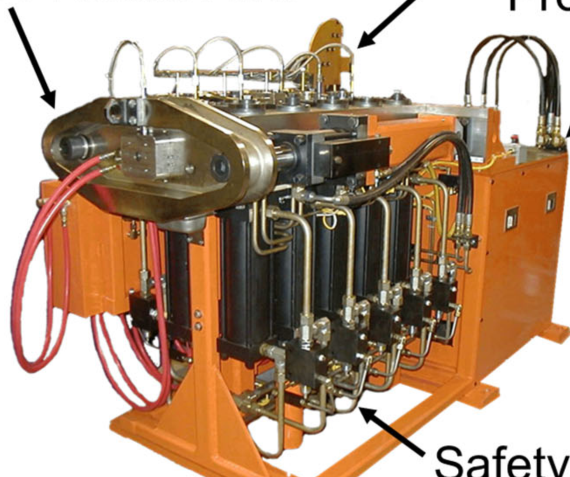
(U) Universal Twin Screw Extrusion Facility Armaments Center (AC), Picatinny Arsenal, NJ



- Access and Security
- On-site Emergency Services
- Energetics Storage Magazines
- Powder Processing and Conditioning
- Rheology Lab
- On-site Waste Incinerator
- PLC Remote Control Monitoring
- Engineering and Technical Staff

- Federal, State and Local Regulated
- Environmental Safety Plan
- Industrial and Academia Partners
- Collaboration with AC Programs
- Large Portfolio of Successful Projects

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(U) Test Design - Computer Modeling

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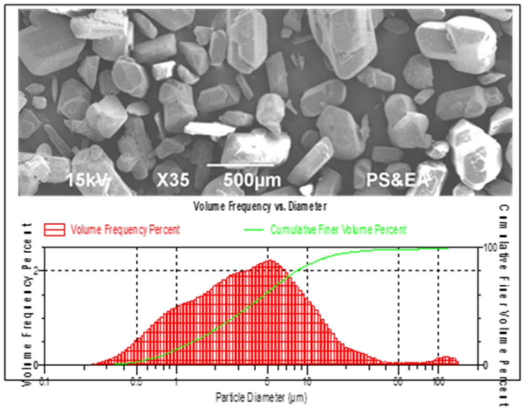
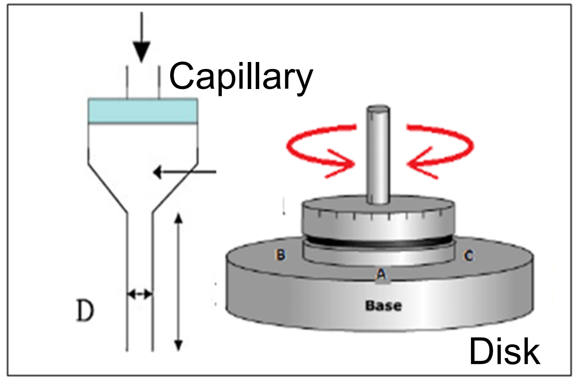
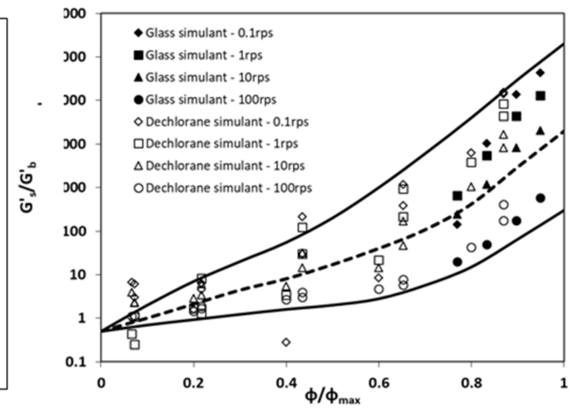


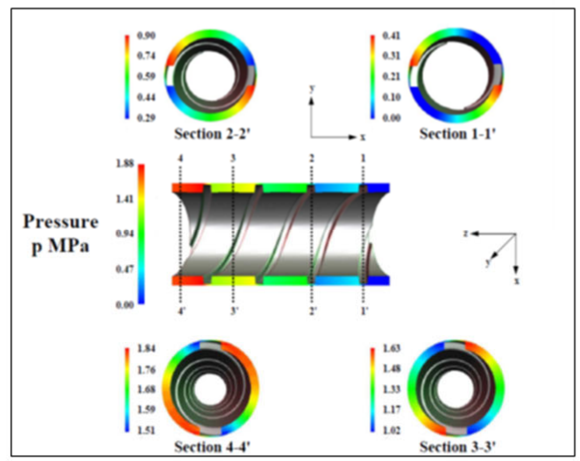
1. Particle Analysis



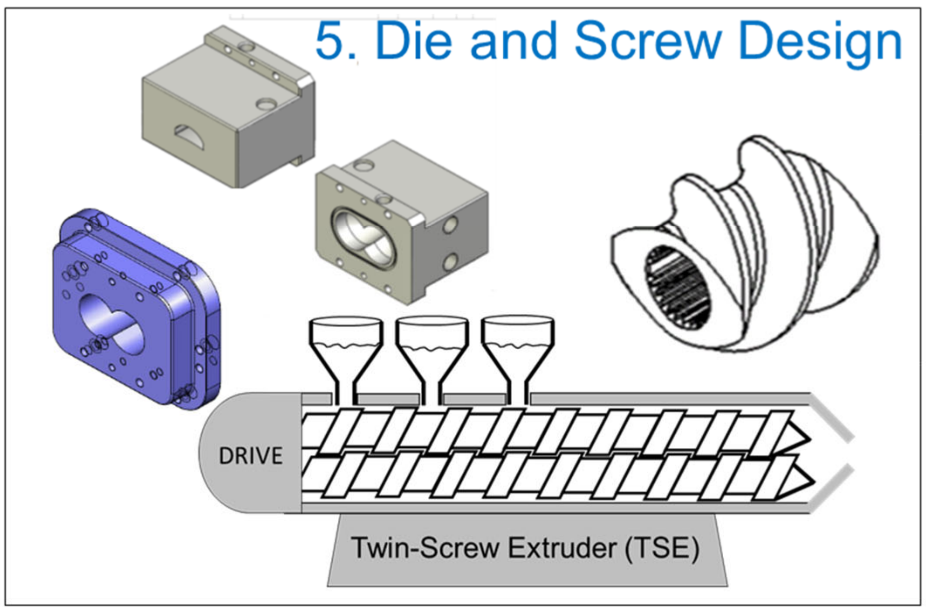
2. Rheology



3. Data Analysis



4. Finite Element Modeling



5. Die and Screw Design

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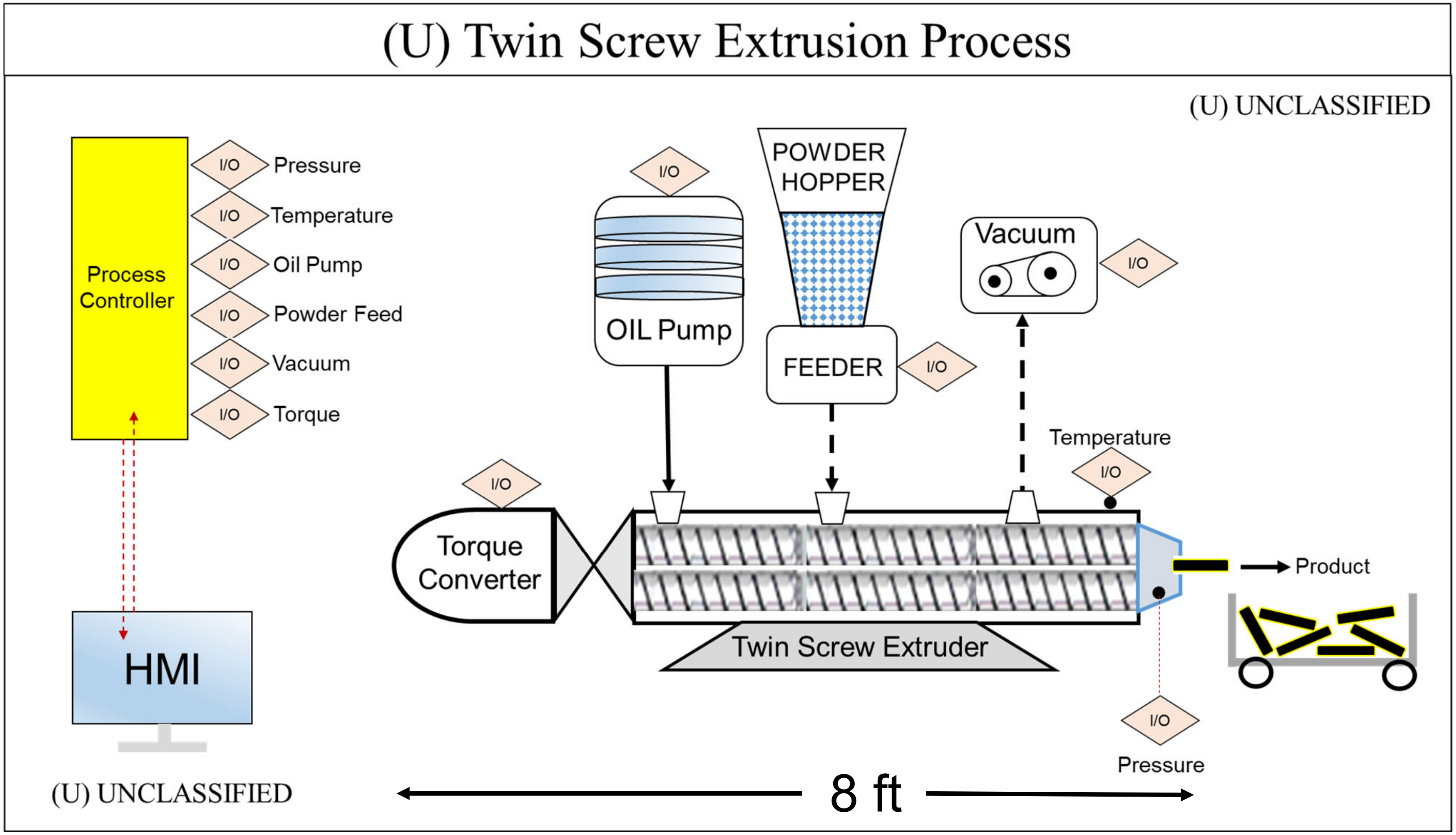
(U) Test Design - Twin Screw Extruder

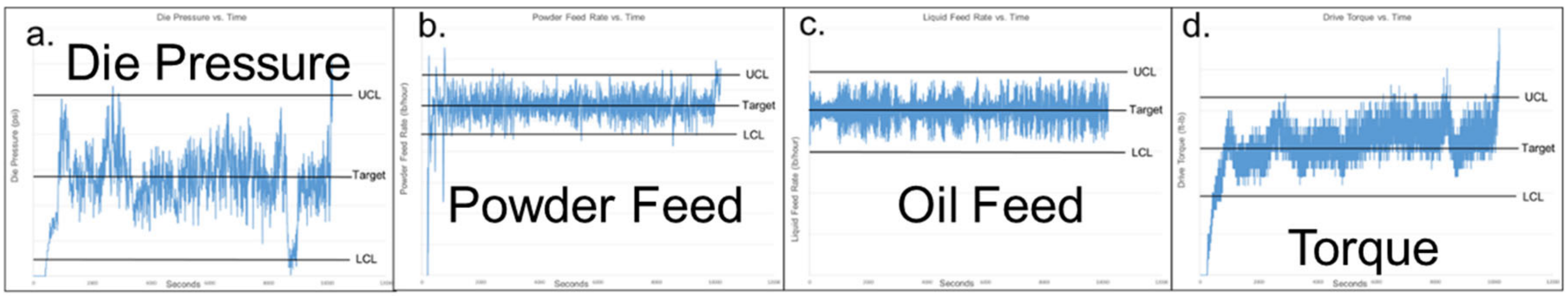


(U) Test Design – Continuous Process and Product

(U) Steady State Control: pressure, temperature and torque.
(U) Measured by three standard deviations from target.
(U) During three hours of continuous processing.

(U) TSE Process Control

Unclassified



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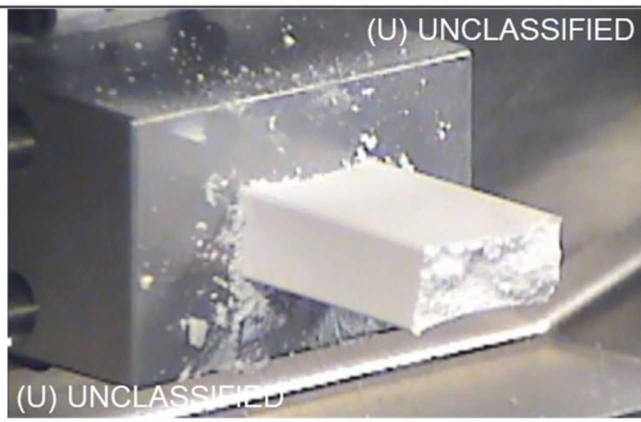
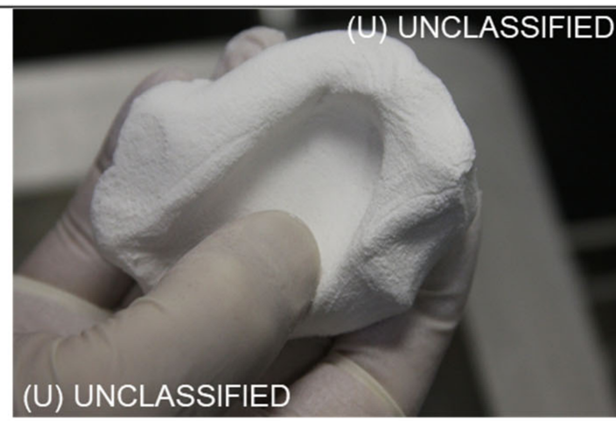


(U) Visual Monitoring



(U) Three-finger Rheology

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(U) Test Design – Quantitative Test and Evaluate

(U) Laboratory Tests:

- Composition Analysis – HPLC
- Sensitivity: ESD, Impact and Friction
- Specific Gravity, Plasticity
- Homogeneity
- Thermal and Chemical Stability
- Small Scale Burning

(U) Field Tests:

- Detonation Velocity and Pressure
- Cap Sensitivity
- Steel Plate Cutting Test
- IHE Card Gap Test
- Variable Closed Confinement Test
- RDX/HMX Deposition Study
- Workplace Exposure

(U) Test Design – Qualitative Test and Evaluate

(U) Packaging Evaluation
- Formability
- Strength
- Weight

(U) User Evaluation
- Combat Engineers
- Bomb Sniffing Dogs
- Explosive Ordnance Disposal

(U) Test Design – Test and Evaluate

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Cold Weather Deposition Rate Test

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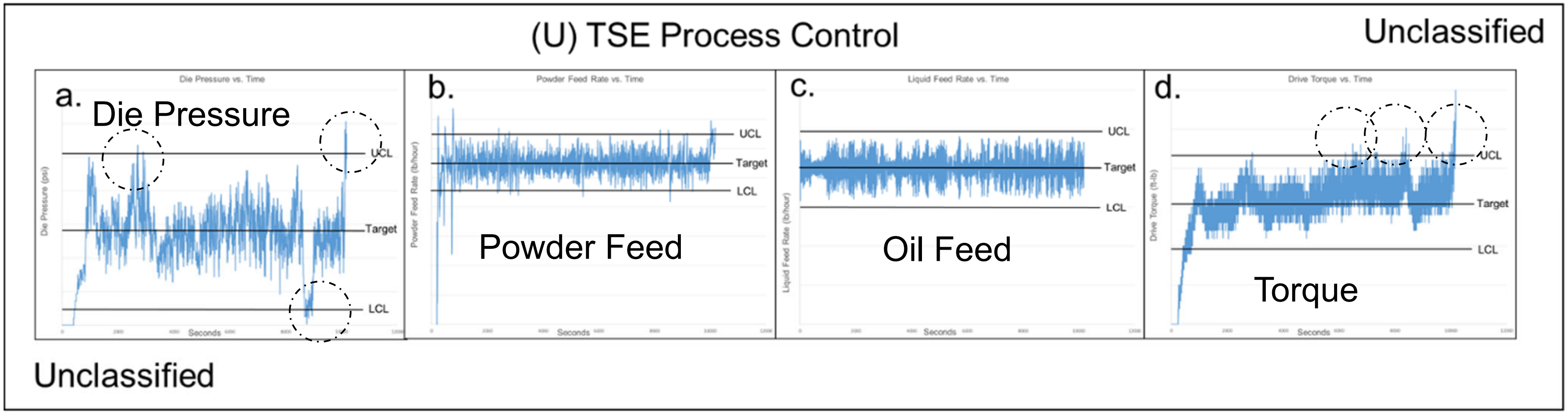
- (U) Defence Research and Development Canada (DRDC)
- (U) Tested PAX-52 in pristine snowpack.
- (U) Analyzed multiple samples drawn from an array.
- (U) Detected RDX in small amounts.

(U) Performance Assessment – Continuous Process and Product

- (U) Steady State Control: pressure, temperature and torque.
- (U) Measured by three standard deviations (6σ) from target.
- (U) During three hours of continuous processing.



- (U) Missing data requirements for <u>Temperature</u>. T-axis error.
- (U) Slight loss of process control for <u>Die Pressure</u>.
- (U) Missed <u>Time</u> requirement. Ran low on powder feed stock.
- (U) Partially successful in meeting objective.

(U) Performance Assessment – Physical Properties

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(U) PAX-52: Compositional Analysis by HPLC				
LOT Number	HMX		Silicone	
	wt %	s.d. (wt %)	wt %	s.d. (wt %)
RDD17B046-001	Achieved	0.3	Achieved	0.3

(U) Objective: Demonstration product >85 wt % HMX.

(U) Successful in meeting objective.

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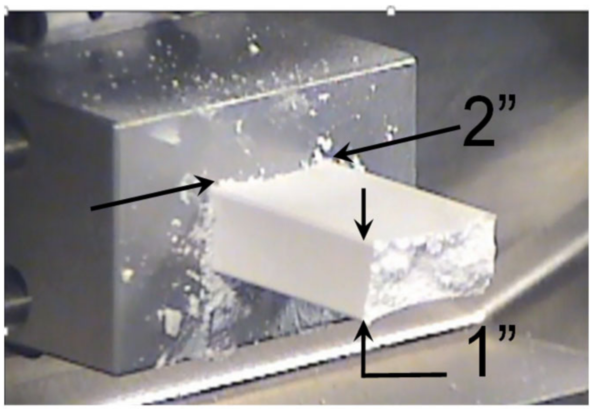

(U) Objective: Dimensions 2"x 1"

(U) Allowance for concavity.

(U) Successful in meeting objective.

(U) Plasticity Objective: 2-8 lb_{force}

(U) No Test. Penetrometer not available for test.

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(U) Performance Assessment – Physical Properties

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(U) PAX-52 Density	
Density, g/cm^3	Std. Dev., g/cm^3
1.688	0.0004

(U) Product Density Objective >1.50 g/cc

(U) Successful in meeting objective.

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(U) PAX-52 Physical Sensitivity

Test	PAX-52	Remark
BOE Impact	4/10 Reactions	Not Impact Sensitive
ERL Impact Sensitivity	4/10 @100 cm	Not Impact Sensitive
BAM Friction Sensitivity	0/10 @ 324 N	Not Friction Sensitive
ESD Static Sensitivity	0/20 GO @ 0.051 J	Not ESD Sensitive

(U) Objectives in accordance with AOP-7 NATO standards

(U) Successful in meeting sensitivity objectives.

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(U) Performance Assessment – Energy Output

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(U) Plate Cutting Test Set-up and Results

(U) Objective: Cut 1" steel plate in two pieces.
(U) Successful in meeting objective.

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(U) Performance Assessment – Shock Sensitivity

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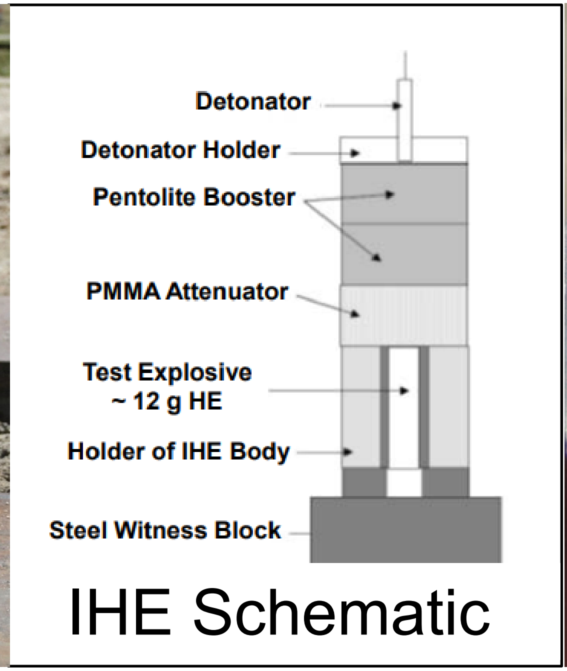

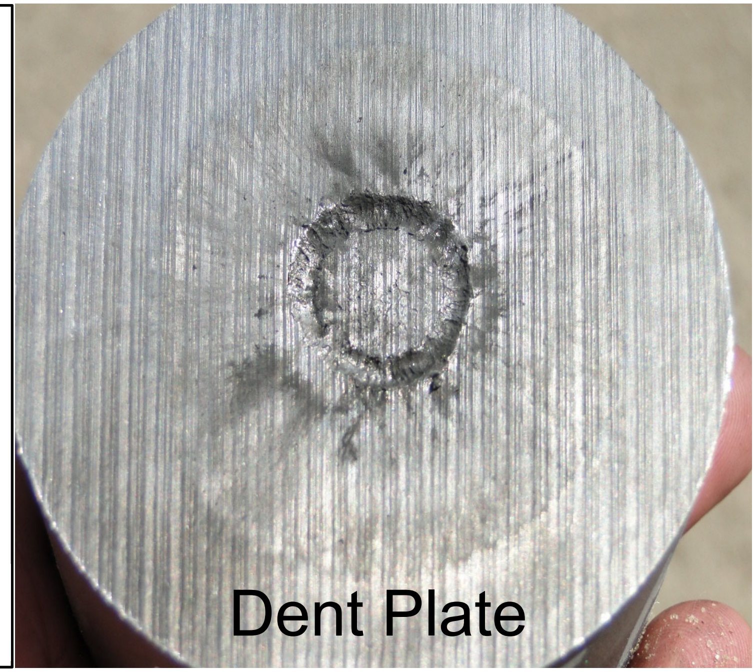

- (U) Insensitive High Explosives (IHE) Test
- (U) Objective: Attenuation Gap 161-171 cards.
- (U) Card gap measured (50% threshold) 159.7 cards.
- (U) Performed slightly better than expected.
- (U) Successful in meeting objective.

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(U) Performance Assessment – Detonation Velocity and Pressure

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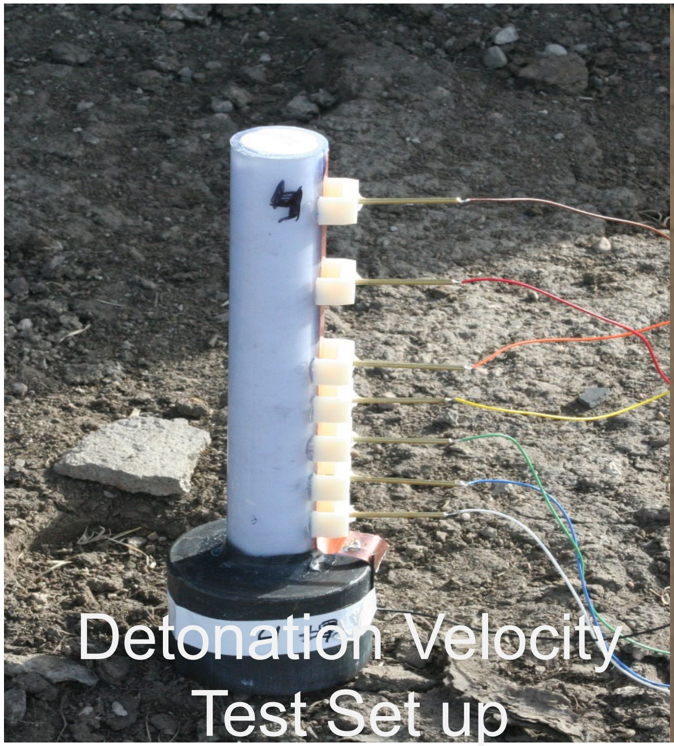

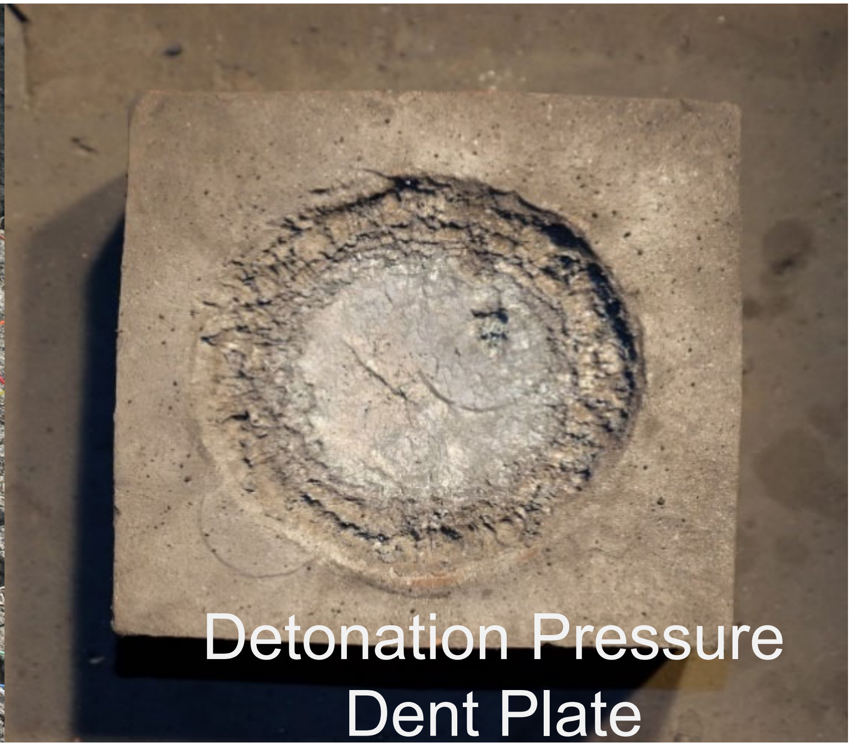

- (U) Objective: VoD of 7.5 km/sec.
- (U) Objective: Detonation Pressure of 25 Gpa.
- (U) Successful in meeting both objectives.
- (U) Packing density influences results.

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(U) Performance Assessment – Response to Ignition

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Variable Closed Confinement Test

Small Scale Burning Test

(U) VCCT Objective: No transition to detonation.
(U) Maximum wall thickness (0.120”) tested first.
(U) Burning Objective: No violent reaction.
(U) Successful in meeting both objectives.

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(U) Performance Assessment – Thermal Stability

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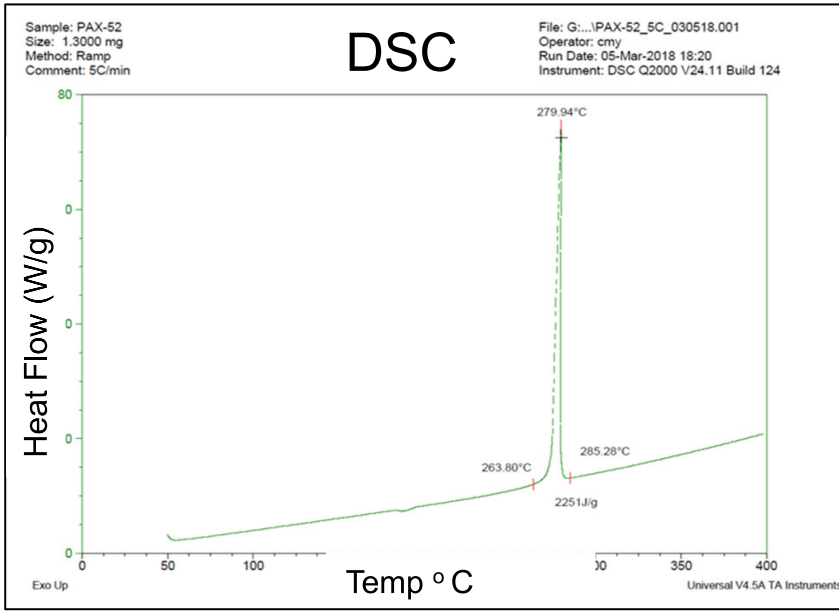
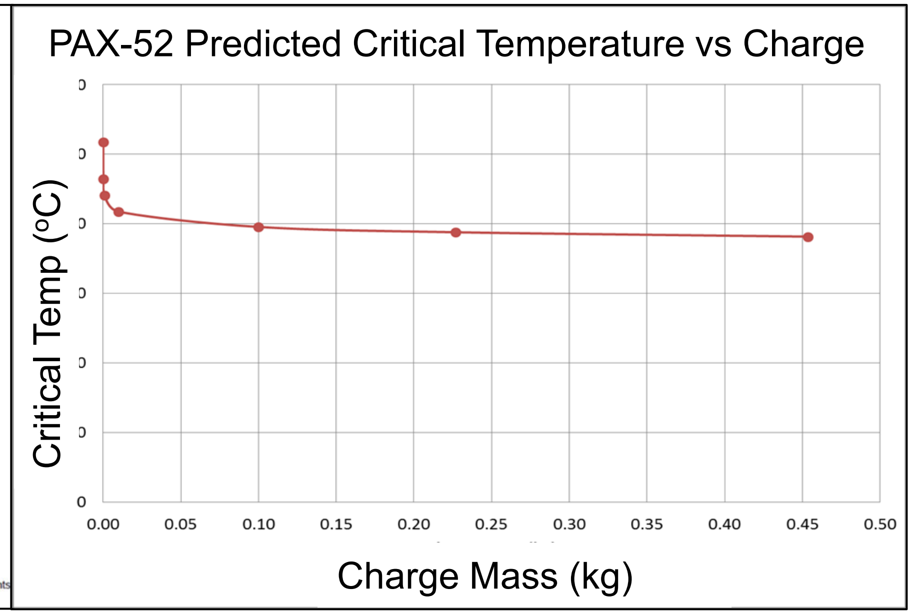


Differential Scanning Calorimetry



Small Scale Arrhenius Kinetics

(U) DSC Objective: HMX critical decomposition temperature.

(U) Stable thermal kinetics.

(U) Successful in meeting objective.

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(U) Performance Assessment – Chemical Stability

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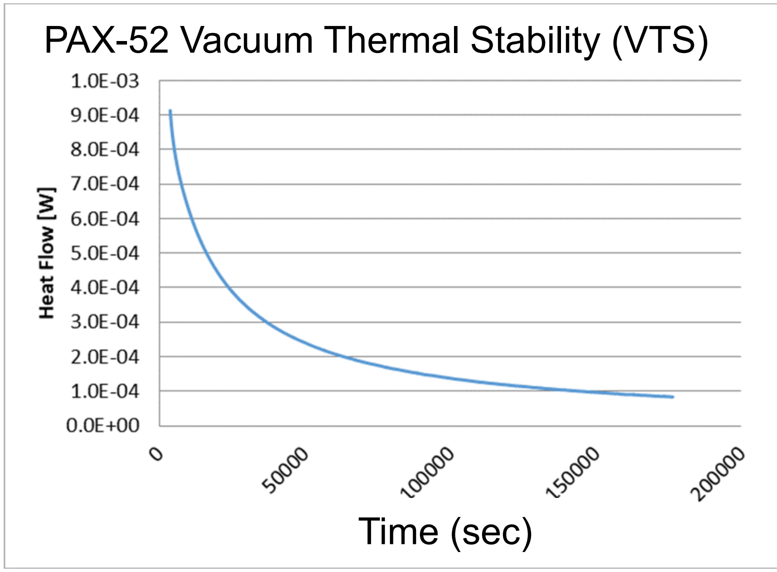
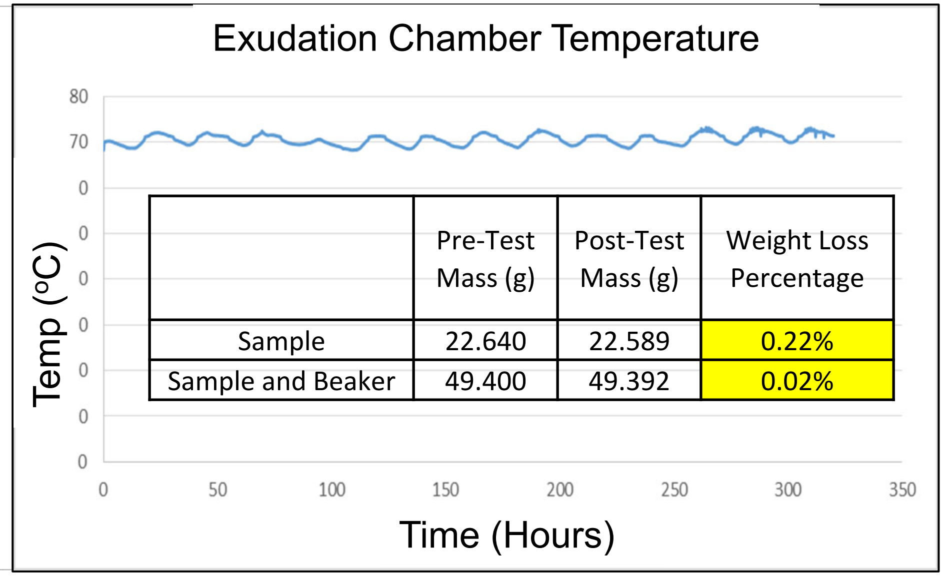


Modified Vacuum Thermal Stability



	Pre-Test Mass (g)	Post-Test Mass (g)	Weight Loss Percentage
Sample	22.640	22.589	0.22%
Sample and Beaker	49.400	49.392	0.02%

Exudation Test

(U) VTS Objective: No significant decomposition or off-gasing.
(U) Exudation Objective: No separation or loss of silicone oil.
(U) Successful in meeting both objectives.

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(U) Performance Assessment: HMX Workplace Exposure

UNCLASSIFIED Twin Screw Extruder, HMX Air Sampling Results

Bldg 1403, Twin Screw Extruder, HMX (Octogen) Air Sampling Results				
Twin Screw Extruder (TSE)	**Sample Time (min)**	**TWA Results for Sampling Period (mg/m3)**	**8-hr TLV-TWA (mg/m3)**	**Exceeds ACGIH-TLV?**
	211	0.011	0.005	No

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(U) American Conference of Governmental Industrial Hygienists- Threshold Limit Values (ACGIH-TLV): 0.5 mg/m^3

(U) HMX Exposure Objective: Does not exceed ACGIH-TLV.

(U) Successful in meeting objective.

(U) Performance Assessment: Homogeneity

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Mixing Index Calculations

$$\overline{c} = \frac{1}{N}\sum_{i=0}^{N} c_i \qquad \text{Eq (1)}$$

$$s^2 = \frac{1}{(N-1)}\sum_{i=1}^{N} (c_i - \overline{c})^2 \qquad \text{Eq (2)}$$

$$s_0^2 = \overline{c}(1-\overline{c}) \qquad \text{Eq (3)}$$

$$MI = 1 - \frac{s}{s_0} \qquad \text{Eq (4)}$$

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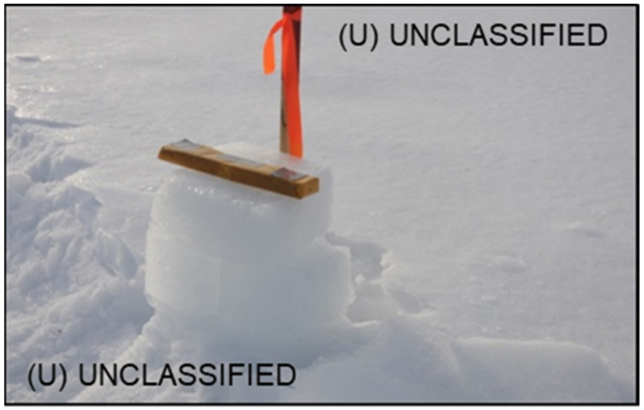
- (U) Homogeneity Objective: >.99
- (U) 10 random samples analyzed for HMX content by HPLC.
- (U) Calculated mixing index to be 0.995
- (U) Successful in meeting objective.

(U) Performance Assessment: Environmental Impact



PAX-52 Deposition Rate Test

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Mass of Residual RDX and HMX		
Plastic Explosive	**Mass of RDX Deposited (mg)**	**Mass of HMX Deposited (mg)**
C-4	65	1
PAX-52	0.08	47

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Test Results

(U) Environmental Objective: < 1wt % RDX
(U) 2.91 orders of magnitude less than C4
(U) log (64/0.08) = 2.91
(U) Successful in meeting objective.

(U) Performance Assessment: Packaging and User Evaluations

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(U) PAX-52 Packaging Process

(U) Users and Mission

(U) Packaging Objective: Meet M112 specifications

(U) Successful in meeting objective

(U) User Evaluation Objective: Consistent Quality

(U) Performance not measured

(U) Successful in meeting objective.

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(U) Cost Assessment: C4/M112 Cost Basis

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Eight-year Average of Bulk C4 and M112 Unit Costs in Todays Dollars						
Financial Year	M112			Bulk C4		
	Total Units	Unit Cost ($/Unit)	Present Value ($/Unit)	Total Pounds	Unit Cost ($/lb)	Present Value ($/Unit)
2010	487815	6.69	6.78	643915	13.68	13.87
2011	112159	10.35	10.47	148050	22.34	22.61
2012	1027889	4.19	4.23	1356803	15.64	15.80
2013	280058	9.59	9.67	369776	23.92	24.11
2014	320277	10.11	10.17	422716	21.93	22.06
2015	162947	6.46	6.49	216090	14.49	14.55
2016	116160	10.46	10.48	153318	23.05	23.10
2017	180101	7.3	7.30	237733	18.31	18.31
Average	**335926**	**8.14**	**8.20**	**443550**	**19.17**	**19.30**

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$35/unit

DEMO CHG BLK M112 1-1/4 LB COMP C-4 W/TAGGANT (013893854)								
POM Unit Price Budget Values (POM17)								
Service	2014	2015	2016	2017	2018	2019	2020	2021
ARMY	$0.00	$33.05	$43.80	$0.00	$45.68	$46.93	$50.87	$51.75
NSOF	$0.00	$27.07	$0.00	$0.00	$41.11	$0.00	$0.00	$0.00
USAF	$0.00	$26.57	$53.46	$44.96	$41.11	$42.23	$45.79	$46.58
USNS	$0.00	$0.00	$0.00	$44.96	$0.00	$42.23	$0.00	$0.00

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$46/unit

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(U) Cost Assessment: PAX-52 Engineering Model Fixed Costs

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PAX-52 Production Fixed Costs	
Universal Twin Screw Extrusion System:	
Machine base, hydrostatic drive, housing assembly	
Barrel shell assembly, manifold assembly,	
Fully intermeshing co-rotating twin screw module	
Agitator shafts, agitator components, liners	
Figure 8 to "O" adopter, Feed portsa dn vent port	
Gear Box, 6 heating and cooling units,	
Feeder platform for up to four feeders	
Sub-Total	**$839,960**
Rectangular Slit Die	**$35,000**
Power, Controls and Data Acquisition System	**$175,835**
Delivery and Installation of the Universal Extrusion System	**$221,375**
Feeding Equipment:	
Feeder #1: Loss in weight feeder for HMX	$43,920
Feeder #2: Loss in weight feeder for HMX	$43,920
Feeder #3: Loss in weight for additives	$45,506
Feeder #4: Loss in weight for purge compound	$44,208
Feeder #5: Loss in weight feeder for silicone oil binder	$39,719
Enclosure and feeder controls	$24,194
Sub-Total	**$241,467**
Overhead Water Deluge System	**$250,000**
Squeeze Flow Rheometer	**$65,000**
Xray Diffraction Unit	**$200,000**
Ancillary Subsystems	**$275,558**
Production Facility Construction	**$750,000**
Total Fixed Costs	**$3,054,195**

(U) PAX-52 Fixed Costs

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(U) Assumptions made from market research and practical experience.

(U) Cost Assessment: PAX-52 Engineering Model Variable Costs

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PAX-52 Annual Variable Costs				
Line Item	**Description**	**Cost**	**Quantity**	**Total**
Production of PAX-52	Gross Production		80000	80000
Labor	Production Engineers	$90,000	2	$180,000
	Fringe Benefits (30%)	$27,000	2	$54,000
	Technicians	$65,000	2	$130,000
	Fringe Benefits (30%)	$19,500	2	$39,000
	Consultants	$600	5	$3,000
			Sub-Total	**$406,000**
Utilities	Electricity (per pound)	$5.04	80000	$403,200
	Water (per pound)	$0.03	80000	$2,400
			Sub-Total	**$405,600**
Supplies	Inert gases			$1,500
	Safety supplies			$2,000
			Sub-Total	**$3,500**
Raw Materials	HMX		80000	$2,542,520
	PDMS		80000	$94,518
	DMDNB		80000	$17,802
			Sub-Total	**$2,654,840**
Total Annual Variable Costs				**$3,469,940**

(U) Electricity is over-estimated in model.

(U) HMX is the real cost driver. Almost three-quarters of annual costs

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(U) Cost Assessment: PAX-52 Engineering Model Amortization of Fixed Costs

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Amortization of Fixed Costs		
Amortization Rate of Fixed Costs		
Buildings	39 Years	
Equipment	5 Years	
Fixed Building Costs		$750,000
Building Amortization		**$19,231**
Fixed Equipment Cost		$2,304,195
Equipment Amortization		**$460,839**
Annual Amortized Fixed Costs		**$480,070**

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(U) Cost Assessment: PAX-52 Engineering Model Amortization of Fixed Costs

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Annual Variable and Fixed Cost per Pound	
Annual variable costs:	$3,469,940
Annual Amortized Fixed Costs	$480,070
Production rate, pounds/year	80000
Cost per Pound	$49.38

(U) PAX-52 M112 = $62/block

(U) 10% reduction in HMX cost yields 7% reduction in price of product. Significant influence on price.

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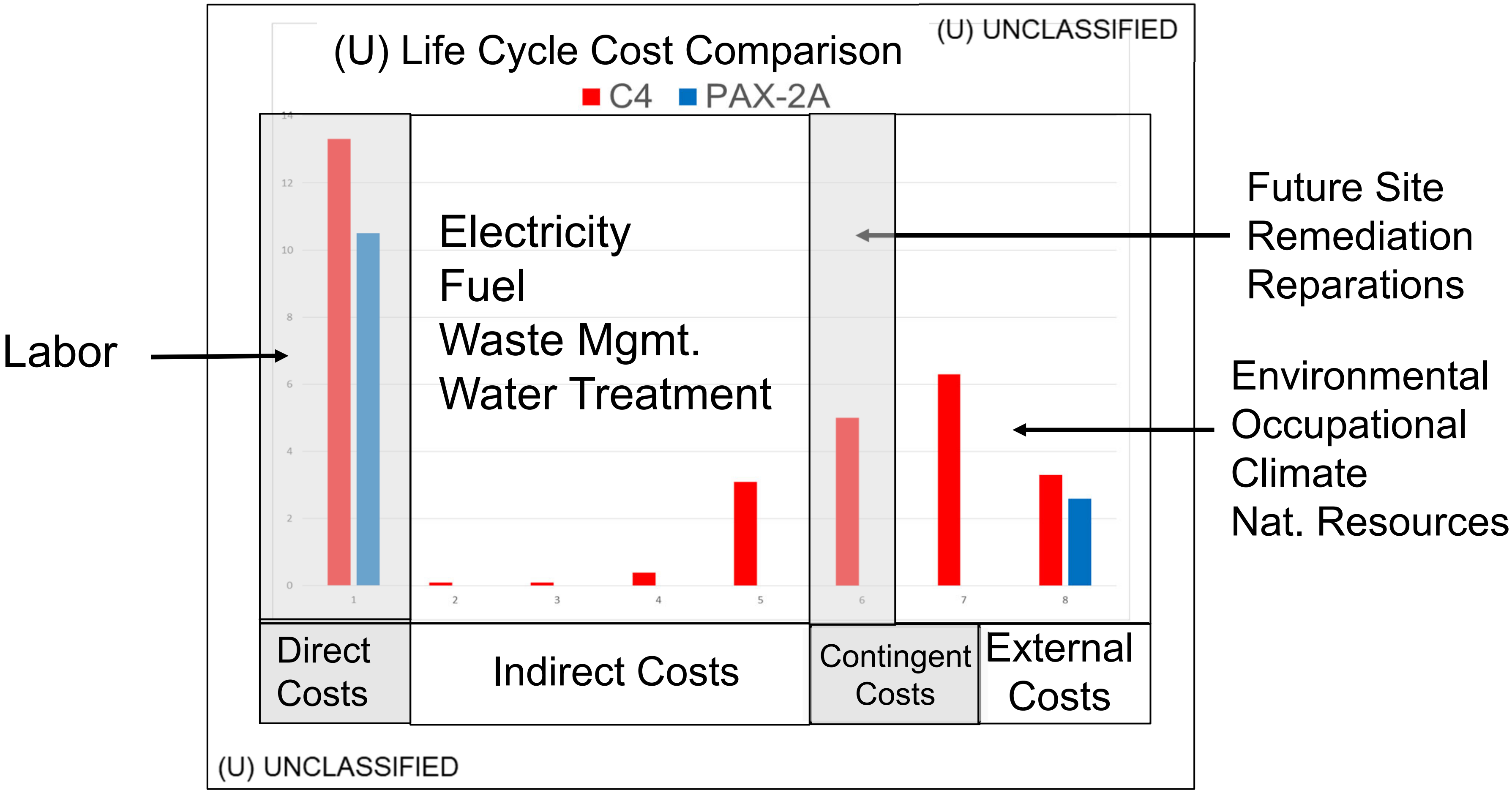
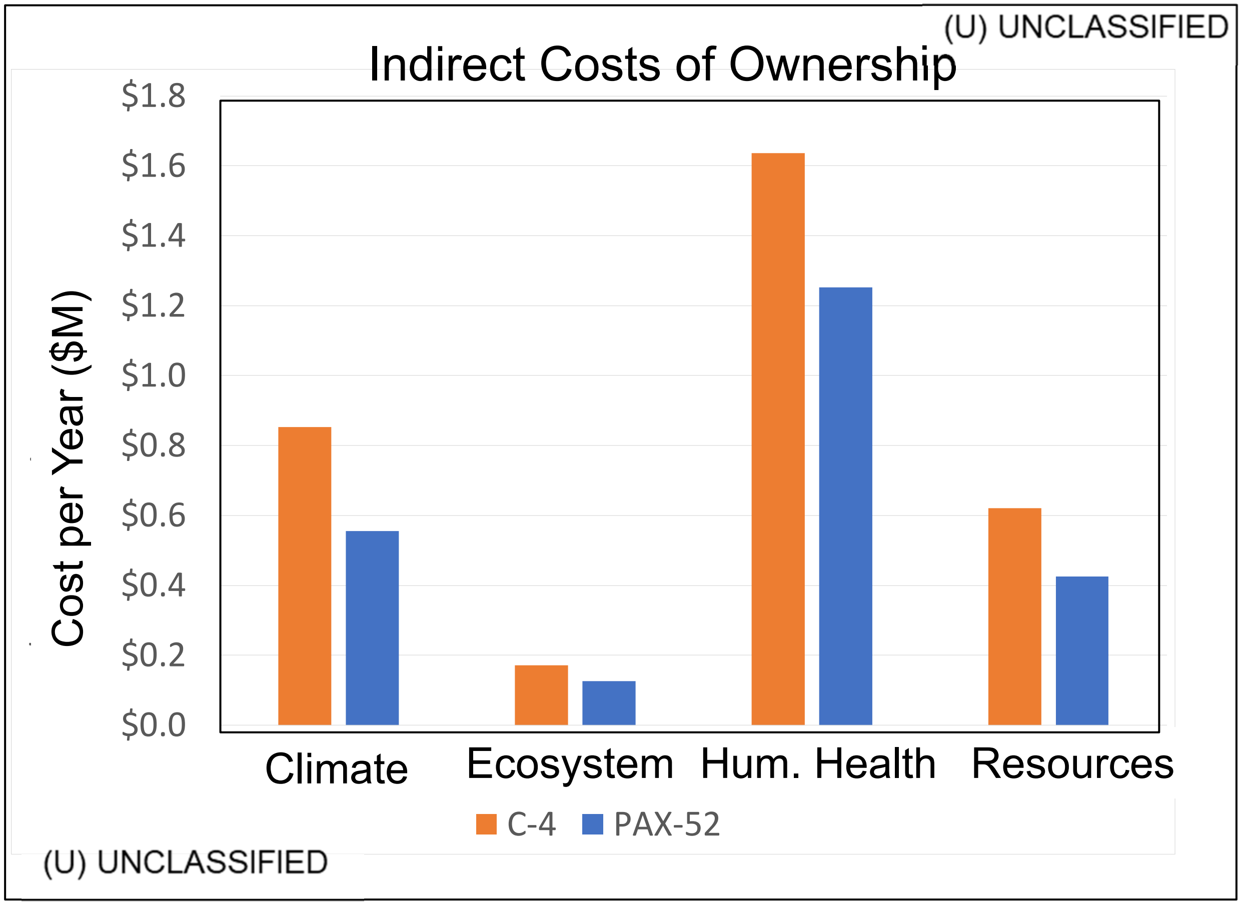
(U) Cost Assessment: Life Cycle Analysis DoD Total Cost of Ownership



(U) Office of the Assistant Secretary of Defense – Sustainment

(U) Direct, Indirect, Contingent and External costs.

(U) Cost Assessment: Life Cycle Analysis
External Cost Comparison



(U) Scale-up Issues: Advantages and Constraints

1. (U) Formulation will not change with increased mass flow.
2. (U) TSE mixing protocol may need to be modeled for safety and quality.
3. (U) Silicone binder is widely available in the United States.
4. (U) M112 packaging unit can be attached to TSE directly for greatest production efficiency.
5. (U) HMX powder will have to be conditioned before processing: drying or pre-coated. Can be processed wet (not studied here.)
6. (U) Production costs move inversely to production quantity.

(U) Technology Transfer

1. PAX-52 development is considered a success at Armaments Center.
2. Endorsement from Program Executive Office (PEO) Chief Scientist.
3. Endorsement from Joint Insensitive Munitions Technology Program.
4. Direct contact with PM C4 Product Manager.
5. Relationships and communications with C4 working group members.
6. Presentations to Combat Engineering (82nd Airborne) and Explosive Ordnance Disposal (EOD) demolitions groups:
   - Special Ops and ARDEC Institute for Special Warfare
   - Counter Explosives Hazard Center
   - Cold Regions Test Center
7. Office of Secretary of Defense-Sustainment: Life Cycle Analysis
8. Armaments Center - Science and Technology Networking Day. 3-years.
9. 6 Gigabytes of compiled data for information sharing and presenting
10. Weekly Activity Report staffed to AMC Headquarters; Gen Gustave Perna.
11. Canadian Defense interested in PAX-52 as C4 replacement.

(U) Key Points

1. (U) Do not trade down to RDX for cost savings.
    - Lost environmental benefits
    - Lost energy
2. (U) Qualify PAX-52 as a C4 alternate, not direct replacement.
3. (U) Formulation can be adapted for varied applications.
    - Warheads, CXM, extrusion loading.
4. (U) Utilize commercial modeling ANSYS Polyflow fluid dynamics software.
5. (U) Take advantage of cold-weather moldability for regional missions.

(U) Backup Slides

(U) Publications

(U) Journal of Rheology 2019

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Shear viscosity and wall slip behavior of dense suspensions of polydisperse particles

Jing He[1,2], Stephanie S. Lee[2], *and* Dilhan M. Kalyon[1,2,3,b)]

Journal of Rheology 2019 63:1, 19-32

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(U) 201508: One Step No Waste Composition C-4 Production

(U) Performers:
- ARDEC: PI, Formulations, technology demonstration and testing
- Stevens Institute of Technology: Computer modeling and TSE design.
- Rocky Mountain Laboratory: Qualification testing.

(U) Technology Focus:
- Compound and extrude on a single production platform. Demonstrate a powder-to-product continuous process.
- Replace RDX nitramine with HMX for environmental benefits and to enhance performance. Use a silicone binder system.

(U) Demonstration Site:
- Universal Twin Screw Extrusion Facility, Picatinny Arsenal, NJ.

(U) Demonstration Objectives:
- Compound HMX and Silicone: Continuous process.
- Performance: Sensitivity, stability and energy output tests.
- Environmental Impact: HMX vs RDX.

(U) Project Progress and Results
- 3D Modeling and simulation of TSE.
- Technology demonstration completed. Testing complete.

(U) Project Implementation Outlook
- Target completion date: Sept 2018
- Seeking end-user transfer agreements and qualification funding.