Applied Research and Development of DoD-Relevant Energetic Materials - The Planning, the Process, and the Products

Dr. Kimberly Yearick Spangler

Chemist

US Army ARDEC – Explosives Development Branch

SERDP • ESTCP SYMPOSIUM
2018 | Enhancing DoD's Mission Effectiveness

Contributors

- **ARDEC**
- John Centrella
- Dr. Reddy Damavarapu
- Dr. Natasha Khatri
- Keyur Patel

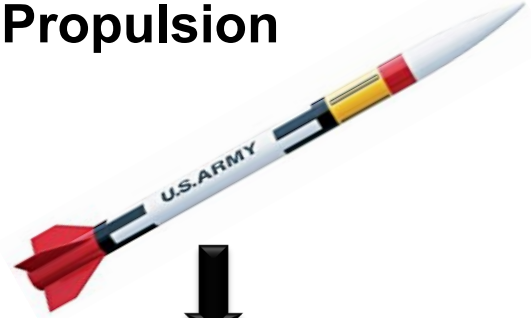
- **ARL**
- Dr. Niru Trivedi
- Dr. Brian Roos

DISTRIBUTION A. Approved for public release: distribution unlimited.

Energetic Materials Applications

Warheads:
- Artillery (IMX-101)
- Mortar (IMX-104)
- TOW (LX-14)

Rocket Propulsion
~2 s



Rockets:
Javelin
TOW
HELLFIRE
GMLRS
PAC-3

Explosives
~50 µs

microseconds……milliseconds……..seconds

Pyrotechnics
~ ms to >10 s

Gun Propellant
~10 ms

Propellants:
- Artillery (MACS)
- Mortars
- Tank Main Gun
- Small Arms

Pyrotechnics:
Flares
Ejection Seat
Signals

DISTRIBUTION A. Approved for public release: distribution unlimited.

Energy Content of Materials

Storage material	Energy type	Specific energy (MJ/kg)	Energy density (MJ/L)	Direct uses
Uranium-235	Nuclear fission	83 140 000	1 546 000 000	Electric power plants (nuclear reactors)
Hydrogen (compressed at 70 MPa)	Chemical	123	5.6	Experimental automotive engines
Gasoline (petrol) / Diesel	Chemical	~46	~36	Automotive engines
Propane (including LPG)	Chemical	46.4	26	Cooking, home heating, automotive engines
Fat (animal/vegetable)	Chemical	37		Human/animal nutrition
Coal	Chemical	24		Electric power plants, home heating
Lithium-air battery (theoretical)	Electrochemical	18.7[2]		Electronic devices, vehicles
Carbohydrates (including sugars)	Chemical	17		Human/animal nutrition
Protein	Chemical	16.8		Human/animal nutrition
Wood	Chemical	16.2		Heating, outdoor cooking
TNT	Chemical	4.6		Explosives
Gunpowder	Chemical	3		Explosives
Lithium battery (non-rechargeable)	Electrochemical	1.8	4.32	Portable electronic devices, flashlights
Lithium-ion battery	Electrochemical	0.36[3]–0.875	0.9–2.63	Laptop computers, mobile devices, some modern electric vehicles
Alkaline battery	Electrochemical	0.67	1.8	Portable electronic devices, flashlights
Ni				
Le				
Su				
Electrostatic capacitor	Electrical	0.000036		Electronic circuits

Not very energetic but…… it's the power that matters!

http://en.wikipedia.org/wiki/Energy_density

DISTRIBUTION A. Approved for public release: distribution unlimited.

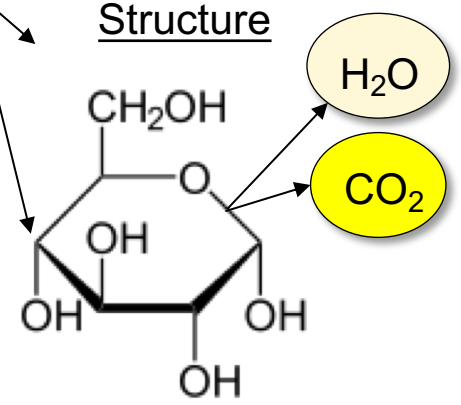
Molecular Attributes of Energetic Materials

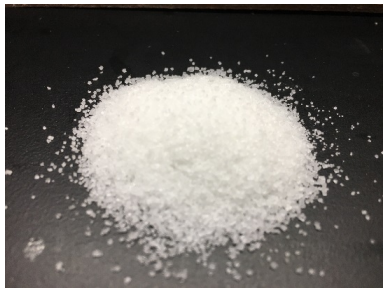
Sugar

$C_6H_{12}O_6$

Strong Bonds

Very Stable Structure





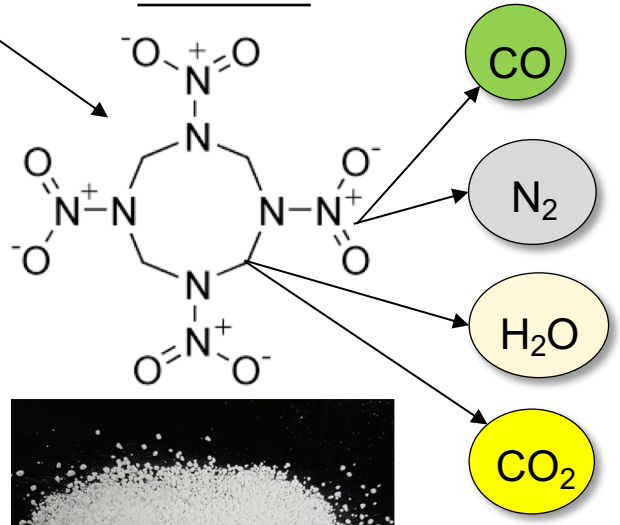
Specific Energy: 16 MJ/kg

HMX

$C_4H_8N_8O_8$

Weak Bonds

Very Unstable Structure



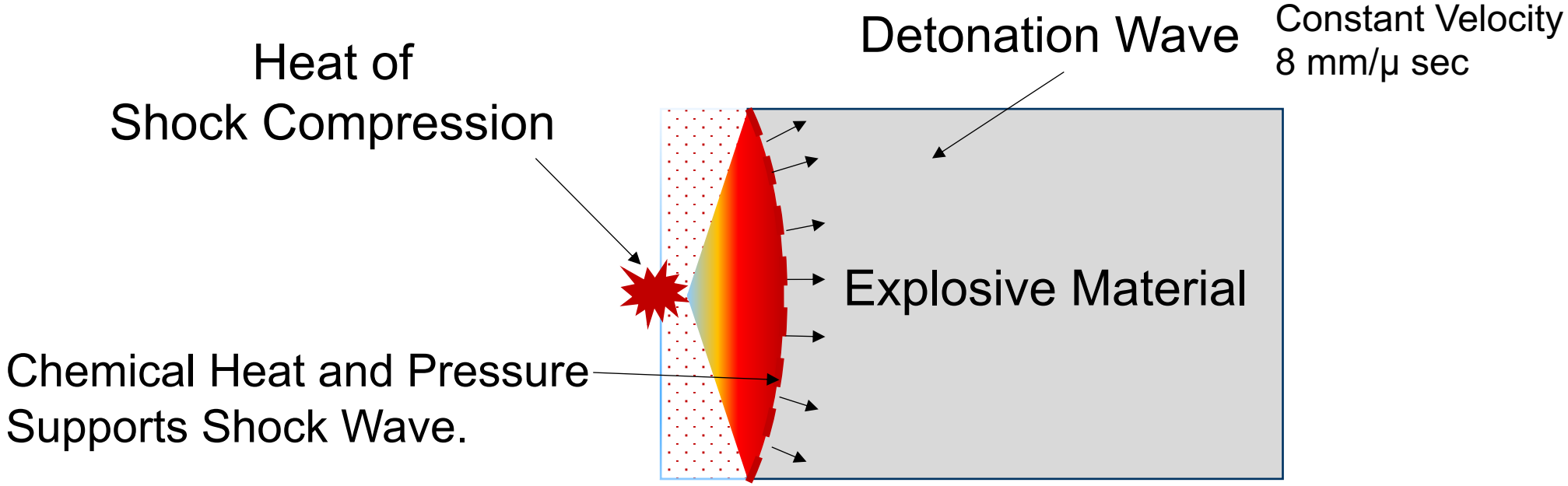
Specific Energy: 6 MJ/kg

DISTRIBUTION A. Approved for public release: distribution unlimited.

#SerdpEstcp2018

Energetic Materials and Detonation

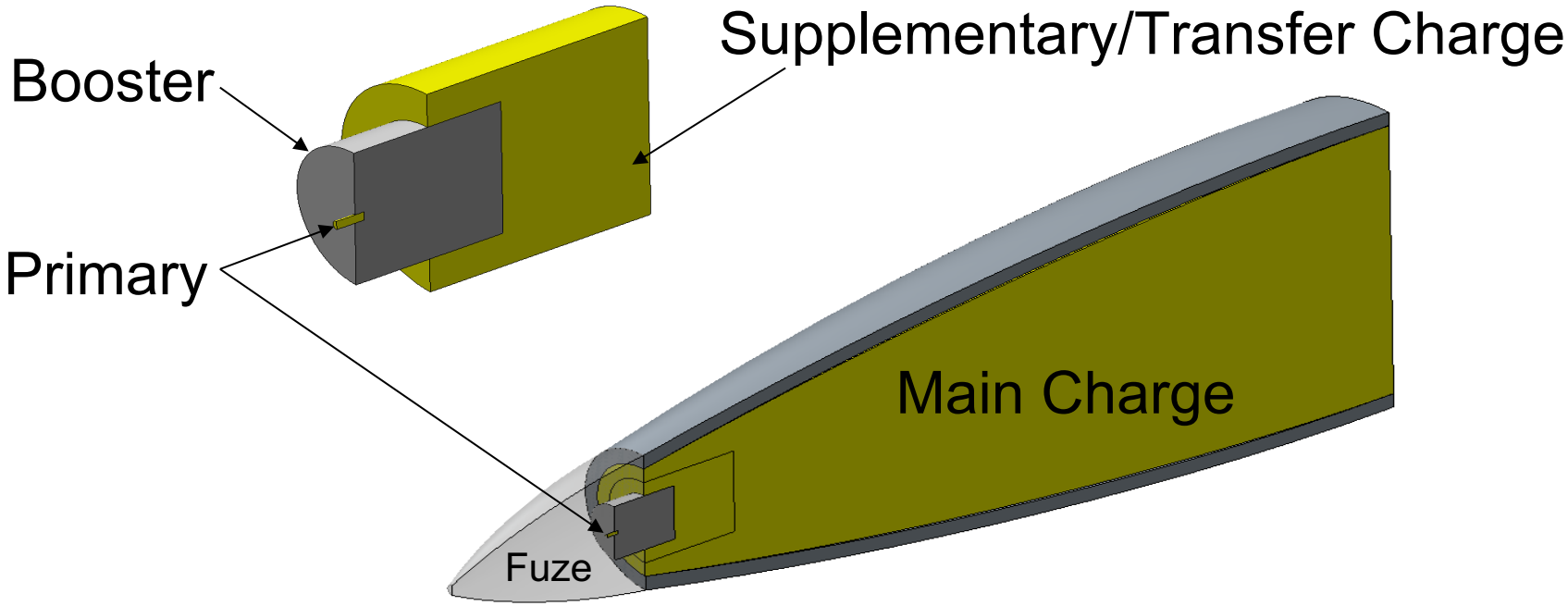
"A detonation is a shock-induced chemical reaction. The shock wave in turn is supported/propagated by the pressures of the chemical reaction." [1]



1. Dr. B.E. Fuchs, Presentation at Texas Technical University, May 2017

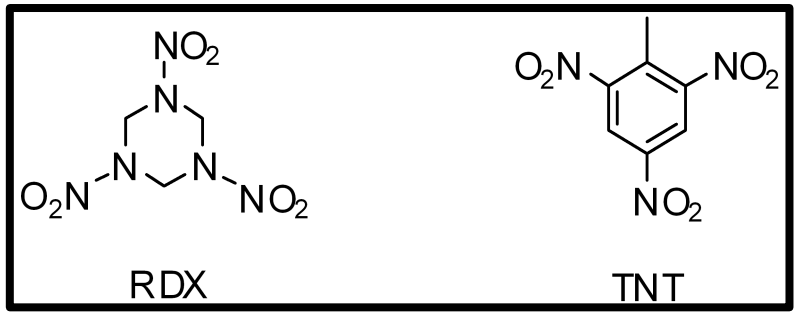
DISTRIBUTION A. Approved for public release: distribution unlimited.

Explosive System



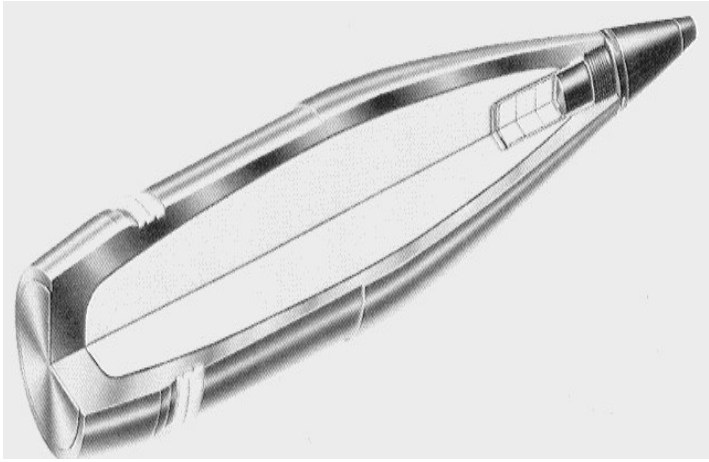
DISTRIBUTION A. Approved for public release: distribution unlimited.

What is an Explosive Formulation?



Composition B

Explosive formulations are composed of specific ratios of energetic materials and may add a binder such as a polymer or wax



DISTRIBUTION A. Approved for public release: distribution unlimited.

What do our Customers Want? Army Futures Command

SECRETARY OF THE ARMY
WASHINGTON

06 OCT 2017

MEMORANDUM FOR SEE DISTRIBUTION

SUBJECT: Army Directive 2017-24 (Cross-Functional Team Pilot In Support of Materiel Development)

1. Reference Army Directive 2017-22 (Implementation of Acquisition Reform Initiatives 1 and 2), 12 Sep 2017.

2. The Army's capabilities development and acquisition enterprise is exploring an innovative organizational construct to integrate and synchronize processes across multiple stakeholders. The Army will leverage designated Cross-Functional Team (CFT) pilots to embrace horizontal and vertical integration and improve the quality and speed of materiel development activities. The CFTs will follow a Developmental Operations methodology defined as warfighters and developers working together to prepare sound capability documents that enable the rapid and frequent delivery of capabilities to the warfighter to inform a potential program of record. The use of designated CFTs supports the authority of the Chief of Staff of the Army (CSA) to assist the Secretary of the Army in the development and approval of requirements.

3. We are establishing CFTs that will narrow an existing capability gap by developing capability documents, informed in appropriate cases by experimentation and technical demonstrations, and rapidly transition leader-approved capability requirements to the Army Acquisition System. This approach will allow us to develop capabilities faster and in a less costly manner to enable our Soldiers to fight and win.

4. The purpose of this directive is to establish a scalable CFT pilot consisting of personnel from the following domains: Requirements, Acquisition, Science and Technology, Test and Evaluation, Resourcing, Contracting, Costing, Acquisition Logisticians, and U.S. Army Forces Command (as well as Army Service Component Commands as applicable). The CFTs will also leverage industry and academia where appropriate to help inform the capabilities development process. The end state is an empowered team that rapidly integrates and synchronizes Developmental Operations activities that enable the delivery of leader-approved capabilities to the operating force.

5. The concept for the CFT is to develop a requirement, informed in appropriate cases by experimentation and technical demonstrations, through teaming, agility, and rapid feedback to enable the development of a capability document and improve the decision making for a potential program of record. The Army will stand up eight priority CFTs to pilot a flat organizational construct enhanced by centralized planning and decentralized execution to deliver the best possible return on investment for Soldiers. Each CFT will

SUBJECT: Army Directive 2017-24 (Cross-Functional Team Pilot In Support of Materiel Development)

be led by a Director (Brigadier General) who reports directly to the Under Secretary of the Army (USA) at the direction of the Secretary of the Army and Vice Chief of Staff of the Army (VCSA) at the direction of the CSA. The VCSA will chair a panel that includes the Assistant Secretary of the Army (Acquisition, Logistics and Technology); Commanders of U.S. Army Forces Command, U.S. Army Training and Doctrine Command, and U.S. Army Materiel Command (AMC); Deputy Under Secretary of the Army; Deputy Chief of Staff, G-1; Deputy Chief of Staff, G-8; Director of Business Transformation; Chief, General Officer Management Office; and Director of the Office of Process Innovation and Integration. The panel will assess nominees for CFT Directors and make final recommendations to the CSA for approval. The CFTs will consist of empowered subject matter experts from across the Requirements, Acquisition, Science and Technology, Test and Evaluation, Resourcing, Contracting, Costing, and Sustainment communities that participate for the duration of the mission.

a. The eight CFT pilots, aligned with the CSA's six modernization priorities, are:

(1) Long Range Precision Fires: Long Range Precision Fires CFT pilot.

(2) Next Generation Combat Vehicle: Next Generation Combat Vehicle CFT pilot.

(3) Future Vertical Lift: Future Vertical Lift CFT pilot.

(4) Network Command, Control, Communication, and Intelligence:

(a) Network Command, Control, Communication, and Intelligence CFT pilot; and

(b) Assured Positioning, Navigation, and Timing CFT pilot.

(5) Air and Missile Defense: Air and Missile Defense CFT pilot.

(6) Soldier Lethality:

(a) Soldier Lethality CFT pilot, and

(b) Synthetic Training Environment CFT pilot.

b. We will achieve initial operating capability 14 days from the date of this directive and will focus on existing priority capability gaps. These teams will be responsible for developing the respective capability documents, informed in appropriate cases by pre-Materiel Solution Analysis Phase experimentation and technical demonstrations to ensure that planned capabilities are technologically feasible, affordable, and available

2

DISTRIBUTION A. Approved for public release: distribution unlimited.

What do our Customers Want? Army Futures Command (cont.)

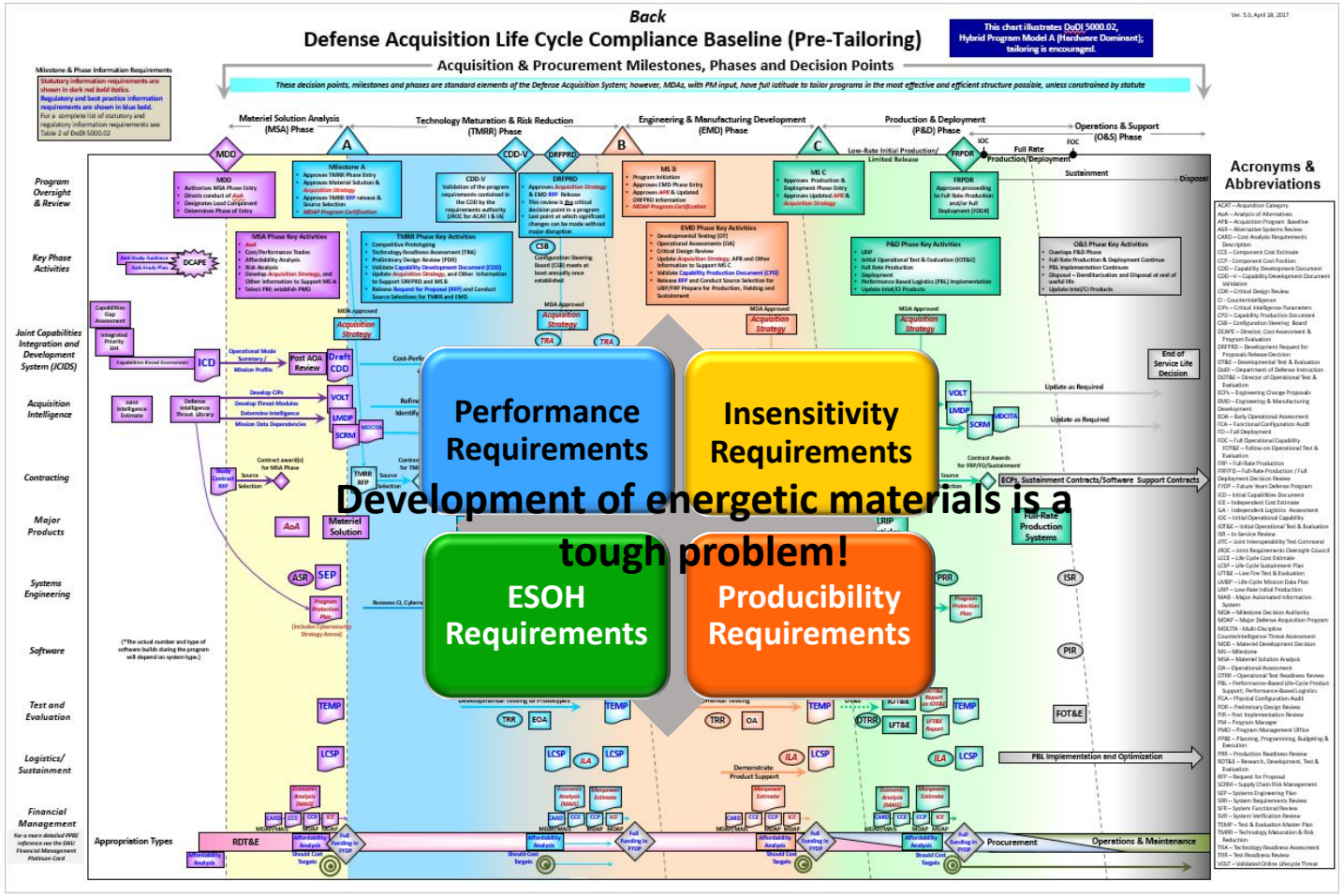
- Acceleration of surface-to-surface fires capability and capacity
- Deep Fires – penetration of peer adversary defensive capabilities at strategic ranges
- Long-Range Precision Fires Missile – “10x” missile capability
  - Increased range
  - Doubled launcher capacity
  - Improved lethality
  - Faster time of flight to target
  - Increase rate of fire
  - Jamming resistance
- Extended Range Cannon Artillery – “10x” artillery capability
  - Increased range
  - Increased rate of fire
  - Increased lethality
  - Increased reliability
  - Greater survivability

> “Our adversaries have studied our way of war and adapted by investing in capabilities and developing concepts to gain advantages over us across the domains of air, land, sea, space and cyberspace...”
>
> - Brig. Gen. Stephen J. Maranian, director, Long-Range Precision Fires Cross-Functional Team

https://www.army.mil/standto/2018-01-17

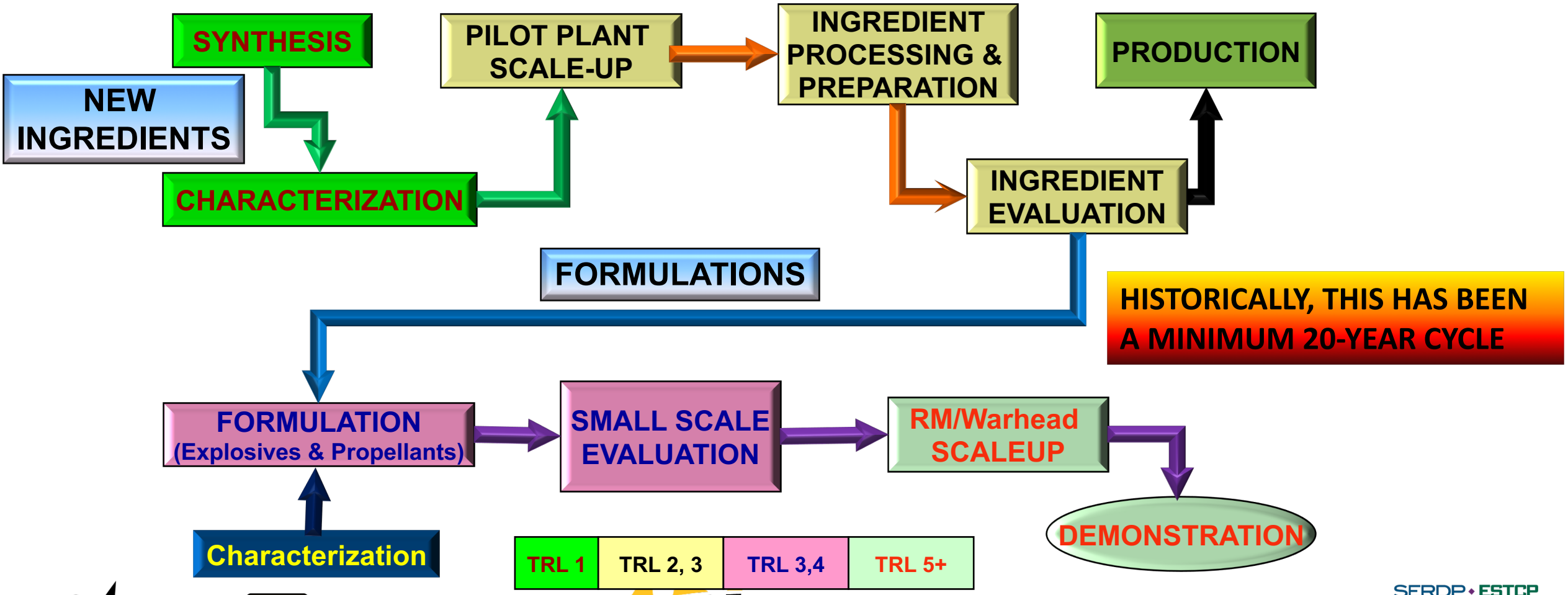
DISTRIBUTION A. Approved for public release: distribution unlimited.

What Do Our Customers Want?
Acquisition Considerations



DISTRIBUTION A. Approved for public release: distribution unlimited.

Generic Process Overview



DISTRIBUTION A. Approved for public release: distribution unlimited.

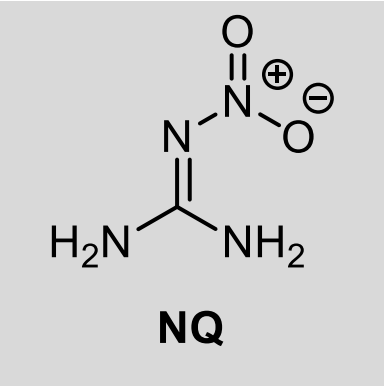
A Highlight of DoD Environmentally-Focused Energetic Materials R&D Projects

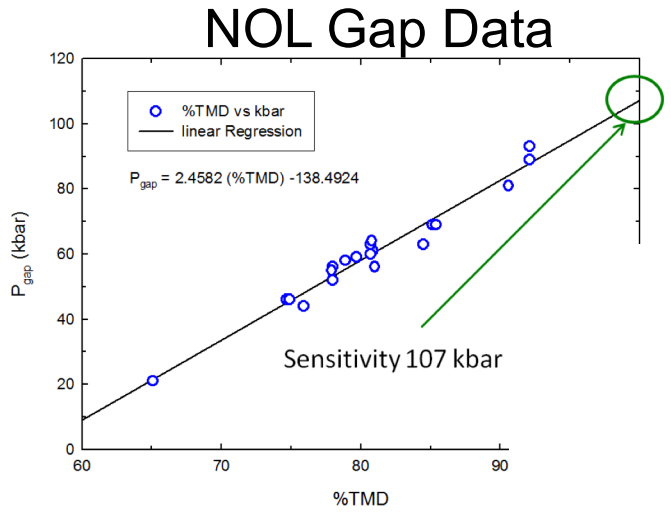
DISTRIBUTION A. Approved for public release: distribution unlimited.

Ingredient Background

Nitroguanidine

- Advantageous properties for use as a powerful insensitive fill
  - Extremely insensitive to shock (SR)
  - Large critical diameter (SCJ)
  - Mild SCO response (liberates water, cools decomposition)
- NQ decomposes upon melting (T_{dec} = 250 °C)
- Requires PBX formulation
- Inert binders dilute explosive power



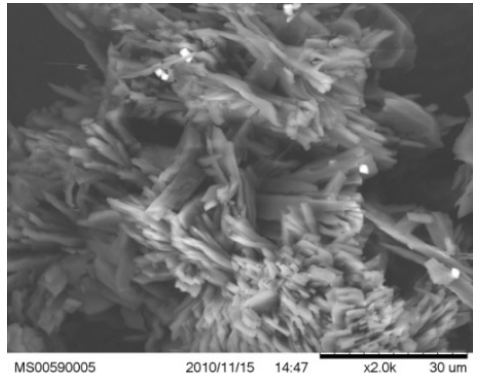


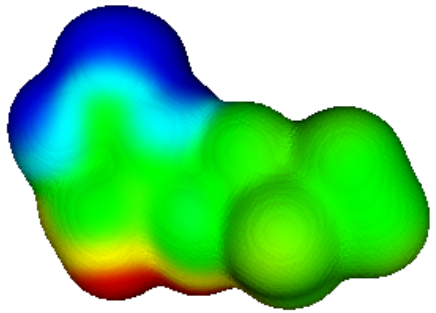
DISTRIBUTION A. Approved for public release: distribution unlimited.

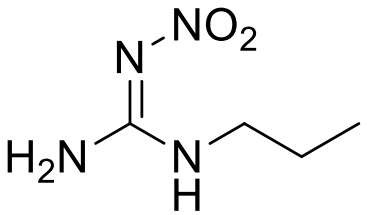
PrNQ

PrNQ

- Simply adds propyl alkyl group to nitroguanidine
- Decreases NQ melting point to 98-100 ^{o}C
- Decomposition starts at 220 ^{o}C
- Allows for steam-based melt cast processing
- Propyl group expected to further desensitize NQ with a manageable performance diminishment







DISTRIBUTION A. Approved for public release: distribution unlimited.

#SerdpEstcp2018

DGX-Al Formulation Family

DGX-Al Formulations

- PrNQ will be combined with aluminum and other particulate solids to comprise DGX-Al family of formulations
- DGX-Al formulations will be highly insensitive, enhanced blast, and environmentally friendly
- Initial Goal: Determine detonation velocity and critical diameter of candidate DGX-Al formulations

DISTRIBUTION A. Approved for public release: distribution unlimited.

Performance Calculations

Formulation Name	Ingredients	Detonation Velocity (% of PBXN-109)	Detonation Pressure (% of PBXN-109)
DGX-1	PrNQ·Al	88.6	63.8
DGX-2	PrNQ·Ingredient A·Al	89.3	65.4
DGX-3	PrNQ·Ingredient B·Al	98.6	87.8
DGX-4	PrNQ·Ingredient A·Ingredient B·Al	99.1	89.2
DGX-5	PrNQ·Ingredient B·Ingredient C·Al	97.4	101.5
DGX-6	PrNQ· Ingredient B·Ingredient C·Al (more Ingredient C)	95.8	98.3

Ingredients B and C are solid particulates

Ingredient C is a sensitizer

Cheetah 6.0 User's Manual, LLNL-SM-416166, 2010.

DISTRIBUTION A. Approved for public release: distribution unlimited.

DGX-3 Formulation Processing

DGX-3a
(PrNQ, Ingredient B,
Type III Class 7 Al)

Processed poorly- mix did not pour

DGX-3b
(PrNQ, Ingredient B,
Type IV spherical Al)

Processed well- mix poured easily

DISTRIBUTION A. Approved for public release: distribution unlimited.

DGX-4 Formulation Processing

DGX-4a
(PrNQ, Ingredient A, Ingredient B,
Type III Class 7 Al)

Processed marginally - mix poured with difficulty

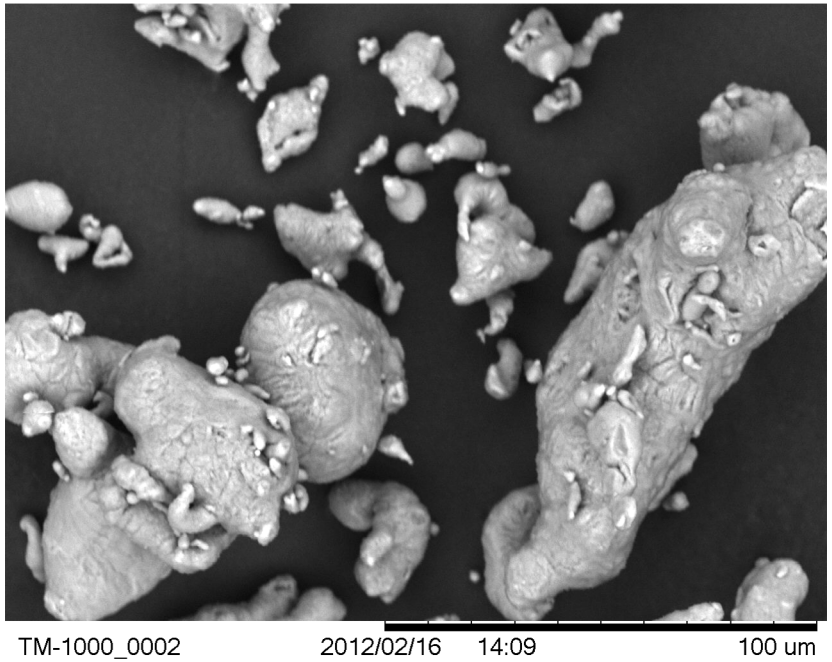
DGX-4b
(PrNQ, Ingredient A, Ingredient B,
Type IV spherical Al)

Processed well - mix poured easily

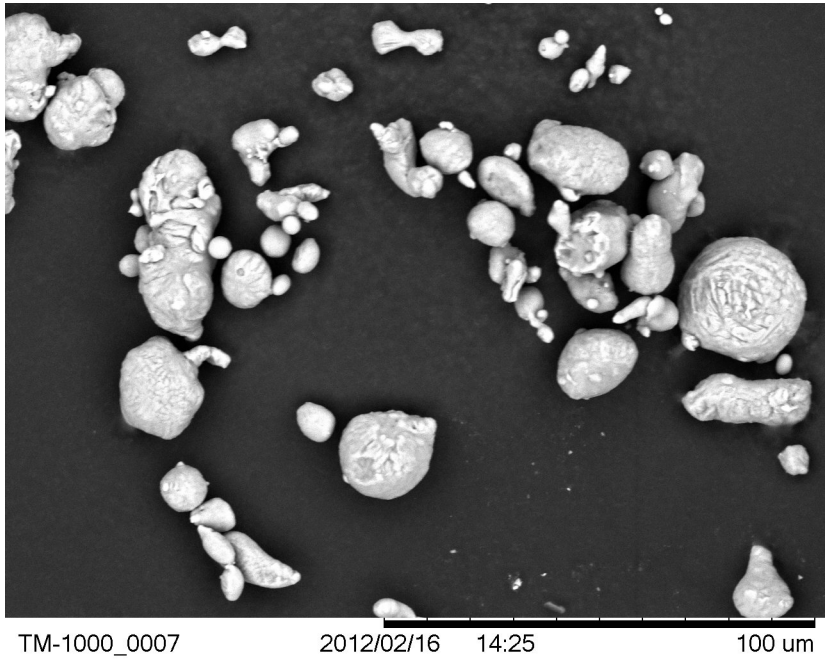
DISTRIBUTION A. Approved for public release: distribution unlimited.

Aluminum SEM Images

Type III Class 7 Aluminum



Type IV Spherical Aluminum



- Type III Class 7 aluminum particles larger and more irregularly shaped
- Type IV spherical aluminum smaller, but spherical
- Surface area differences likely affected processing success of formulations with solid particulates

DISTRIBUTION A. Approved for public release: distribution unlimited.

Small-Scale Sensitivity: DGX-3b and DGX-4b

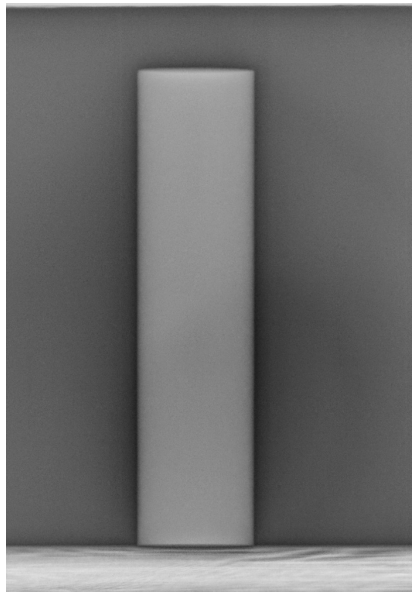
Material	Impact (H_{50}, in)	BAM Friction (N)	ESD (J)
DGX-3b	>61	247	0.625
DGX-4b	>61	318	0.250
RDX	8.6	125	0.063

The insensitivity shown by the small-scale sensitivity testing coupled with favorable thermal safety testing permitted scale-up to 1-gallon mixes

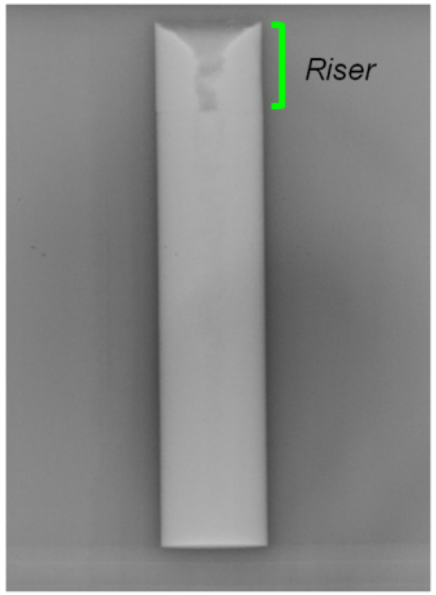
DISTRIBUTION A. Approved for public release: distribution unlimited.

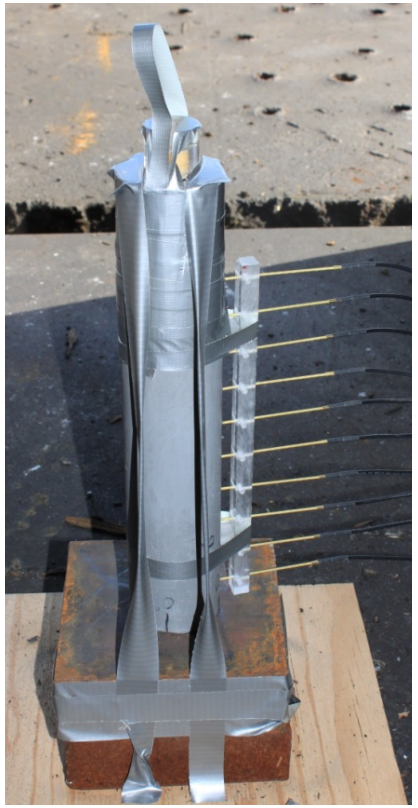
Generation 1 Detonation Velocity Testing

DGX-3b x-ray image



DGX-4b x-ray image



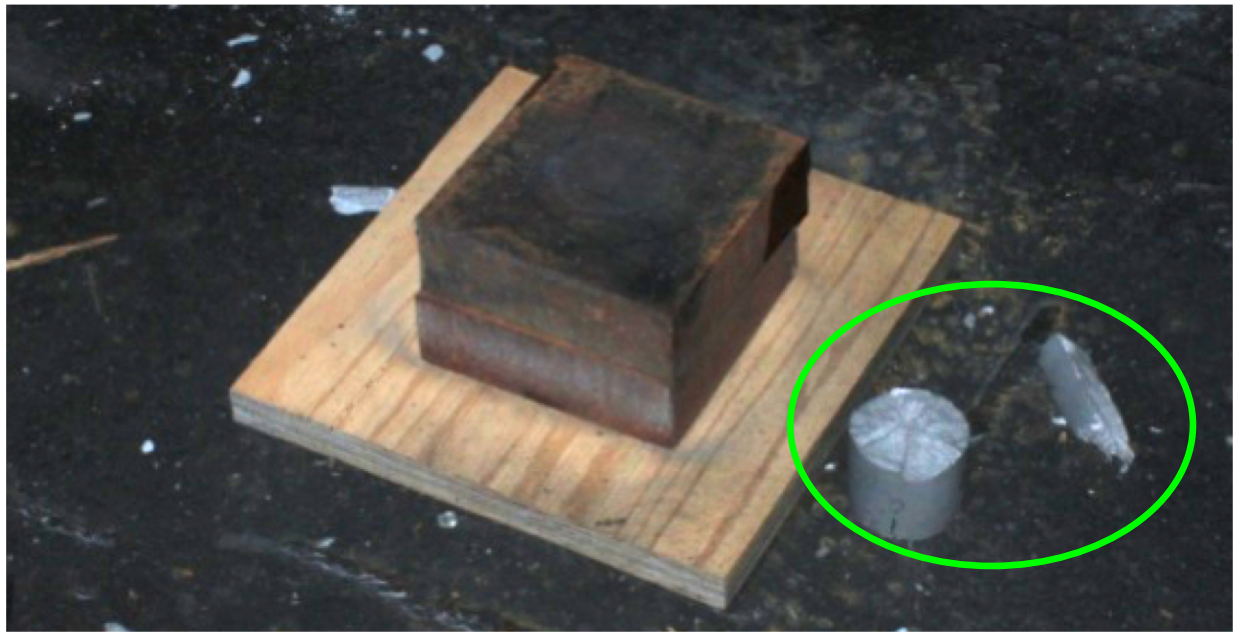


2.5” diameter x 10” long charges cast at high theoretical maximum density

Test set-up

DISTRIBUTION A. Approved for public release: distribution unlimited.

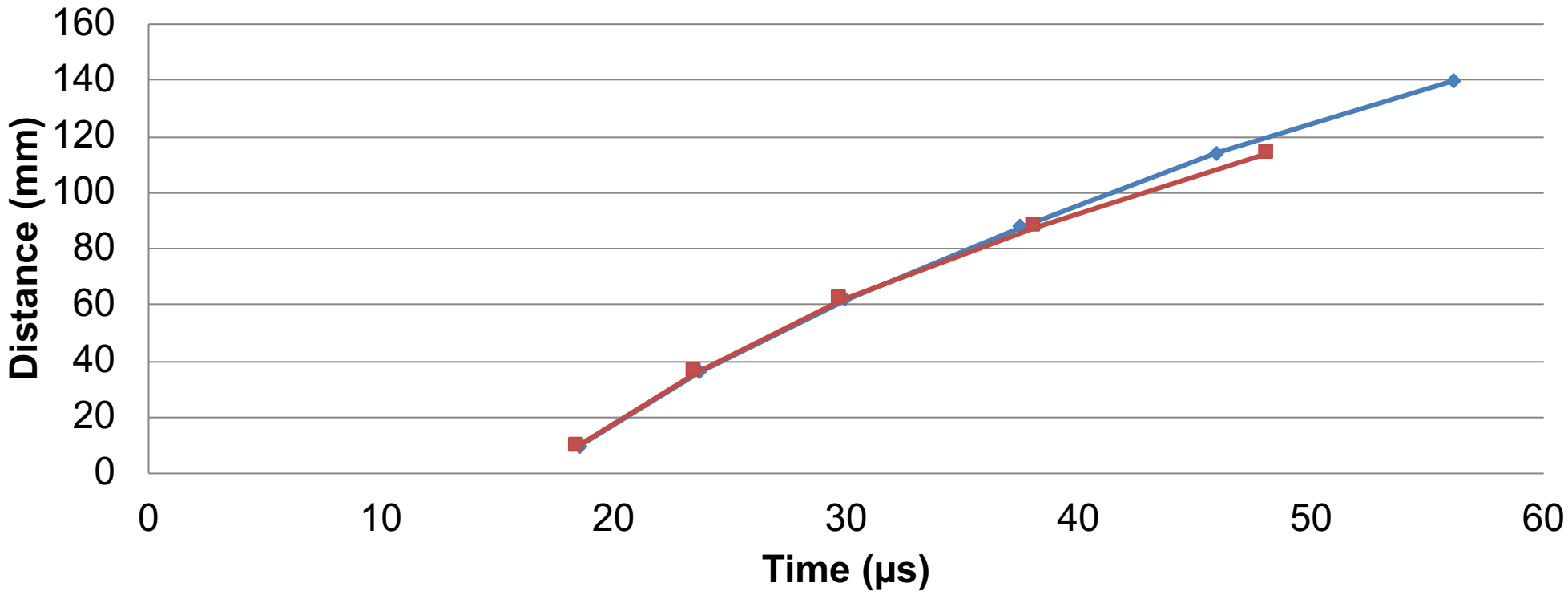
Generation 1 Detonation Velocity Testing Results



- No detonation observed for either DGX-3b or DGX-4b
- Material recovered after both tests
- Conclusion- critical diameter >2.5” for both

DISTRIBUTION A. Approved for public release: distribution unlimited.

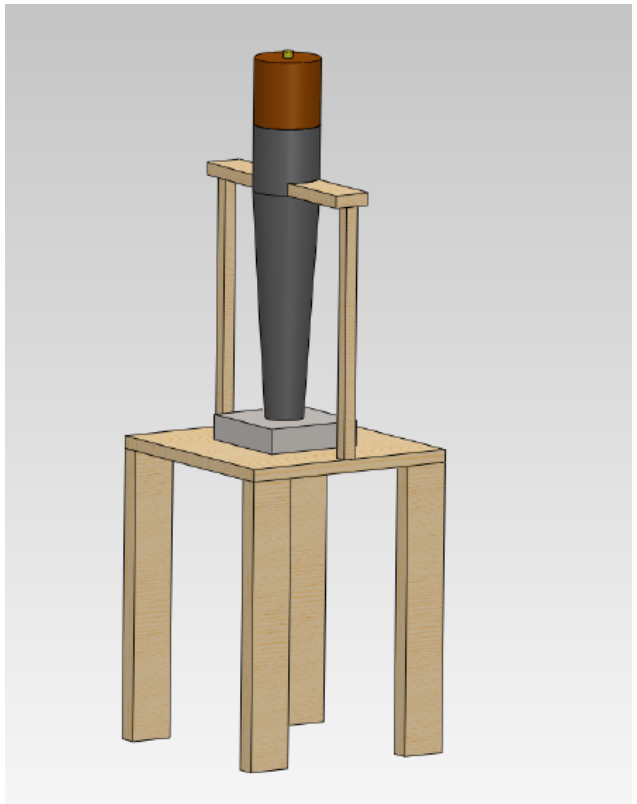
Generation 1 Decaying Shock Waves



- DGX-3b (blue), DGX-4b (red)
- Maximum shock velocity observed <5 km/s
- Roughly half of pins on each charge did not receive signal for passing shock wave

DISTRIBUTION A. Approved for public release: distribution unlimited.

Detonation Velocity Cone Tests



- Why a cone test?
  - Eliminates need to test multiple right-cylinder charges to determine critical diameter
  - Minimizes material needs (but still a big charge)
- Drawback- provides only an estimate of critical diameter due to overdriven detonation wave
- Cone description:
  - 5.25” diameter by 5.25” long lead-in section
  - 18” long taper section (3.6º) down to 3” diameter
  - 5.25” diameter by 5.25” long composition B booster

DISTRIBUTION A. Approved for public release: distribution unlimited.

Detonation Velocity Cone Test Formulations

- DGX-3b
  - PrNQ, Ingredient B, and Type IV spherical aluminum
  - Did not detonate at 2.5” diameter
  - Contains fewer ingredients than DGX-4b
  - Approved for processing on the 1-gallon scale

- DGX-6b
  - DGX-3b + a sensitizing ingredient (Ingredient C)
  - Should detonate at a smaller diameter than DGX-3b (good if critical diameter of DGX-3b is excessively large)
  - Approved for processing on the laboratory scale

DISTRIBUTION A. Approved for public release: distribution unlimited.

Safety Testing for Approval of 10-Gallon Mixes

- DGX-3b
  - Only remaining data piece was 1-liter slow cook-off
  - 1-liter slow cook-off results were favorable
  - Approval was granted to process on the 10-gallon scale

- DGX-6b
  - Needed small-scale sensitivity and thermal analysis

Material	Impact (H_{50}, in)	BAM Friction (N)	ESD (J)
DGX-6b	>61	282.24	0.250
RDX	10.12	141.12	0.125

  - Also needed 1-liter slow cook-off data
  - 1-liter slow cook-off results were favorable
  - Approval was granted to process on the 10-gallon scale

DISTRIBUTION A. Approved for public release: distribution unlimited.

10-Gallon Scale Processing

Insulated 3 piece cone mold

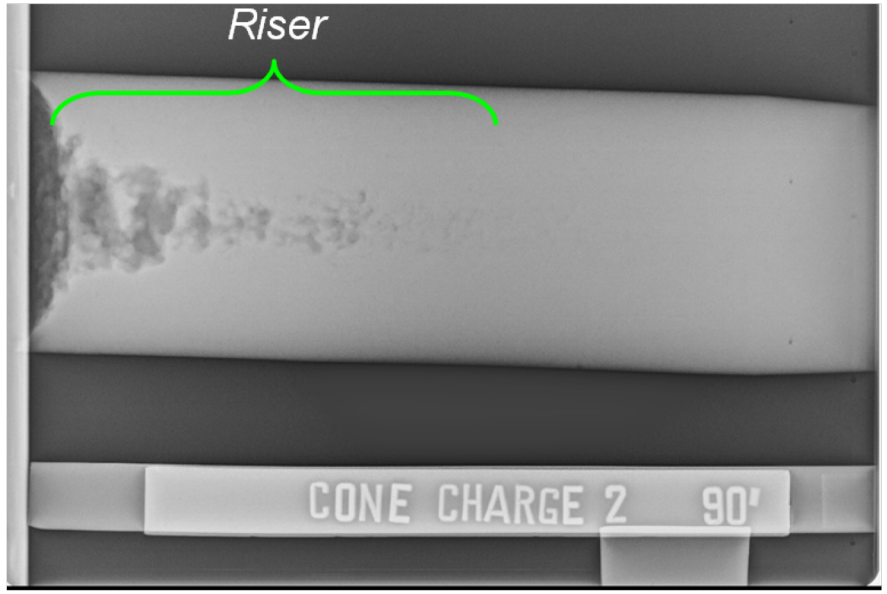
DISTRIBUTION A. Approved for public release: distribution unlimited.

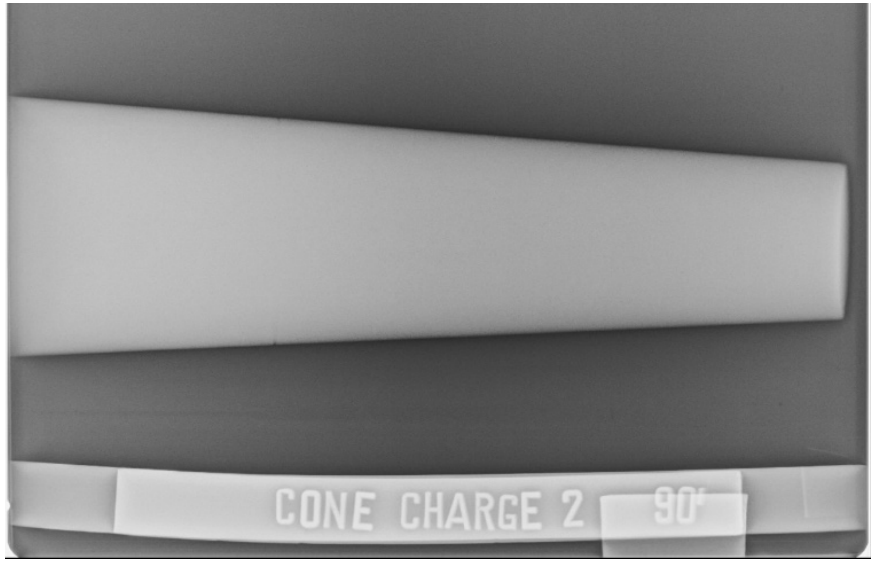
10-Gallon Scale Processing (cont.)

Charge after removal from mold

DISTRIBUTION A. Approved for public release: distribution unlimited.

Cone Charge X-Ray Images





No voids observed in the experimental section of charge

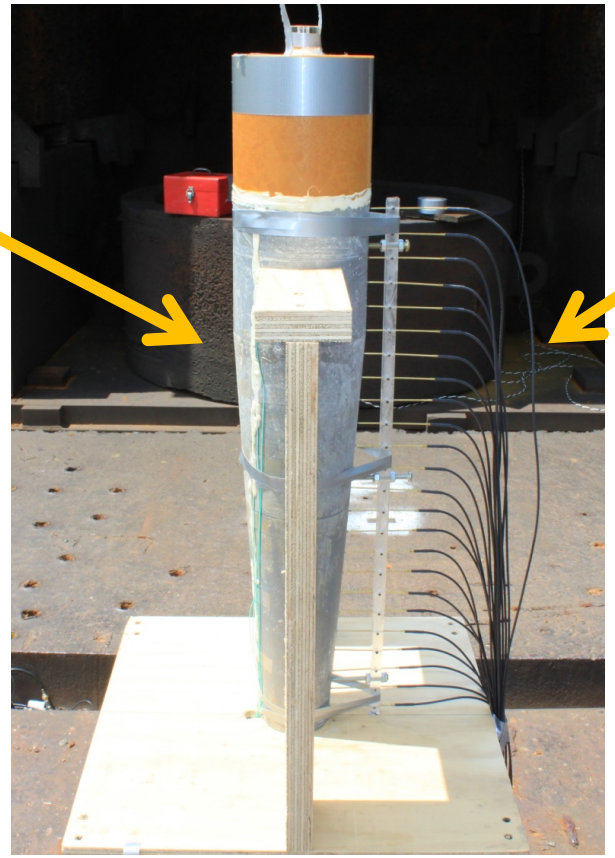
DISTRIBUTION A. Approved for public release: distribution unlimited.

Detonation Velocity Monitoring

Chirped fiber Bragg grating

Collaboration with LANL, funded by JMP (POC: George Rodriguez)

Hi fidelity record of passing detonation wave



Piezopins

1” pin spacing

Traditional detonation velocity measurement technique

DISTRIBUTION A. Approved for public release: distribution unlimited.

Detonation Velocity Cone Test Results

- DGX-3b
  - PrNQ, Ingredient B, and Type IV spherical aluminum
  - Did not detonate
  - Material recovered after test
  - Critical diameter >5.25”

- DGX-6b
  - Fully detonated at all diameters
  - Large dent in witness plate
  - Detonation velocity near tritonal and PBXN-109
  - Critical diameter <5.25”

Recovered DGX-3b

DGX-4b witness plate

DISTRIBUTION A. Approved for public release: distribution unlimited.

DGX-Al Conclusions

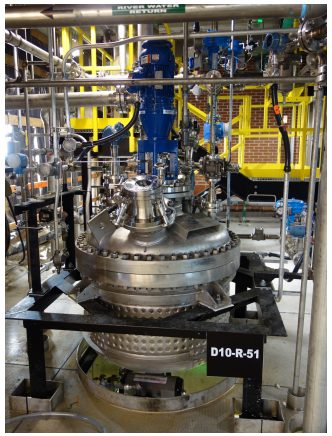
- Demonstrated that PrNQ can be used a melt-base for energetic formulations
- Conical detonation velocity tests were conducted on DGX-3b and DGX-6b
- DGX-3b critical diameter > 5.25”
- DGX-6b critical diameter < 3”, detonation velocity near tritonal and PBXN-109
- Future work will be to tailor formulations to achieve desired detonation velocity, critical diameter, detonation pressure, and shock sensitivity

DISTRIBUTION A. Approved for public release: distribution unlimited.

Green Granular IMX-104 Production (OEP 18-02)

PROJECT DESCRIPTION

- ARDEC will develop a granular IMX-104 production process using green performance fluids and prepare a processing specification
- Legacy slurry-coating method to produce granular IMX-104 uses a performance fluid which may have potential global warming concern (GWP 8600 for 100 yr)
- Granular IMX-104 is receiving interest by acquisition community due to high performance, facile loading



REQUIREMENT/IMPACT

- Addresses AERTA PP-14-12-02 by replacing the current performance fluid with an alternative fluid that has zero/low Global Warming Potential and AERTA PP-3-02-07 by reducing water use in energetics production
- Performance fluids do not dissolve IMX-104 ingredients (NTO) = drastic processing waste reduction
- Supports Army CFTs

PROGRESS REPORT

- Recent accomplishments/issue
  - Completed down-select to 3 fluids

DISTRIBUTION A. Approved for public release: distribution unlimited.

Conclusions

- Over 100 federal laws and regulations addressing ESOH issues
- Great opportunity for reducing environmental impact of weapons development phase
- Technology currently being developed and can reduce impact
  - New ingredients
  - New synthesis methods
  - New processing methods

DISTRIBUTION A. Approved for public release: distribution unlimited.