NDIA

2022 INSENSITIVE MUNITIONS AND ENERGETIC MATERIALS (IMEM) TECHNOLOGY SYMPOSIUM

Enhancing The Performance of Insensitive Munitions

October 18 – 20, 2022 | Indianapolis, IN | NDIA.org/IMEM

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WHO WE ARE

The National Defense Industrial Association is the trusted leader in defense and national security associations. As a 501(c)(3) corporate and individual membership association, NDIA engages thoughtful and innovative leaders to exchange ideas, information, and capabilities that lead to the development of the best policies, practices, products, and technologies to ensure the safety and security of our nation. NDIA's membership embodies the full spectrum of corporate, government, academic, and individual stakeholders who form a vigorous, responsive, and collaborative community in support of defense and national security. For more than 100 years, NDIA and its predecessor organizations have been at the heart of the mission by dedicating their time, expertise, and energy to ensuring our warfighters have the best training, equipment, and support. For more information, visit **NDIA.org**

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SCHEDULE AT A GLANCE

MONDAY, OCT 17

Registration
Cosmopolitan Foyer
4:00 pm - 6:00 pm

TUESDAY, OCT 18

Registration
Cosmopolitan Foye
8:00 am - 5:30 pm

Keynote: Dr. Brian Fuchs
Cosmopolitan AB
8:10 am - 9:00 am

Reception
Cosmopolitan Foyer
5:10 pm – 6:10 pm

WEDNESDAY, OCT 19

Registration
Cosmopolitan Foyer
7:00 am - 12:00 pm

Keynote: Dr. Robert Wardle
Cosmopolitan AB
8:35 am - 9:15 am

THURSDAY, OCT 20

Registration
Cosmopolitan Foyer
7:00 am - 5:00 pm

Keynote: Dr. Jason Jouet
Cosmopolitan AB
9:00 am – 10:00 am

WELCOME TO 2022 IMEM TECHNOLOGY SYMPOSIUM

On behalf of the Insensitive Munitions and Energetic Materials Committee and our MSIAC partner, I would like to welcome you to the 2022 Insensitive Munitions and Energetic Materials Technology Symposium. This international gathering of the top chemists, system designers and engineers from government laboratories, industry, and academia provides a venue for the exchange and dissemination of the latest research in synthesis, formulation, system design, testing, characterization and safety – all aimed at advancing munitions effectiveness while improving safety for the warfighter. In recent decades, great advances have been made and our munitions are less vulnerable to attack than ever before; however, challenges persist. It is through the continuing work of the authors, presenters, sponsors, and attendees at this conference and across our worldwide defense industry that these challenges will be overcome resulting in safer munitions being produced in our factories and fielded to our warfighters.

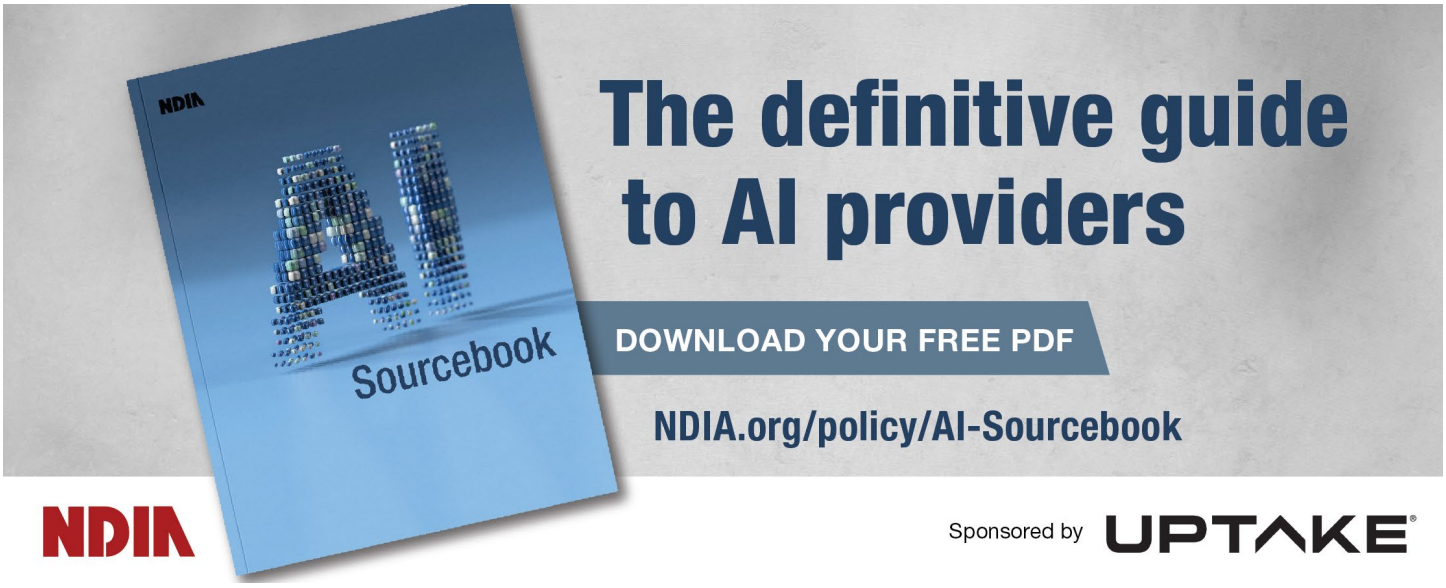
Paul Braithwaite
Fellow, Propulsion Systems IR&D Lead
Northrop Grumman Corporation

GET INVOLVED
Learn more about NDIA's Divisions and how to join one at **NDIA.org/Divisions**

MUNITIONS TECHNOLOGY

WHO WE ARE

The Munitions Technology Division maintains an open exchange of technical information among government and industry programs and technical managers, and to identify changes and trends in policy, guidance, and organizational functions that impact the development, production, maintenance, and demilitarization of munitions.



EVENT INFORMATION

LOCATION

Hyatt Regency
One South Capital Avenue
Indianapolis, IN 46204

ATTIRE

Civilian: Business Casual
Military: Uniform of the Day

SURVEY AND PARTICIPANT LIST

You will receive via email a survey and list of participants (name and organization) after the conference. Please complete the survey to make our event even more successful in the future.

EVENT CONTACT

Kimberly Hurley
Director, Meetings
(703) 247-9494
khurley@NDIA.org

PLANNING COMMITTEE

Paul Braithwaite
Symposium Chair

Ken Graham
Committee Member

Christelle Collet
Committee Member

Steve Nicolich
Committee Member

Stephen Struck
Committee Member

SPEAKER GIFTS

In lieu of speaker gifts, a donation is being made to the Fisher House Foundation.

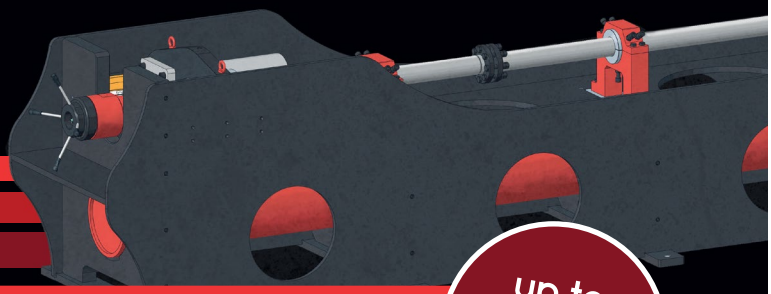
HARASSMENT STATEMENT

NDIA is committed to providing a professional environment free from physical, psychological and verbal harassment. NDIA will not tolerate harassment of any kind, including but not limited to harassment based on ethnicity, religion, disability, physical appearance, gender, or sexual orientation. This policy applies to all participants and attendees at NDIA conferences, meetings and events. Harassment includes offensive gestures and verbal comments, deliberate intimidation, stalking, following, inappropriate photography and recording, sustained disruption of talks or other events, inappropriate physical contact, and unwelcome attention. Participants requested to cease harassing behavior are expected to comply immediately, and failure will serve as grounds for revoking access to the NDIA event.

EVENT CODE OF CONDUCT

NDIA's Event Code of Conduct applies to all National Defense Industrial Association (NDIA), National Training & Simulation Association (NTSA), and Women In Defense (WID) meeting-related events, whether in person at public or private facilities, online, or during virtual events. NDIA, NTSA, and WID are committed to providing a productive and welcoming environment for all participants. All participants are expected to abide by this code as well as NDIA's ethical principles and practices. Visit NDIA.org/CodeOfConduct to review the full policy.

THIOT INGENIERIE



POWDER GUNS ZOLTAN 40 & ZOLTAN 90

up to 2530m/s at 15m

IMPACTS OF FRAGMENTS
EVALUATION & DEVELOPMENT OF INSENSITIVE AMMUNITION
EVALUATION OF ARMORED VEHICLES' LEVEL OF PROTECTION

STANAG AOP 4496

QUALITY OF IMPACT

- **Impact point at 15mm maximum** from the aimed point at 15m
- **Tilt at impact less than 2°** at 15m
- **Total separation of the sabot** before impact

EASE OF USE

- **Complete supply** including launcher and projectiles
- **Easy installation and removal** of the launcher without special adjustment

SMART MAINTENANCE

- **Easy cleaning** after each shot
- **30 shots** before replacement of wear parts
- **300 shots** before replacement of the interchangeable part of the tube

Customization of the launcher depending on the nature of the powder used by the customer*

TECHNICAL CAPABILITIES

ZOLTAN 40 Ø

14.30mm @ 18.6g FSP
V 15m: 2530 ± 90m/s

20.00mm @ 52.73g FSP
V 15m: 1830 ± 60m/s

ZOLTAN 90 Ø

Up to 300g fragment
V 15m: 2000 ± 90m/s

*performance to be validated according to the nature of the powder

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46130 Puybrun - FRANCE

AGENDA

MONDAY, OCTOBER 17

4:00 – 6:00 pm

REGISTRATION
COSMOPOLITAN FOYER

TUESDAY, OCTOBER 18

7:00 am – 5:30 pm

REGISTRATION
COSMOPOLITAN FOYER

8:00 – 8:10 am

WELCOME REMARKS
COSMOPOLITAN AB

MG James Boozer, USA (Ret)
Executive Vice President, NDIA

8:10 – 9:00 am

KEYNOTE: INSENSITIVE MUNITIONS, IMPORTANT NOW MORE THAN EVER
COSMOPOLITAN AB

Dr. Brian Fuchs
Senior Research Scientist, Insensitive Munitions, U.S. Army Picatinny Arsenal

9:00 – 9:40 am

MSIAC AWARDS PRESENTATION
COSMOPOLITAN AB

Christelle Collet
Technical Specialist Officer, MSIAC

9:40 – 10:10 am

NETWORKING BREAK
COSMOPOLITAN FOYER

10:15 – 10:35 am

ENERGETIC MATERIALS & THE DEFENSE PRODUCTION ACT
COSMOPOLITAN AB

Anthony Di Stasio
Director, Industrial Base Support, USD (A&S)

10:35 – 10:55 am

COMPARISON OF IM THREATS VERSUS THE REAL WORLD
COSMOPOLITAN AB

Christelle Collet
Technical Specialist Officer, MSIAC

10:55 – 11:15 am

NATO INSENSITIVE MUNITIONS PORTFOLIO PROGRESSION LEADING TO INSENSITIVE MUNITIONS – HAZARD CLASSIFICATION (IM-HC) HARMONIZATION

COSMOPOLITAN AB

Daniel Pudlak
CCDC-AC, U.S. Army

11:15 – 11:35 am

INSENSITIVE MUNITIONS – HAZARD CLASSIFICATION HARMONIZATION WORKING GROUP (IM-HC WG) UPDATE & DEVELOPMENT OF AOP-4864

COSMOPOLITAN AB

Daniel Pudlak
CCDC-AC, U.S. Army

11:35 – 11:55 am

MSIAC HIGHLIGHTS & FUTURE PRIORITIES

COSMOPOLITAN AB

Christelle Collet
Technical Specialist Officer, MSIAC

11:55 am – 1:00 pm

NETWORKING LUNCH

COSMOPOLITAN AB

CONCURRENT BREAKOUT SESSIONS

	Insensitive Munitions Policy & Requirements	Energetic Material Formulations & Synthesis
	COSMOPOLITAN AB Session Chair: Joseph LiVolsi	COSMOPOLITAN CD Session Chair: Dr. Jacob Morris
1:00 – 1:20 pm	**24847 – The Status of International & National IM Policies Across Nations** Christelle Collet Technical Specialist Officer, MSIAC	**24923 – Estimation of Elastic Constants of Composite Energetic Materials** Dr. Kevin Jaansalu TSO Materials Technology, Munitions Safety Information and Analysis Center (MSIAC)
1:25 – 1:45 pm	**24765 – An International Review of Stanag 4488 Gap Testing** Dr. Ernest Baker Warheads TSO, NATO MSIAC	**24861 – Improved Continuous Microfluidic Synthesis of Energetic Compounds** Dr. Christina Christensen Principal Research Scientist, Northrop Grumman Corporation

1:50 – 2:10 pm

24766 – Recent Advances of the MSIAC Gap Test Tool & Database

Dr. Ernest Baker
Warheads TSO, NATO MSIAC

24850 – The Story of Ethylenedinitrarmine (EDNA): Synthesis, Crystallization, Formulation & Applications

Dr. Arthur Delage
R&D Project Manager, EURENCO

2:15 – 2:35 pm

24854 – Comparison Of Performance & Insensitivity Properties of Enhanced Blast Plastic Bonded Explosives with Conventional Explosives

Serhat Bilgen
Senior Research, TUBITAK SAGE

2:35 – 3:10 pm

NETWORKING BREAK
COSMOPOLITAN FOYER

CONCURRENT BREAKOUT SESSIONS

	Insensitive Munitions Test Methods	Energetic Materials Processing
	COSMOPOLITAN AB Session Chair: Nausheen Al-Shehab	COSMOPOLITAN CD Session Chair: Wendy Hummers
3:10 – 3:30 pm	**24857 – The Fundamentals of IM Testing** Jon Toreheim Marketing and Sales Manager, Bofors Test Center	**24781 – Development of ResonantAcoustic® Continuous Microreactor and ResonantAcoustic® Continuous Crystallizer** Dr. Joseph Mayne Senior Chemical Engineer, Resodyn Corporation
3:35 – 3:55 pm	**24865 – Air Drag Measurements for the NATO Insensitive Munitions Fragment** Kevin Miers Mechanical Engineer, U.S. Army DEVCOM Armaments Center	**24834 – Process Improvement of Melt Pour Explosive 3,4-Dinitropyrazole (DNP)** Dr. Tomasz Modzelewski Principal Scientist, BAE Systems, Inc.
4:00 – 4:20 pm	**24852 – Mitigation of Flat 2-Dimensional Shocks to Prevent Sympathetic Reactions** Stefan de Koster Junior Scientist Innovator, TNO	**24843 – Continuous ResonantAcoustic® Production of Energetic Material** Joe Mayne Senior Chemical Engineer, Resodyn Corporation

4:25 – 4:45 pm

CLOSING REMARKS

Nausheen Al-Shehab
Chemical Engineer, U.S. Army DEVCOM AC

24862 – Advances in Resodyn Acoustic Mixer Processing Methods & Characterization

Justin Whaley
Senior Controls Engineer, Resodyn Corporation

4:45 – 4:50 pm

CLOSING REMARKS

Wendy Hummers
Program Director, Elbit Systems Ltd.

5:10 – 6:10 pm

RECEPTION

COSMOPOLITAN FOYER

WEDNESDAY, OCTOBER 19

7:30 am – 12:00 pm

REGISTRATION

COSMOPOLITAN FOYER

8:30 – 8:35 am

OPENING REMARKS

COSMOPOLITAN AB

Paul Braithwaite
Fellow, Propulsion Systems IR&D Lead, Northrop Grumman Corporation
Symposium Chair

8:35 – 9:15 am

KEYNOTE: PATHS FOR EM/IM TO PROVIDE STRATEGIC DIFFERENTIATION

COSMOPOLITAN AB

Dr. Robert Wardle
Principal, Wardle Enterprises: Energetics, Services and Technologies, LLC

9:15 – 10:00 am

ENERGETIC MATERIALS: MOVING FORWARD IN THE 21ST CENTURY

COSMOPOLITAN AB

Paul Braithwaite
Fellow, Propulsion Systems IR&D Lead, Northrop Grumman Corporation
Moderator

Dr. Jacob Morris
Chief, Energetics Material Branch, Munitions Directorate, Air Force Research Laboratory

Laurent Bonhomme
Roxel Group

Dr. David Price
Director of Business Development, NALAS Engineering

Jon Toreheim
Marketing and Sales Manager, Bofors Test Center

10:00 – 10:30 am

NETWORKING BREAK

COSMPOLITAN FOYER

CONCURRENT BREAKOUT SESSIONS

	Insensitive Munitions Modeling	Energetic Material Characteristics
	COSMOPOLITAN AB Session Chair: Dr. Ernest Baker	COSMOPOLITAN CD Session Chair: Melissa Mileham
10:30 – 10:50 am	**24851 – Implementation of Munition Vulnerability Models in the Ship Vulnerability Code Resist** Gert Scholtes Senior Research Scientist, TNO DSS	**24839 – Characterization of Impact Induced Reaction of Explosives Using the AFRL High Explosive Survivability Test (HEST)** Dr. Jesus Mares, Jr. Engineer, U.S. Air Force Research Laboratory
10:55 – 11:15 am	**24860 – Evaluation of Critical Temperatures via Thermal Runaway Models and Slow Cook Off Testing** Dr. Jeremy Headrick R&D Technical Manager, BAE Systems, Inc.	**24872 – Life Cycle Assessment and Aging Characteristics of Novel Signal Pyrotechnics, and Comparison to a Military Reference Composition** Dr. Richard Bouma Senior Scientist, TNO
11:20 – 11:40 am	**24993 – Concept for Improving Cook-off Performance of Propellants & Explosives** Dr. Jon Yagla Mechanical Engineer, Axient	**24844 – Recent Advancement on Enhanced Blast Explosives Manufacturing at Holston Army Ammunition Plant** Kyle Bittner R&D Formulation Chemist, BAE Systems, Inc.
11:45 am – 12:05 pm	**CLOSING REMARKS** Dr. Ernest Baker Warheads TSO, NATO MSIAC	**24893 – Comparison of the High-Speed Deformation Behavior of Cast & Additive Manufactured Polymer Bonded Mock Explosives** Kerry-Ann Stirrup PhD Candidate, Impact Science Laboratory, Purdue College of Engineering
12:05 – 12:10 pm		**CLOSING REMARKS** Dr. Melissa Mileham Staff Research Scientist, Northrop Grumman Corporation
12:10 pm	**ADJOURN**	

THURSDAY, OCTOBER 20

8:00 am – 5:00 pm

REGISTRATION
COSMOPOLITAN FOYER

8:50 – 9:00 am

OPENING REMARKS
COSMOPOLITAN AB

Paul Braithwaite
Fellow, Propulsion Systems IR&D Lead, Northrop Grumman Corporation
Symposium Chair

9:00 – 10:00 am

KEYNOTE: NATIONAL ENERGETIC PLAN
COSMOPOLITAN AB

Jason Jouet
Director of Munitions Technology, Office of the Under Secretary of Defense for Research & Engineering (OUSD(R&E))

10:00 – 10:30 am

NETWORKING BREAK
COSMOPOLITAN FOYER

10:30 – 10:50 am

RECENT VULNERABILITY EVENTS DUE TO NON-IM MUNITIONS
COSMPOLOTIAN AB

Dr. Ernest Baker
Warheads TSO, NATO MSIAC

10:50 – 11:10 am

THE MSIAC SELF-AUDIT TO IMPROVE HOW TESTING FACILITIES CONDUCT IM & HC TESTS
COSMOPOLITAN AB

Christelle Collet
Technical Specialist Officer, MSIAC

11:10 – 11:30 am

COOKOFF ANALYSIS USING AN IMPLICIT AMR APPROACH
COSMOPOLITAN AB

Dr. J. Keith Clutter
Senior Consultant, Integrated Solutions for Systems (IS4S), Inc.

11:30 – 11:50 am

GUN BARREL & PROJECTILE HEATING FOR HOT GUN SAFETY
COSMOPOLITAN AB

Dr. Jon Yagla
Mechanical Engineer, Axient

11:50 am – 1:00 pm

NETWORKING LUNCH
COSMOPOLITAN AB

CONCURRENT BREAKOUT SESSIONS

	Insensitive Munitions Protection Systems	Energetic Materials Modeling
	COSMOPOLITAN AB Session Chair: Ken Graham	COSMOPOLITAN CD Session Chair: Gert Sholtes
1:00 – 1:20 pm	**24749 – Novel Rocket Motor Protection** Daniel Turner Senior Design Authority, Roxel (UK Rocket Motors), Ltd	**24869 – A Numerical Model for Explosive Cook Off** Dr. Brian Fuchs Senior Research Scientist, U.S. Army Picatinny Arsenal
1:25 – 1:45 pm	**24864 – Lightweight IM Impact Protection System for Reducing Reaction of Solid Rocket Motors** Andrew Witzig President & CEO, Shearwater Technology, Inc.	**24959 – A Comprehensive Approach for the Development of the Fundamental Comprehension of How Energetic Defects Form, Propagate & Affect Initiation** Daniel Pudlak CCDC-AC, U.S. Army
1:50 – 2:10 pm	**24867 – SR Barriers for IMX-104 Filled 155mm Artillery Projectiles** Kevin Miers Mechanical Engineer, U.S. Army DEVCOM Armaments Center	**24955 – AI For Energetic Defect Characterization** Antonio Aguirre, Jr. Mathematician, Picatinny Arsenal
2:15 – 2:35 pm	**24866 – Steel FI Barriers Hardness & Obliquity Effects** Kevin Miers Mechanical Engineer, U.S. Army DEVCOM Armaments Center	**24856 – Sample Extraction & Analysis Techniques for Simultaneous Determination of Legacy & IM Constituents** Dr. Austin Scircle Research Chemist, USACE Engineer Research & Development Center
2:35 – 3:05 pm	**NETWORKING BREAK** COSMOPOLITAN FOYER	

CONCURRENT BREAKOUT SESSIONS

	Insensitive Munitions Technology Applications	Energetic Materials: Design & Integration
	COSMOPOLITAN AB Session Chair: Steve Struck	COSMOPOLITAN CD Session Chair: Dr. Arthur Delage
3:10 – 3:30 pm	**24840 – Insensitive Hydro-reactive Munitions** Dr. Nicholas Nechitailo Senior Subject Matter Expert, Weapons Effects, Fluid-Structure Interactions, Materials Failure, Naval Surface Warfare Center Indian Head EOD Technology Division	**24853 – Investigation of Slow Cook-Off Behavior of Castable PBXs** Z. Taner Kaya Senior Researcher, TUBITAK SAGE
3:35 – 3:55 pm	**24863 – Cook-Off Mitigation for Medium Caliber Ammunition** Nausheen Al-Shehab Chemical Engineer, U.S. Army DEVCOM AC	**24820 – Development of IM Naval Countermining Charges with Increased Performance** Chris Reams RWM Italia
4:00 – 4:20 pm	**24848 – New Test Method for Single Package Test for Transportation** Erik Tunestål R&D Project Manager, Eurenco Bofors AB	**CLOSING REMARKS** Dr. Arthur Delage R&D Project Manager, EURENCO
4:25 – 4:45 pm	**24876 – Simplified Numerical Methodology to Size Munitions to Withstand Sympathetic Reaction** Sébastien Bodard R&D Modelling Team Lead, EURENCO	
4:55 – 5:00 pm	**CLOSING REMARKS** Steve Struck Program Manager, U.S. Air Force Research Laboratory (AFRL)	

NDIA has a policy of strict compliance with federal and state antitrust laws. The antitrust laws prohibit competitors from engaging in actions that could result in an unreasonable restraint of trade. Consequently, NDIA members must avoid discussing certain topics when they are together at formal association membership, board, committee, and other meetings and in informal contacts with other industry members: prices, fees, rates, profit margins, or other terms or conditions of sale (including allowances, credit terms, and warranties); allocation of markets or customers or division of territories; or refusals to deal with or boycotts of suppliers, customers or other third parties, or topics that may lead participants not to deal with a particular supplier, customer or third party.

ABSTRACT DESCRIPTIONS

ENERGETIC MATERIAL CHARACTERISTICS

24839

Characterization of Impact Induced Reaction of Explosives Using the AFRL High Explosive Survivability Test (HEST)

Dr. Mares, J. Jr.

We characterize two Air Force explosives and present lessons learned in the development and utilization of the High Explosive Survivability Test (HEST).

24872

Life Cycle Assessment and Aging Characteristics of Novel Signal Pyrotechnics, and Comparison to a Military Reference Composition

Dr. Bouma, R.

Novel red and green signal NC-based compositions are being developed. A sufficient thermal stability is demonstrated in accelerated ageing experiments. Assessment of the environmental hazards and human health impacts, and a quick scan life cycle analysis, demonstrated the reduced damage costs in comparison to their current military counterparts.

24844

Recent Advancement on Enhanced Blast Explosives Manufacturing at Holston Army Ammunition Plant

Bittner, K.

This paper details the recent advancement in process development, production manufacturing and future process improvement of EB explosives at HSAAP. To date, over 17,000 lbs. of EB explosives had been successfully manufactured at HSAAP; and the quantity will exceed 20,000 lbs. by the end of 2022, and significantly more (> 30,000 lbs.) expected in 2023 and beyond.

24893

Comparison of the High-speed Deformation Behavior of Cast and Additive Manufactured Polymer Bonded Mock Explosives

Stirrup, K.

Samples of mock Polymer Bonded Explosives (PBX) were produced using traditional casting methods and via Vibration Assisted Printing (VAP). To evaluate material behavior while deformed at high speeds, samples were impacted using a single stage gas gun located at the Dynamic Compression Sector of the Advanced Photon Source. In-Situ Phase Contrast Imaging (PCI) showed the printed samples failed due to the collapse of pores inherent to the printing process.

ENERGETIC MATERIAL FORMULATIONS & SYNTHESIS

24923

Estimation of Elastic Constraints of Composite Energetic Materials

Dr. Jaansalu, K.

The best model for prediction of elastic composites is a variation of the logarithmic sum. Any further evaluation or model development would be greatly facilitated by more experimental data.

24861

Improved Continuous Microfluidic Synthesis of Energetic Compounds

Dr. Christensen, C.

Our group has designed and tested a system for the continuous microfluidic synthesis and in-line extraction and purification of energetic materials using commercially available components. This system will reduce hazards associated with batch synthesis of energetics and the need for attended work by employing remote operation of the equipment. The system has been used to demonstrate the continuous processing of glycidyl nitrate from glycerol, an important precursor to poly(glycidyl nitrate) (PGN), an ingredient of significant interest for use in high performance formulations.

24850

The Full Story of Ethylenedinitrarmine (EDNA): Synthesis, Crystallization, Formulation and Applications

Dr. Delage, A.

EthyleneDiNitrAmine (EDNA, C2H6N4O4) has been identified as the best candidate and has been selected as the main filler for new generation powders (thermoplastic) and for explosives applications such as cast PBX formulation based on the less sensitivity of EDNA to shock and friction compared to RDX. This work includes all the steps from synthesis to final applications.

24854

Comparison of Performance and Insensitivity Properties of Enhanced Blast Plastic Bonded Explosives with Conventional Explosives

Bilgen, S.

In this study, plastic-bonded EBXs that contain different type of energetic materials (RDX, HMX) and different amount of metallic powder (30wt% and 45wt%), namely TSP-01-2, TSP-02-1 and TSP-02-2 was developed and compared with conventional explosives such as TNT and Comp-B in terms of performance and insensitivity properties. For performance properties, total pressure impulse, thermal performance (fireball diameter and fireball duration time) properties, detonation velocity and fragmentation test results were compared. For insensitivity properties, shock sensitivity measurements of EBXs were compared with literature values of conventional explosives.

ENERGETIC MATERIALS MODELING

24869

A Numerical Model for Explosive Cook Off

Dr. Fuchs, B.

The generalized equation for conductive heat transfer (without mass transfer) with internal heat generation in a spherical configuration and allowing for degradation was used to study general trends in cook-off behavior. The explosive RDX was selected for the study, as it is a common energetic material used in many compositions. A Python language computer program was written to study two cases, initially uniform material with the surface maintained at a uniform temperature, and a uniform temperature material with the surface heated at a steady rate. It was determined that, slower heating rates tend to have reactions towards the center of the charge, but increase the amount of material degradation, and that there may be no observable heat rise on the surface to indicate impending violent reactions.

24959

A Comprehensive Approach for the Development of the Fundamental Comprehension of How Energetic Defects Form, Propagate, and Affect Initiation

Pudlak, D.

Defects in artillery High Explosive (HE) main-fills have caused catastrophic failures during gun launch, resulting in fatalities and damage to personnel and their weapon systems/platforms. With the new Long Range Performance Fires (LRPF) requirements exceeding gun/barrel designs and flight environments, energetic defect characterization is now more important than ever. Several attempts to investigate particular facets of energetic defects are still on-going, however a new, comprehensive effort has been developed that addresses all facets of energetic defects, in an all-compassing manner. The U.S. Army, DEVCOM-AC is currently executing a comprehensive effort, 'Energetic Defect Characterization – Capability Development Effort (EDC-CDE)', that focuses on the development of the fundamental understanding of energetic defects, including how they form/propagate, how they affect initiation (focusing on interior ballistics specifically, but also taking into account their exterior and terminal ballistics influences), determination of critical defects (including critical parameters, metrics, criteria, etc.), and ultimately the mitigation of critical defects, with visionary goals of implementing improvements to the LAP inspection equipment/processes, such as Smart XCT 3D (X-Ray) embedded with w/ Automated Intelligence / Machine Learning (AI/ML) codes.

24955

AI For Energetic Defect Characterization

Aguirre, A. Jr.

24856

Sample Extraction and Analysis Techniques for Simultaneous Determination of Legacy and IM Constituents

Dr. Scircle, A

Novel methodology development using artificial intelligence to augment human-in-the-loop efforts for identifying the presence of defects in x-ray image datasets of explosively filled ordnance.

ENERGETIC MATERIALS PROCESSING

24781

Development of ResonantAcoustic® Continuous Microreactor and ResonantAcoustic® Continuous Crystallizer

Dr. Mayne, J.

Resodyn has developed novel continuous chemical reactor and continuous crystallizer technologies built on the ResonantAcoustic® Mixing (RAM) platform. This technology is applied to the synthesis and recrystallization of energetic and energetic precursor compounds.

24834

Process Improvement of Melt Pour Explosive 3,4-Dinitropyrazole (DNP)

Dr. Modzelewski, T.

Development of a highly simplified, and environmentally and economically friendly, synthesis method for the manufacture of 3,4-Dinitropyrazole (DNP)

24843

Continuous ResonantAcoustic® Production of Energetic Material

Dr. Joseph Mayne

A Continuous Acoustic Mixing (CAM) Clean-in-Place (CIP) process has been developed at Resodyn Corp. to significantly increase the safety, reduce the cost, and reduce the environmental impact of producing Plastic Bonded Explosive (PBX) and propellant.

24862

Advances in Resodyn Acoustic Mixer Processing Methods and Characterization

Whaley, J.

ResonantAcoustic® Mixers (RAM) have become a technology of choice in the energetics but operation can be non-intuitive to the mixologist accustomed to using conventional mixing processes. Even for advanced users, the behavior of materials can vary drastically in responses to subtle parameter changes. To fully utilize the advantages of RAM manufacturing a set of mixing metrics is used for improving the RAM process and measuring mixedness of the product.

ENERGETIC MATERIALS: DESIGN & INTEGRATION

24853

Investigation of Slow Cook-off Behavior off Castable PBXs

Kaya, T. Z.

Slow heating response of small-scale test items and full-scale munitions due to thermal decomposition of castable polymer bonded explosives (PBXs) (PBXN-109/110/111/113 composition equivalents) was investigated by testing and thermal/CFD modelling efforts.

24820

Development of IM Naval Countermining Charges with Increased Performance

Reams, C

RWM Italia have developed new naval countermining charges to replace legacy, non-IM munitions that were at the end of their service life. The new munitions showed much better IM characteristics and also improved performance vs the legacy munitions.

INSENSITIVE MUNITIONS MODELING

24851

Implementation of a Munition Vulnerability Models in the Ship Vulnerability Code Resist

Scholtes, G.

Stochastic approach to implement munition vulnerability models in platform vulnerability codes to estimate the response of stored munition after a hostile impact.

24860

Evaluation of Critical Temperatures via Thermal Runaway Models and Slow Cook Off Testing

Dr. Headrick, J.

Evaluation of critical temperatures of RDX & HMX explosives formulations via thermal runaway modeling and slow cook off testing.

24993

Concept for Improving Cook-off Performance of Propellants and Explosives

Dr. Yagla, J.

Concept For Improving Cook-off Performance of Propellants and Explosives – Oriented fibers or strands of material of high thermal conductivity are embedded in a mass of energetic material. The strands are arranged to draw heat out of potential hot spots to prevent thermal runaway and explosive reactions. Examples, mathematical principles, and possible means for orienting the strands are provided.

INSENSITIVE MUNITIONS POLICY & REQUIREMENTS

24847

The Status of Internal and National IM Policies Across the Nations

Collet, C.

The recent review that was conducted at MSIAC provides insight to international and national IM policies. After an overview of the IM policy in place for each nation, an analysis of the differences across policies is provided that highlights possible ways of improvement at a NATO level. This overview may also provide useful information to those nations that have not yet implemented their own IM policy.

24765

An International Review of STANAG 4488 Gap Testing

Dr. Baker, E.

MSIAC has recently completed an international review of STANAG 4488 Gap Testing.

24766

Recent Advances of the MSIAC Gap Testing Tool and Database

Dr. Baker, E.

MSIAC recently completed a project that extended the NEWGATES database for gap test results and increased its predictive capabilities. As a result, an updated version of NEWGATES (v1.12) has been released.

INSENSITIVE MUNITIONS PROTECTION SYSTEMS

24749

Novel Rocket Motor Protection

Turner, D.

Roxel UK have been investigating the potential of a new, novel, armour system to provide protection to rocket motors against impact IM threats to mitigate against the use of higher performance, more sensitive, propellants."

24864

Lightweight IM Impact Protection System for Reducing Reaction of Solid Rocket Motors

Witzig, A.

This paper details the development and evaluation of a lightweight insensitive munition ballistic protection system for reducing the reactive response of solid rocket motors.

24867

SR Barriers for IMX-104 Filled 155mm Artillery Projectiles

Miers, K.

SR barriers were computationally designed, fabricated and tested on IMX-104 filled 155mm artillery projectiles. At least one of the designs provided a successful passing reaction, and this work documents the design process and experimental results.

24866

Steel FI Barriers Hardness and Obliquity Effects

Miers, K.

Steel armor has traditionally been able to mitigate the NATO FI threat in a cost effective and reasonably weight-efficient manner. However it has been suggested that further improvements in FI mitigation may be achieved by increasing steel hardness and toughness, as well as by taking advantage of potential obliquity effects. Steel plates of 4340 RC38 and D2 tool steel hardened to RC60 were fabricated and subjected to FI testing at both 0 and 45 degrees obliquity. The behind armor debris was captured with celotex panels, and the residual velocity was measured with high speed video. It was determined that spall failure dominates the fragment breakup behavior, and that the improvement in velocity reduction afforded by increased hardness and obliquity is limited by brittle failure.

INSENSITIVE MUNITIONS TECHNOLOGY APPLICATIONS

24840

Insensitive Hydro-Reactive Munitions

Dr. Nechitailo, N.

This paper describes the explosive reaction of aluminum projectiles with wet sand. Understanding the underlying phenomena may lead to the development of a new class of low-cost no-fuze, no-explosives insensitive munitions.

24863

Cook-Off Mitigation for Medium Caliber Ammunition

Al-Shehab, N.

This paper discusses development of Particle Impact Mitigation Sleeve (PIMS) to improve munition response to Fragment Impact Threats.

24848

New Test Method for Single Package Test for Transportation

Tunestål, E.

Eurenco has developed and evaluated a new test method for 16.4.1 Test 6(a) Single package test. The new method has a quick setup method, can be pre-fabricated and from the tests a methodology to classify propellants without testing has also been proposed.

24876

Simplified Numerical Methodology to Size Munitions to Withstand Sympathetic Reaction

Bodard, S.

In this presentation, we address a step by step numerical methodology to study sympathetic reaction modeling, from 1D computation to select viable candidates, to 2D computations with validated hypothesis for finer analysis. This methodology aims to be fast and general enough to treat cases where the donor has fragmented or not before interacting with the acceptor.

INSENSITIVE MUNITIONS TEST METHODS

24857

The Fundamentals of IM Testing

Toreheim, J.

In this presentation a detailed method of how to design test setups and how to conduct each of the six standardized IM tests in a cost efficient way is given.

24865

Air Drag Measurements for the NATO Insensitive Munitions Fragment

Miers, K. T.

In this work, we have performed a series of drag coefficient measurements for the NATO IM fragment at the test velocities of interest (2530 m/s). The theory of drag measurement is discussed, with accurate measurements requiring many timing stations and long total range lengths in excess of 1000 calibers for hypersonic projectiles. Several experiments were performed indicating a drag coefficient of approximately 1.2-1.5, on the high end of what was expected. Accounting for air drag and correctly computing velocity should help provide increased confidence that the required impact velocities are being achieved for a given test configuration.

24852

Mitigation of Flat 2-Dimensional Shocks to Prevent Sympathetic Reactions

De Koster, S.

Investigation in the mitigation of a flat 2-Dimensional shock wave to prevent sympathetic reactions of plastic explosives in a wooden box.

KEYNOTE BIOGRAPHIES

DR. BRIAN FUCHS

Senior Research Scientist
U.S. Army Picatinny Arsenal

Dr. Brian Fuchs is the Senior Research Scientist for Insensitive Munitions at the Combat Capabilities Development Command Armaments Center at Picatinny Arsenal. Fuchs conducts research pertaining to energetic materials, energetic materials printing, warheads technology and explosive safety. He serves as a technical consultant in the areas of Insensitive Munitions, testing, safety and detonation physics to other organizations.

Employment highlight include having been awarded the department of the Army Research and Development Achievement Awards in 1989, 1999, 2002, 2003, and 2009, and the Army Research and Development Achievement Award for excellence in Leadership in 2009. He received the 2016 National Defense Industrial Award Firepower technology Award. He is a member of the Army Insensitive Munitions Board, past chairman of the Joint Services Insensitive Munitions Technical Panel, serves on the Combat Capabilities Development Command Armaments Center, Energetic Material Qualification Board for Explosives and is Chairman of NATO's Munitions Safety Information Analysis Center steering Committee (MSIAC).

Fuchs has received 13 patents in the areas in the areas of explosive formulations, loading techniques, warheads, fuze technologies, printed detonators, and printed detonators, and printed electronics. He is a faculty member for Picatinny Arsenal's Armament Graduate school and an adjunct professor for the Stevens Institute of Technology.

DR. ROBERT WARDLE

Principal
Wardle Enterprises: Energetics, Services and Technologies, LLC

Dr. Robert Wardle is the principal at Wardle Enterprises: Energetics, Services & Technologies. Before holding his current position, he was senior director of advanced programs at Northrop Grumman (NGC) and he spent 35 years at the research and development department at Northrop and predecessor organizations back to Thiokol Corporation. He received his Ph.D. in chemistry from Caltech. At NGC since 1986, he was involved in synthesis, characterization, formulation, fielding and aging/surveillance of energetic materials. At NGC, he moved through a series of increasingly responsible positions from lab chemist to director of R&D Laboratories.

In his role as Senior Director of Advanced Programs, he led the Propulsion Systems IR&D effort, built and commissioned a full scale AP plant, led hypersonic glide body development and production, synthesis of energetic materials including CL-20, production of military flares and decoys, and a broad spectrum of propellant, explosives and pyrotechnics related R&D programs.

DR. JASON JOUET

Director of Munitions Technologies
Office of the Under Secretary of Defense for Research and Engineering

Dr. Jason Jouet is responsible for the strategy, oversight, and supervision of the Department's munitions-relevant science and technology (S&T) investments. Munitions S&T comprises activities to improve or enhance kinetic weapon lethality, propulsion, target detection, fuzing, guidance, navigation and control, manufacturing, and advanced material development. Jouet also directs the OSD Joint DoD/DOE Munitions Program and the Joint Enhanced Munitions Technology Program with a total cumulative budget of $64m, maturing cross-cutting, enabling technologies that are beyond service risk tolerance, to increase lethality, performance, and readiness for warfighters' weapons systems to bolster U.S. technical superiority for decisive and asymmetric advantage.

Prior to this appointment, Jouet was Deputy Director for Manufacturing Technology within the Manufacturing & Industrial Base Policy office of OUSD (AT&L). In this role, he directed the OSD Manufacturing Science & Technology Program, focusing on the advancement of cross-cutting manufacturing technology to enable production of technology at cost, quality, and quantity suitable for acquisition.

Prior to coming to OSD, from 2001 to 2016, Jouet served as the Head, High Energy Materials Branch, Senior Research Scientist, and Program Manager at the Naval Surface Warfare Center Indian Head Division and was a recipient of the Dr. Dolores M. Etter Award for Top Navy Scientists and Engineers of the Year in 2010.

Jouet earned a Bachelor of Science in Chemistry from the University of Texas-Austin in 1995 and a Ph.D. in Chemistry from Duke University in 2000.

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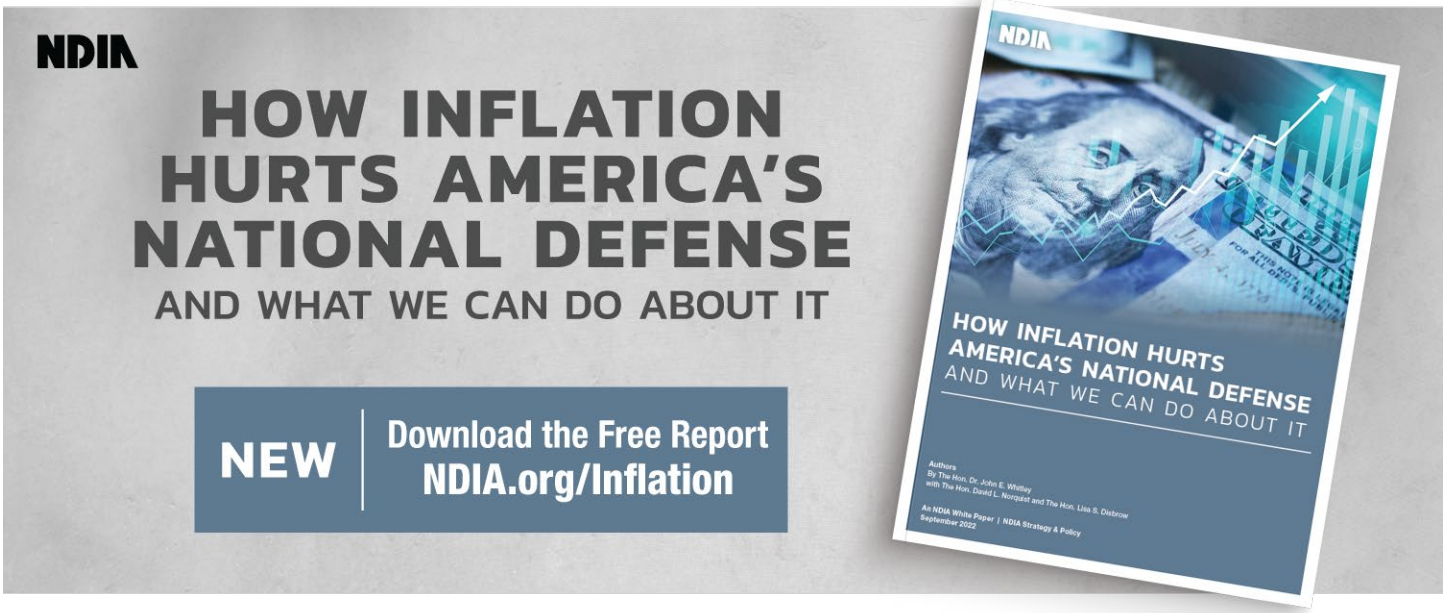
BAE Systems Ordnance Systems Inc. (OSI) produces a full range of high quality explosive and propellant products for the U.S. Department of Defense, Department of Energy and commercial customers. We are the operating contractor for the Holston Army Ammunition Plant located in Kingsport, Tennessee, and for the Radford Army Ammunition Plant in Radford, Virginia.

As the recognized leader in managing government-owned, contractor-operated facilities, OSI supports the U.S. Government to safely, efficiently and cost effectively develop and produce reliable propellant and explosive ordnance products. Our award-winning innovations also include munition-related services such as modernization program management, energetics research and development, engineering design, and inventory management.

energetics
technology center

REGISTRATION

ETC provides engineering and data analytics services, policy development, and technology development to the government, academia, and private industry. We are a 501 (c)(3) non-profit organization incorporated in 2006 to support national military policy development projects. Our team looks for opportunities to conduct impactful work for the Defense Department, State, Regional, and Local governments, and the private sector. At ETC, we proudly support our Warfighters and our National Security Enterprise. Visit us at etcmd.com.



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Security Clearance Reforms | Insider Threat Guidance | Cybersecurity Policy

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February 22 – 24, 2023 | Arlington, VA

Maritime Electronic Warfare | Naval Fires And Aviation | Seabasing

AIRCRAFT SURVIVABILITY SYMPOSIUM

November 1 – 3*, 2022 | Monterey, CA

Combat Survivability | Concealment and Deception | Countermeasures | Urban Warfare | Vulnerability Reduction

2023 TACTICAL WHEELED VEHICLES CONFERENCE

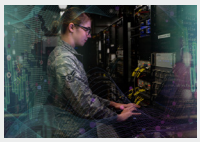
February 27 – March 1, 2023 | Columbus, OH

Autonomous Vehicles | Electric Drive | Modernization & Sustainment | Acquisition

25TH ANNUAL SYSTEMS & MISSION ENGINEERING CONFERENCE

November 1 – 3, 2022 | Orlando, FL

Program Management | Security Models | Test & Evaluation | Manufacturing



2023 HUMAN SYSTEMS CONFERENCE

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Human Systems Integration | Human Factors Engineering | Artificial Intelligence

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November 17 – 18, 2022 | Washington, DC

Special Operations Forces | Strategic Competition

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Regional Security | Science & Engineering Technology | Technology Engagement

I/ITSEC 2022

November 28 – December 2, 2022 | Orlando, FL

Simulation | Training | Virtual Reality

MODSIM WORLD 2023

May 22 – 23, 2023 | Norfolk, VA

Medical Simulation | Machine Learning | Extended Reality | Gamification

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USD(R&E)

FY2020 NDAA Section 253 and FY2021 NDAA Section 273 Energetics Plan

Office of the Under Secretary of Defense Research and Engineering

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The Requirement

FY20 NDAA Section 253 and FY21 NDAA Section 273

(a)PLAN REQUIRED—The Under Secretary of Defense for Research and Engineering shall, in coordination with the technical directors at defense laboratories and such other officials as the Under Secretary considers appropriate, develop an energetics research and development plan to ensure a long-term multi-domain research, development, prototyping, and experimentation effort that—

(1) maintains United States technological superiority in energetics technology critical to national security;

(2) efficiently develops new energetics technologies and transitions them into operational use, as appropriate;

(3) maintains a robust industrial base and workforce to support Department of Defense requirements for energetic materials; and

(4) assesses the feasibility and advisability of establishing a program office—

(A) to coordinate energetics research; and

(B) to ensure a robust and sustained energetics material enterprise.

(b)BRIEFING—Not later than one year after the date of the enactment of this Act, the Under Secretary shall brief the congressional defense committees on the plan developed under subsection (a).

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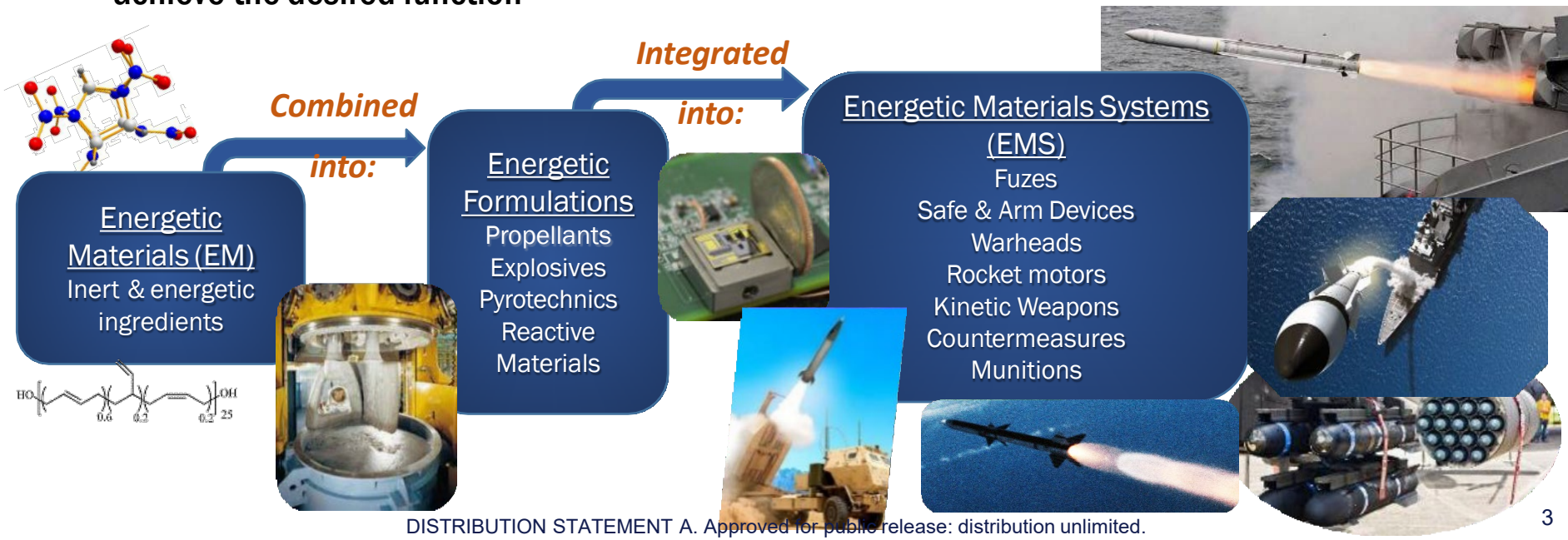
Energetics

- A weapon system's performance is enabled by its energetics
  - Range, Speed, Lethality, Safety, Signature, Size/Weight, Logistics
- Energetics are:
  - Ingredients: monopropellants, fuels, oxidizers, polymer binders, plasticizers, curing agents, organic bonding agents, molecular stabilizers, and other specialized ingredients used in explosives, pyrotechnics, and solid propellants
  - Formulations: Complex combinations of these ingredients custom mixed for particular applications
  - Energetics Systems: Systems based on energetic-material effects (energy-release phenomena) to achieve the desired function



Energetics Problems

- Adversary anti-access and area denial (A2/AD) capabilities present challenges for current systems
  - Range limitations create unacceptable platform risk
  - Even with newly developed technologies U.S. platforms face challenges within enemy targeting zones
- Limited manufacturing capacity to meet current and future requirements
  - Manufacturing facilities, even with modernization upgrades, still need repair and updating
  - Continual industry consolidation has resulted in single points of failure for numerous critical materials
  - No capacity for new energetic materials manufacturing
- Multiple factors inhibit weapon system energetics innovation
  - Inherently hazardous, energetic systems, require extensive safety and qualification of new technology
  - Program offices adopt risk-averse approach of using known and qualified existing materials
- No clear method exists to address section 253 requirement without understanding critical problems with existing capabilities, infrastructure, and industrial base, and then developing solutions for the entire ecosystem

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Study Structured to Meet Requirement

Technology Development

"maintains United States technological superiority in energetics technology critical to national security"

Transition

"efficiently develops new energetics technologies and transitions them into operational use, as appropriate"

Acquisition & Sustainment

"maintains a robust industrial base and workforce to support Department of Defense requirements for energetic materials"

WG1	WG2	WG3	WG4	WG5	WG6	WG7
Energetics S&T	R&D Planning	Barrier to Energetics Implementation	Business & Investment Model	Acquisition Planning	T&E Planning	Manufacturing & Supply

This Energetics Plan represents the collective product of these senior executive-led working groups, conducted over a six-month period, by more than 90 people representing the Services, Missile Defense Agency (MDA), Department of Energy (DOE) - National Nuclear Security Administration (NNSA), and National Aeronautics and Space Administration (NASA).

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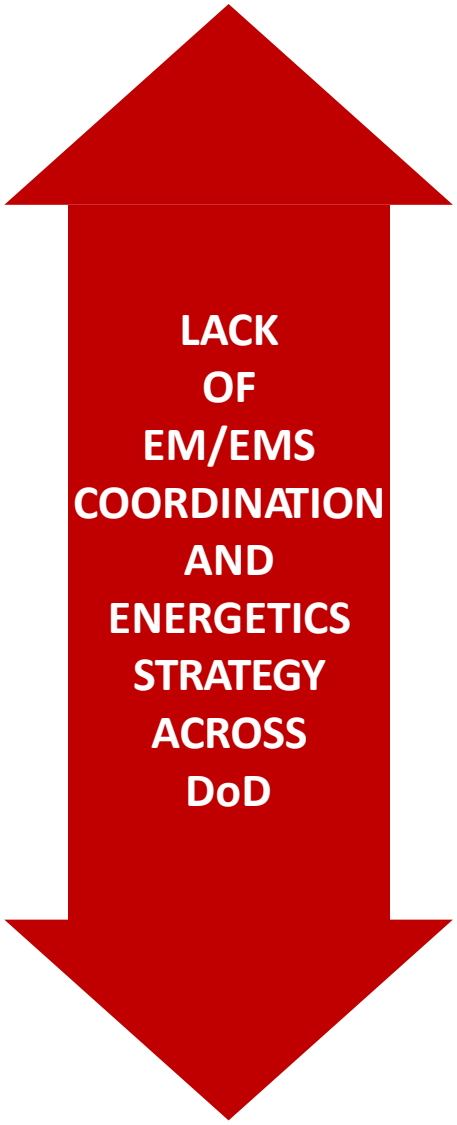
Challenges Identified



- Lack of comprehensive understanding of EM capabilities, needs, and capacities across the enterprise
- Inability to quickly incorporate emerging technologies to EM/EMS
- Erosion of skilled workforce (college-educated and technician)
- Lack of qualification and prototyping resources to mature EMS
- Misaligned EMS Science and Technology (S&T) and Acquisition timelines
- Lack of coordinated Modeling and Simulation (M&S) capabilities enabling prediction, analysis of alternatives, and design
- Antiquated Test and Evaluation (T&E) methods and infrastructure
- Policies, regulations and requirements governing EM/EMS that increase acquisitions costs and extend transition timelines
- Lack of a centralized industrial master plan for energetics manufacturing capability
- Significant supply chain issues – fragile markets, foreign sources, single/sole sources
- Sporadic and weak demand signal leading to obsolescence and single-source failures
- Lack of commercial applications minimizes Industry R&D investments

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Energetics Plan Recommendations

The Department should establish a strategic energetics responsible authority to:

- provide oversight of,
- strategic direction for,
- and support development of,

the DoD's energetics competency to bolster technology development, transition, and sustain the energetics enterprise.

The following functions would be executed by this authority or by groups coordinated and supported by this authority:

- Create and maintain an Energetic Systems Common Operating Picture (ES-COP)
  - Prepare and maintain EM Roadmaps, aligned with Conventional Engagement Capability Roadmaps, for PMs to set EM project objectives, contract requirements, and milestones
  - Provide R&D and T&E project data to identify capability gaps for programs, align schedules, and establish insertion points

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Energetics Plan Recommendations

PROVIDES EM/EMS COORDINATION AND CENTRALIZED ENERGETICS STRATEGY ACROSS DoD

- Establish public-private partnership(s) to facilitate exchange of information, enhanced collaboration, and shared resources
  - Research Consortium conducting S&T and R&D in energetics and propellants
  - Manufacturing Cooperative to coordinate and mature emerging EM-EMS manufacturing methods
- Develop production-quality user-friendly Modeling & Simulation (M&S) software framework for weapons' designers, Acquisition offices, T&E personnel, and operators to:
  - Enable model-based systems engineering (MBSE) design based on system's performance
  - Allow Analysis of Alternatives (AoA) for PMs/PEOs and Acquisition Programs of Record
- Modernize Test & Evaluation (T&E)
  - Establish an "Energetics/EMS" portfolio element in the Test Resource Management Center
  - Utilize M&S for digital estimates of performance & safety, and to replace tests where possible
  - Use T&E facilities to execute independent Verification and Validation of M&S

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Energetics Plan Recommendations

PROVIDES EM/EMS COORDINATION AND CENTRALIZED ENERGETICS STRATEGY ACROSS DoD

- Establish a BA4 program to mature, integrate, prototype, and demonstrate EM/EMS technologies, to reduce risk of integration into new weapon systems, and minimize qualification expenses to program offices
- Resource the OSD Critical Energetic Material Working Group to:
  - Assess critical EM-EMS supply chains as members' primary duties
  - Develop an energetics supply chain support tool of suppliers and manufactures
- Establish additional and sustain pilot-scale plants to mitigate current and future critical-material challenges and mature manufacturing technologies
  - Agile specialty chemical synthesis pilot scale plants
  - Refinery for raw materials to comply with necessary military standards
  - R&D plant to increase MRL and demonstrate new manufacturing technology
- Develop an EM manufacturing modernization plan for Service-owned manufacturing and processing facilities in coordination with the respective Services
- Create an EMS workforce development program for US citizens to work on EM and EMS within government RDT&E sites and the industrial base

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Energetics Plan Recommendations

- Work on establishing the following policy recommendations:
  - Ensure EMS under development and procurement shall incorporate energetic materials improvements, to the extent practicable, by adding to DoD 5000.1 Section 1.2 "z. Ensuring lethality, range and industry sustainment to provide credible deterrence and warfighting capability to the Joint Force, new munitions under development and procurement shall incorporate safe energetic materials and energetic material systems, to the extent practicable, that outperform, through lethality, range and/or other attributes, their previous generation. This evaluation of energetics capabilities shall occur throughout each acquisition phase, EM analysis of alternatives (AoA), technology maturation and risk reduction (TMRR), engineering & manufacturing development (EMD), and be included in milestone decisions."
  - Prioritize U.S. sourcing of critical EM by including critical EM in new legislation requiring domestic sourcing for critical chemicals
  - Increase deliberate use of Government-owned capabilities by amending 10 USC 2563: "Articles and services of industrial facilities: sale to persons outside the Department of Defense" to allow GOGO facilities to collaborate with private industry for energetic materials and components
  - Adjusting DoDI 5160.68 to include Provision of Industrial Facilities (PIF) funding eligibility for GOGO plants

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Summary and Path Forward

- Kinetic weapons that utilize energetic material effects are a primary means to deter adversary aggression and win engagements. Therefore, EM and EMS are critical to US national security.
- Implementing the Energetics Plan recommendations described here are vital to maintaining technological superiority in energetics technology, to efficiently transitioning energetics to operational use, and maintaining a robust industrial base.
- OUSD R&E will work with our partners across DoD to influence POM 2024-2029 and implement recommendations within the PPBE process.

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Mapping: Challenges/Recommendations

	LACK OF STRATEGIC DIRECTION & COORDINATION	INABILITY TO TRANSLATE EMERGING TECHNOLOGIES	WORKFORCE CHALLENGES	LACK OF RESOURCES TO MATURE EM/EMS	LACK OF INTEGRATED M&S	MISSING COMPREHENSIVE UNDERSTANDING	MISALIGNED S&T AND ACQ. TIMELINES	ANTIQUATED T&E METHODS AND INFRASTRUCTURE	POLICY & REGULATION IMPEDIMENTS	LACK OF A CENTRALIZED INDUSTRIAL MASTER PLAN	SIGNIFICANT SUPPLY CHAIN ISSUES	SPORADIC DEMAND SIGNAL	LACK OF COMMERCIAL R&D
STRATEGIC ENERGETICS RESPONSIBLE AUTHORITY	•	•		•	•	•	•		•	•			
ESTABLISH AN EM COMMON OPERATING PICTURE	•	•		•		•	•					•	
ACCELERATE ENABLING M&S CAPABILITIES		•			•			•					
ESTABLISH EMS PUBLIC/PRIVATE PARTNERSHIP	•	•	•										•
EMS WORKFORCE DEVELOPMENT PROGRAM	•	•	•										
IMPROVE EM POLICY & REGULATION	•	•		•					•				
BA4 EMS DEVELOPMENT PROGRAM	•	•		•			•	•					
MODERNIZE TEST & EVALUATION			•		•			•					
SUPPLY CHAIN ASSESSMENT AND TOOL						•				•	•	•	
ESTABLISH EM PILOT-SCALE PLANTS			•								•		
COORDINATE A MANUFACTURING MODERNIZATION PLAN			•					•		•	•	•	•

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MSIAC
Munitions Safety Information Analysis Center

Supporting Munitions Safety

The MSIAC Self-Audit to Improve How Testing Facilities Conduct IM & HC Tests

Insensitive Munitions & Energetic Materials Technology Symposium

18th – 20th October 2022 - Indianapolis, IN, USA

Christelle Collet

TSO Propulsion Technology

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Rationale for Developing an MSIAC Self-Audit

- Today's munitions are often developed and/or manufactured by groups of nations, by multinational corporations or by international consortiums. This may result in a **munition being tested at IM/HC tests in several different test organizations**, sometimes located in different nations. A detrimental consequence could be that IM/HC testing is not consistent across the different test organizations due to different test capabilities and competences, and due to a variability in the way test organizations carry out IM/HC testing.
- The MSIAC catalogues of testing facilities (L-106 for IM testing and L-196 for environmental testing) provide a useful database on testing facilities, but they do not provide sufficient information to assess test organizations' capabilities or competences in any significant manner.
- This is the reason why the MSIAC self-audit procedure was created, to provide confidence in interpretation and implementation of IM test requirements specified within NATO standardization documents, which are not sufficiently prescriptive.
- The **4th version of the MSIAC self-audit** is based on the most recent versions of AOP-39 (Ed D V2), AOP-39.1 (Ed A V1) and IM test AOPs (Ed A V2).

Why Conduct an MSIAC Self-Audit?

- For munition developers, the MSIAC self-audit allows them to have **a common understanding on the way IM/HC tests are conducted in the different test organizations they contract**. It is indeed of the utmost importance that agencies requesting IM/HC testing obtain consistent and reliable information from the different IM/HC test organizations.

- From the test organization point of view, it is of obvious interest for them to **demonstrate their capability to consistently and reliably perform IM/HC testing**.

How?

- The 4th edition of the MSIAC self-audit procedure includes:

1) The **L-150 report** that introduces the self-audit procedure and provides guidance on how to complete it; and
2) An **excel spreadsheet** including different questionnaires that aim to demonstrate the ability for the IM/HC test organization to fulfil the requirements and recommendations of the NATO and UN standardized test procedures related to IM/HC testing

MSIAC

Supporting Munitions Safety

MSIAC L-150
Edition 4

2022

MSIAC SELF-AUDIT PROCEDURE
OF
IM/HC TEST ORGANIZATIONS'
COMPETENCES AND CAPABILITIES

EDITION 4

Christelle Collet (MSIAC)

This document is accompanied by an Excel spreadsheet entitled
"MSIAC Audit Procedure of IM/HC Test Org. Ed. 4.xls"

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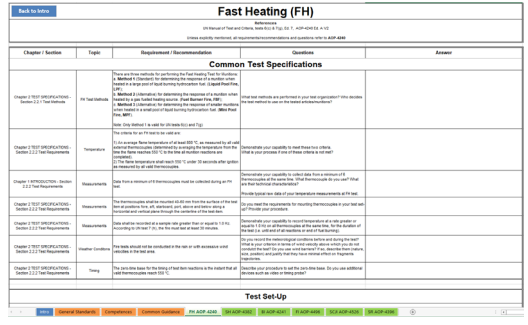
Back to Intro

Fast Heating (FH)

Chapter / Section	Topic	Requirement / Recommendation	Questions	Answer
Common Test Specifications				
Chapter 2 TEST SPECIFICATIONS – Section 2.2.1 Test Methods	FH Test Methods	There are three methods for performing the Fast Heating Test for Munitions (FH): 1. Method 1 (mandatory): for determining the response of a munition when heated by a gas fuelled heating source (Fast Burner Fire, FBF). 2. Method 2 (alternative): for determining the response of a munition when heated in a small pool of liquid burning hydrocarbon fuel. (Mini Pool Fire, MPF). Note: Only Method 1 is valid for UN tests 6(c) and 7(g).	What test methods are performed in your test organization? Who decides the test method to use on the tested articles/munitions?	
Chapter 2 TEST SPECIFICATIONS – Section 2.2.2 Test Requirements	Temperature	The criteria for an FH test to be valid are: 1) An average flame temperature of at least 800 °C, as measured by all valid FH thermocouples between 3 and 7 minutes after ignition of the fuel. 2) The flame reaches 100 °C in the time all munition reactions are completed. 3) The flame temperature shall reach 700 °C under 30 seconds after ignition as measured by all valid thermocouples	Demonstrate your capability to meet these two criteria. What is your process if one of these criteria is not met?	
Chapter 1 INTRODUCTION – Section 2.2.2 Test Requirements	Measurements	Data from a minimum of 9 thermocouples must be collected during an FH test.	Demonstrate your capability to collect data from a minimum of 9 thermocouples at the same time. What thermocouple do you use? What are their technical characteristics? Provide typical raw data of your temperature measurements at FH test.	
Chapter 2 TEST SPECIFICATIONS – Section 2.2.2 Test Requirements	Measurements	The thermocouples shall be mounted ±5.00 mm from the surface of the test item at positions: fore, aft, starboard, port, above and below along a horizontal and vertical plane through the centerline of the test item.	Do you meet the requirements for mounting thermocouples in your test set-up? Provide your procedure.	
Chapter 2 TEST SPECIFICATIONS – Section 2.2.2 Test Requirements	Measurements	Data shall be recorded at a sample rate greater than or equal to 1.0 Hz. According to UN test 7 (h), the fire must last at least 30 minutes.	Demonstrate your capability to record temperature at a rate greater or equal to 1 Hz on all thermocouples at the same time, for the duration of the test (i.e. until end of all reactions or end of fuel burning).	
Chapter 2 TEST SPECIFICATIONS – Section 2.2.2 Test Requirements	Weather Conditions	Fire tests should not be conducted in the rain or with excessive wind velocities in the test area.	Do you record the meteorological conditions before and during the test? Do you have a procedure to define if the weather conditions are fit to conduct the test? Do you use wind barriers? If so, describe them (nature, size, position) and justify that they have minimal effect on fragments trajectories.	
Chapter 2 TEST SPECIFICATIONS – Section 2.2.2 Test Requirements	Timing	The zero-time base for the timing of fast item reactions is the instant that all valid thermocouples reach 500 °C.	Describe your procedure to set the zero-time base. Do you use additional devices such as video or timing probe?	
Test Set-Up				

Intro | General Standards | Competences | Common Guidance | FH AOP-4240 | SM AOP-4242 | BI AOP-4243 | TI AOP-4406 | SCF AOP-4505 | SE AOP-4206

- It can be used:
  - in a **self-audit (or internal audit) mode** to identify their own forces and weaknesses in IM testing, and take actions to improve the way they conduct the tests; or,
  - in **preparation of a formal audit**, as it allows the identification of possible non-conformities.

Who?

- This self-audit is mainly targeted to **IM/HC test organizations** as it represents a way to promote their capabilities and competences in IM/HC testing. It is also beneficial to identify weaknesses and take action to improve the way the test organizations conduct IM/HC testing.

- The self-audit should involve **all personnel related to IM/HC testing**: the project team, the relevant safety authority and, where appropriate, subject matter experts from research establishments as well as from the testing organization itself.

- For those test organizations that rely on contractors, the test organization should seek to involve also **the personnel from any relevant support organizations** as part of the audit process.

When?

- Any time!

- It could even be beneficial to conduct this self-audit more than once, and **ideally on a regular basis**, for a self-assessment of the evolution of the test organization's capabilities and competences. Conducting such a self-audit on a regular basis can also be a good way to ensure that the test organization still meets the requirements of the latest editions of the standards.

- This process may **take a significant time and effort** to be fully accomplished, depending on the extent of IM/HC capabilities and competences of the test organization. A duration of **three to six months is typically necessary** to properly complete the full self-audit procedure for the first time.

Where?

- The questions of the self-audit refer to documents and procedures related to IM/HC personnel and testing, but also to the test set-ups and instrumentation used for IM/HC testing.

- It is then strongly encouraged to conduct the self-audit **in the test organization facility**, where the elements to answer the questionnaires can be easily accessible.

Steps to Conduct the MSIAC Self-Audit

- **Step 1**: Planning the MSIAC self-audit
  - Make sure that the management line supports this activity
  - Define a calendar and work in “project mode”

- **Step 2**: Completing the Excel Spreadsheet
  - This represents the core activity of the self-audit
  - The excel spreadsheet is divided into 3 general tabs and 6 specific tabs for each one of the 6 IM test AOPs
  - In total, it includes 150+ questions/actions

- **Step 3**: Reporting the self-audit results
  - A structure is proposed in order to maintain consistency between self-audit reports

Steps to Conduct the MSIAC Self-Audit

- **Step 4**: Capitalizing, Promoting and sharing the self-audit experience
  - At the minimum, the test organization that have conducted the MSIAC self-audit shall capitalize the results and **take action if it does not fulfil some of the requirements**. The test organization should also consider taking action to improve the way they conduct IM/HC tests.
  - It is also encouraged for the test organization to **share the results of the self-audit** they have conducted by, e.g. providing the self-audit report to MSIAC for the benefit of the MSIAC community or presenting it at an international meeting/conference.
  - This will result in two benefits:
    - For the test organization who conducted the self-audit, **to promote its capabilities and competences to carry out IM/HC tests in a reliant and consistent way**.
    - For the other test organizations, **to encourage them to also conduct an MSIAC self-audit**.

Steps to Conduct the MSIAC Self-Audit

- **Step 5**: Providing feedback
  - Test organizations are encouraged to add to this procedure everything they consider relevant and **provide feedback to MSIAC** on these additions.
  - MSIAC would be very grateful if the test organizations that have conducted this self-audit could help improve this procedure by providing feedback on any improvements that could be introduced in this self-audit procedure, on any aspects.

Conclusion & Way Forward

- The ultimate goal of this self-audit procedure is **to obtain internationally acceptable IM/HC test results**, **reports** and **signatures** as well as **recognized IM/HC test organizations**.

- With as many test organizations as possible following this self-audit procedure, it will hopefully result in **a trustable and internationally recognized network of test organizations suitable to carry out IM/HC certification tests**.

- The next step is to advertise the updated MSIAC self-audit procedure as widely as possible!

Questions?

COOKOFF ANALYSIS USING AN IMPLICIT AMR APPROACH

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Introduction

- Objectives
- Problem Definition
- Modeling Framework
- Parameter Definition
- Benchmark example
- Full-scale system simulation examples

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Objectives

- Advance the use of digital engineering in the IM assessment & design process
- Need to move to point of true prediction of IM concepts to include materials and configurations
- Here highlight analysis of the slow cookoff scenario; fast cookoff, frag/bullet impact, shape charge and sympathetic reaction also being worked
  - Fast cookoff requires thermal loading process discussed here + “flow” analysis
- Help drive better IM system level testing; currently performed as qual tests
- Multi-component energetics represent unique challenges; ingredients may have well known response but when combined “global” response differs

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Governing Equations

- IM scenarios have challenges of heat transfer, chemical reactions and fluid dynamics
- For slow cookoff primary response is a thermal decomposition so can be represented using heat transfer equations
- For fast cookoff, response includes quick gasification and flow of material so must additionally solve
- Definition of reaction rate parameters will be discussed

Heat Transfer Equations

$$\rho C\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) - \frac{\partial \lambda}{\partial t}Q,$$

$$\frac{d\lambda}{dt} = A_\lambda f(\lambda)\exp\left(\frac{-E_\lambda}{RT}\right).$$

Flow Equations (2D Axisymmetric)

$$\frac{\partial \vec{U}}{\partial t} + \frac{\partial \vec{E}}{\partial r} + \frac{\partial \vec{F}}{\partial z} = \vec{S}(\vec{U}),$$

$$\vec{U} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \\ \rho\lambda_{explosive} \end{bmatrix} \vec{E} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ u(\rho E + p) \\ \rho\lambda_{explosive} u \end{bmatrix} \vec{F} = \begin{bmatrix} \rho v \\ \rho vu \\ \rho v^2 + p \\ v(\rho E + p) \\ \rho\lambda_{explosive} v \end{bmatrix} \vec{S} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \cdot \\ k\nabla^2 T + \rho Q\dot{\lambda}_{explosive} \\ \cdot \\ \rho\dot{\lambda}_{explosive} \end{bmatrix}.$$

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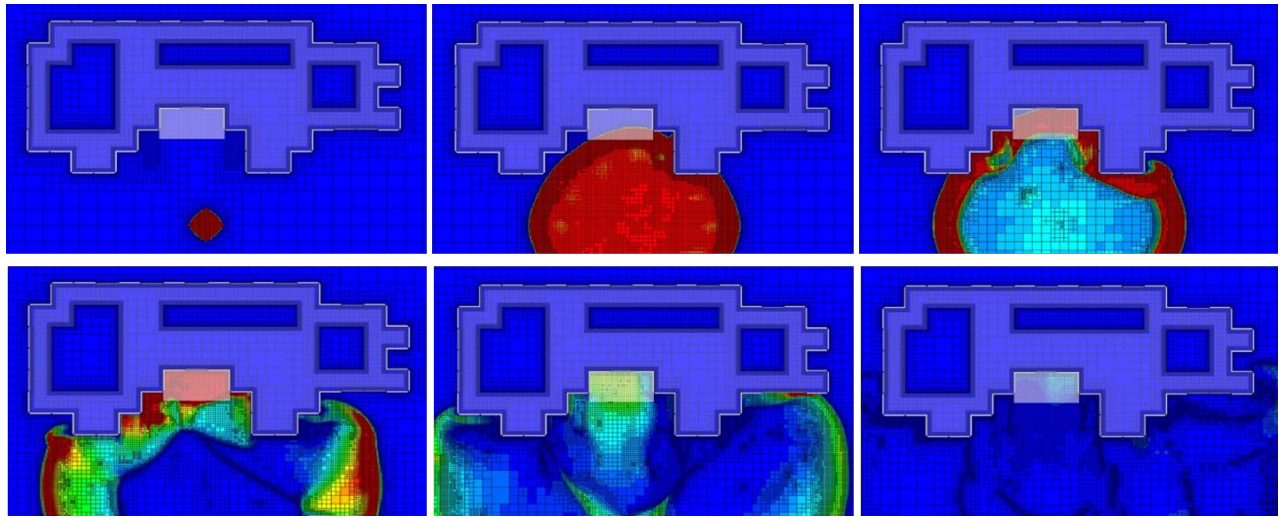
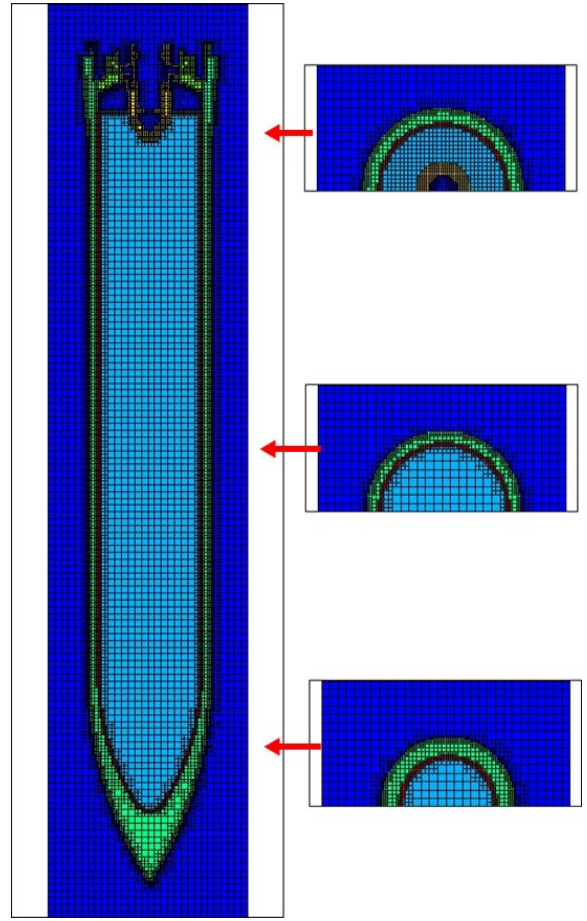
Adaptive Mesh Refinement (AMR) Framework

- Simulations shown here made with a Cartesian Adaptive Mesh code for Blast Explosions & Releases (CAMBER)
  - Finite-volume, multi-material framework
  - Variety of reaction models available
- Greatly increases efficiency, maintaining accuracy
- Adaptation to the solution – refinement in areas with gradients
- Refining to moving waves unique challenge – a method is used that defines location and expected movement of fronts

AMR Used for Blast Modeling



AMR Definition of Object



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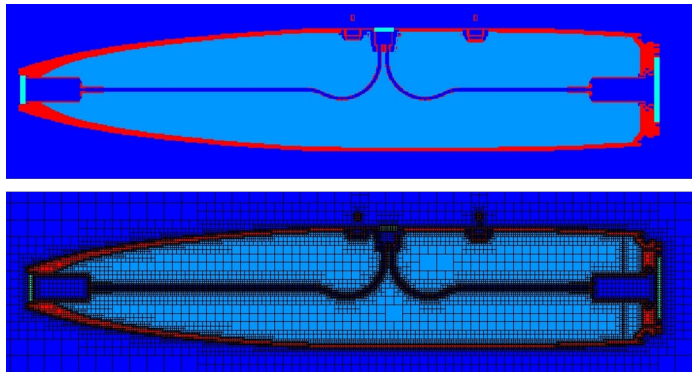
Implicit Approach

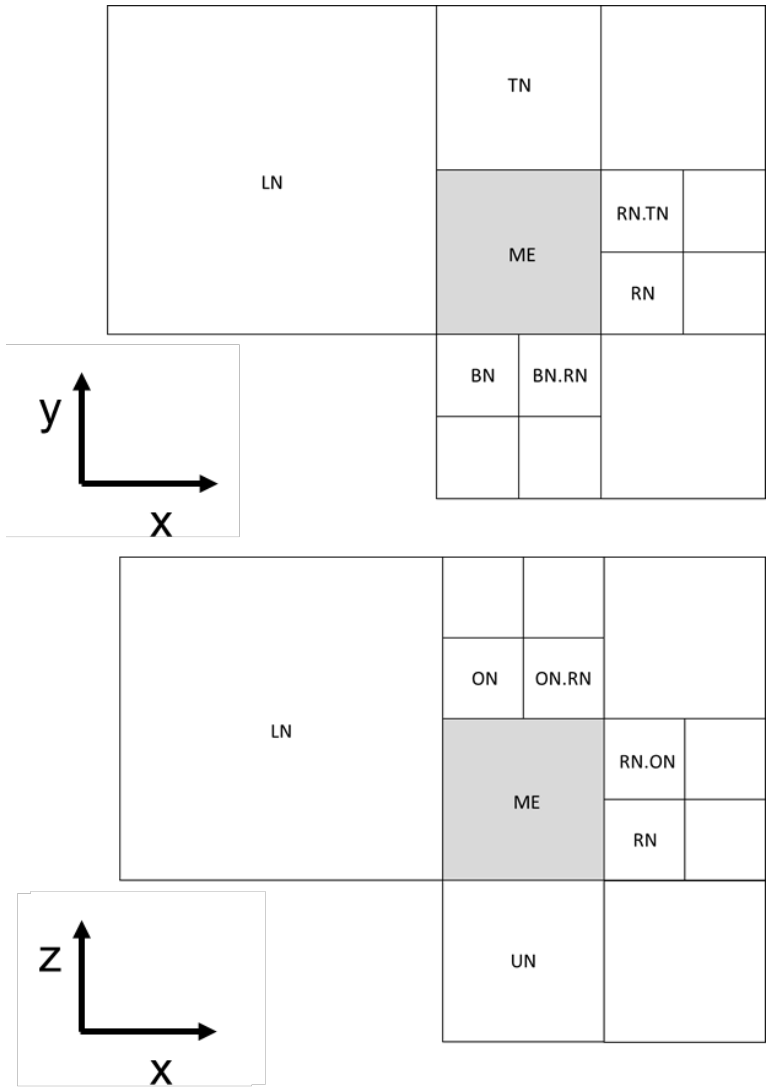
- Timescale of process is such that explicit time integration not practical due to stability requirement is fraction of a second
- Scenarios to be simulated can cover events on the order of several hours or days – implicit methods necessary
- Here an iterative solution method is used
- Leverages fact that AMR structure allows only 1 of 3 potential "neighboring" situations; (1) same, (2) 1/4th, (3) 4x
- Governing equation cast into general form

$$C_{ME}T_{ME} = \sum C_{NB}T_{NB} + S_{ME}$$

- Zero out C_{NB}s based on nature of adaptation

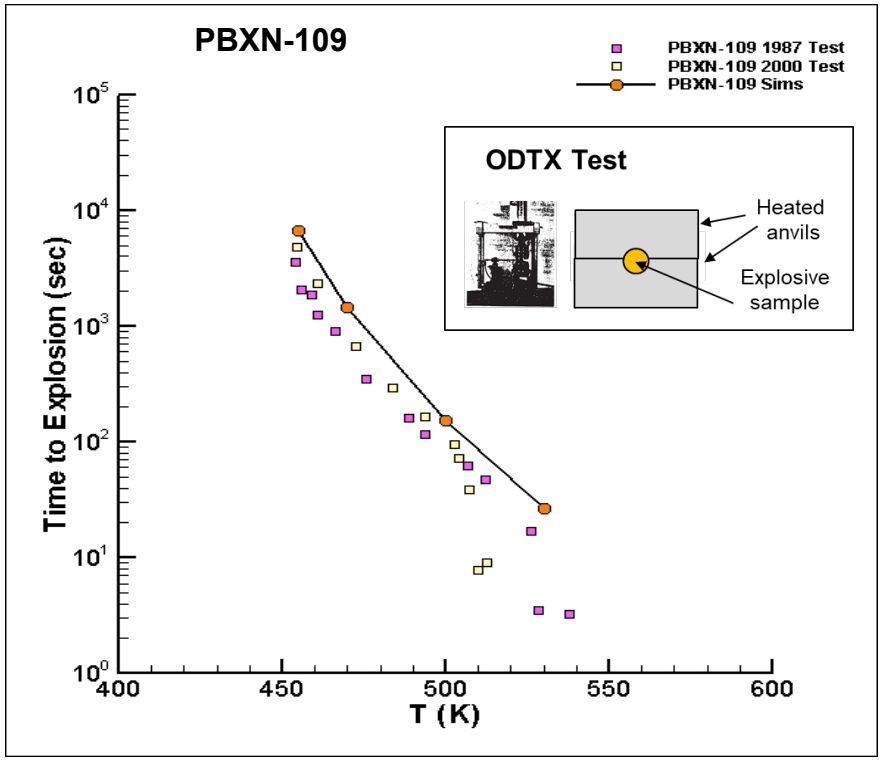


Example Adaptation



Parameter Definition - Multi-step Finite Rate Model

- Key phenomena is transformation & reactions in the energetic during heating
- Two approaches typically taken to address this process
- Studies[1] have shown response to heating can be modeled using a multi-material, multi-step Arrhenius type model
- Parameters derived & validated using ODTX data
- More complex the energetic, the more difficult to define modeling parameters
  - Must work to make "global" characteristics consistent with known behavior of each component
  - Evaluating when a "composite" vs "component" representation is needed



PBXN-109 Kinetic Scheme

$$A \rightarrow B \qquad r_1 = Z_1 exp(-Ea_1/RT)\rho_A$$
$$B \rightarrow C + Al \qquad r_2 = Z_2 exp(-Ea_2/RT)\rho_B$$
$$C \rightarrow D \qquad r_3 = Z_3 exp(-Ea_3/RT)\rho_C^2$$

PBXN-109 Kinetic Parameters

Reaction step	$\ln Z_k$	E_k (kJ/g mole K)	q_k (J/g)
$A \rightarrow B$	43.84 s^{-1}	194.7	268.0 (endothermic)
$B \rightarrow \overline{C}$	39.04 s^{-1}	182.5	−803.9 (exothermic)
$C \rightarrow D$	32.84 $cm^3/s\ g$	141.1	−4241.2 (exothermic)

[1] Yoh, et al,, UCRL-CONF-201173, Nov 25, 2003

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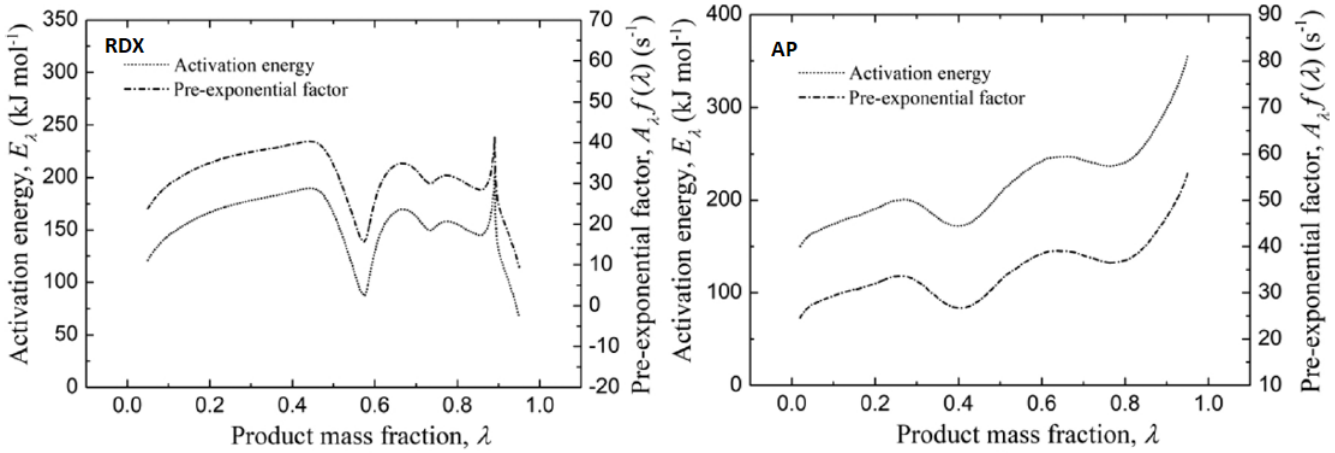
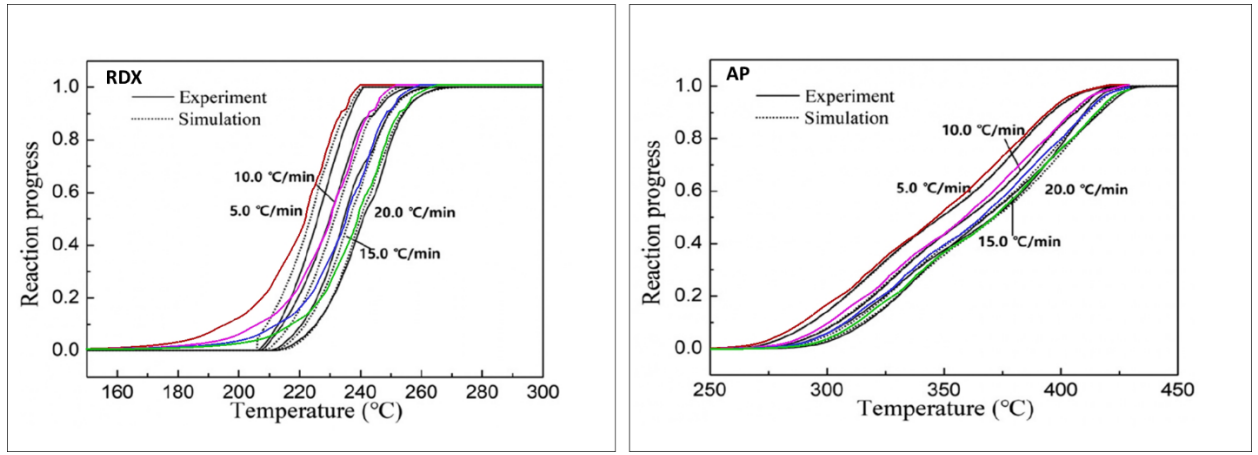
Parameter Definition - Single-step Finite Rate Model

- Another common definition of energetic response uses Self-Accelerating Decomposition Temperature tests [2]
  - Use DSC, TGA
- Single step used to represent the process but not a simple rate law
  - Varying rate parameters replicates the endothermic / exothermic phases
- Max heating temperature was 500 °C, too low for an Al reaction

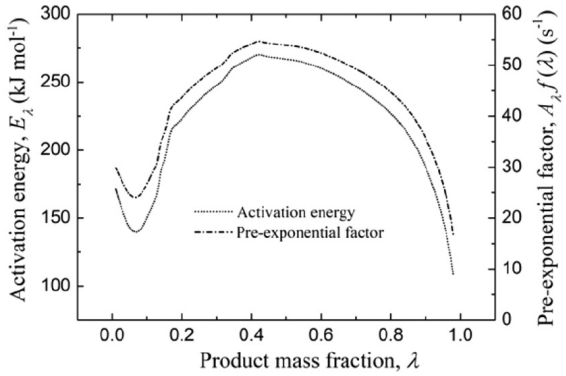
Rate Parameters for RDX & AP[3]



Simulation of RDX & AP Response (Colored curve are current modeling.)



Rate Parameters for PBX#2 (66% HMX, 25% Al)[3]



Note: Figures mislabeled in Ref [3]

[2] Roduit, et al, J. Therm. Anal. Calorim. 93 (2008)

[3] Kim, et al, *Thermochimica Acta,* 678 (2019).

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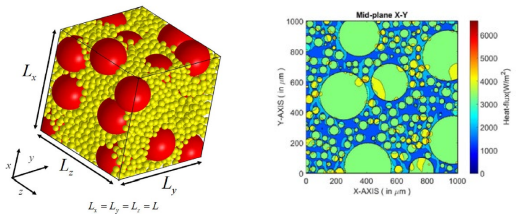
Thermal Properties Definition

- Thermal properties key to process; issue arises if no experimental information is available
- Multi-component energetics; unique challenge
- Density & heat capacity are volume dependent
- Conductivity is a surface property so depends on particle size of each component
  - Originally addressed by Maxwell in 1904

$$k_{eff} = \frac{k_f + 2k_m + 2\phi(k_f - k_m)}{k_f + 2k_m - \phi(k_f - k_m)} \cdot k_m$$

  - Currently working better representation
  - Some approaches uses micro sims of define macro parameters[3]

Example from Ref [3]



AP/Al Energetic
K_{eff} (W/mK)

Calc. = 0.51
Exp. = 0.62

RDX25 in Ref [1], PBX #3 in Ref [2]

Component	% weight	ρ (kg/m^3)	C (J/kg-K)	k (W/m-K)
RDX	25	1,858	1,256	0.167
Al	35	2,700	904	205
AP	25	1,950	1,602	0.430
HTPB	15	930	2,900	0.167
Calculated		1,806	1,466	0.74*
Experimental		1,820	1,080	0.20

PBX #2 in Ref [2]

Component	% weight	ρ (kg/m^3)	C (J/kg-K)	k (W/m-K)
HMX	66	1,716	1,427	0.350
Al	25	2,700	904	205
AP	0	1,950	1,602	0.430
HTPB	9	930	2,900	0.167
Calculated		1,742	1,429	2.42*
Experimental		1,900	1,096	0.997

**Using Maxwell eqn.*

[3] Rajoriya, et al, *International Journal of Thermal Sciences,* 127 (2018).

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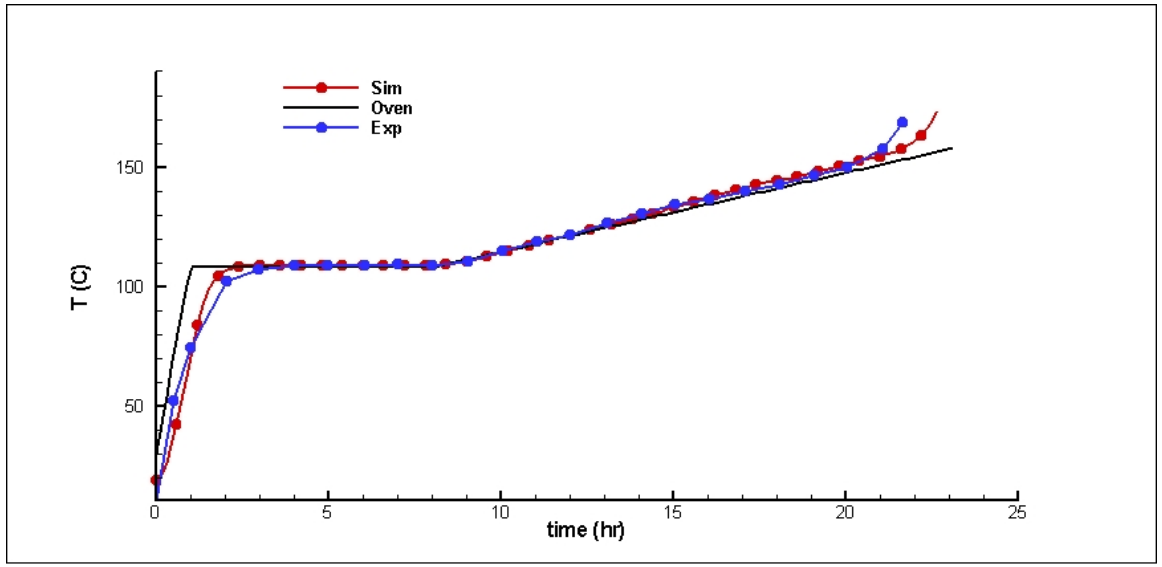
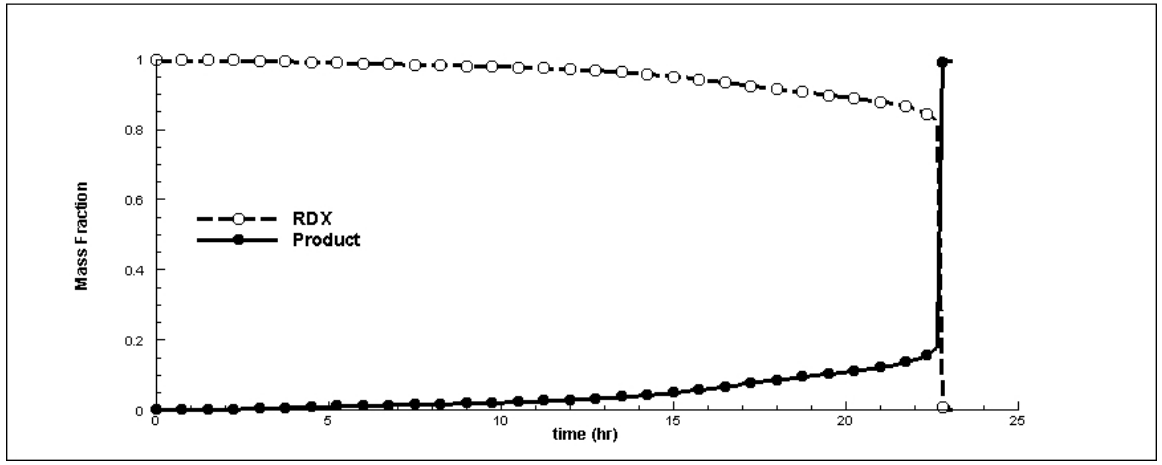
Small-Scale Slow Cookoff Benchmark

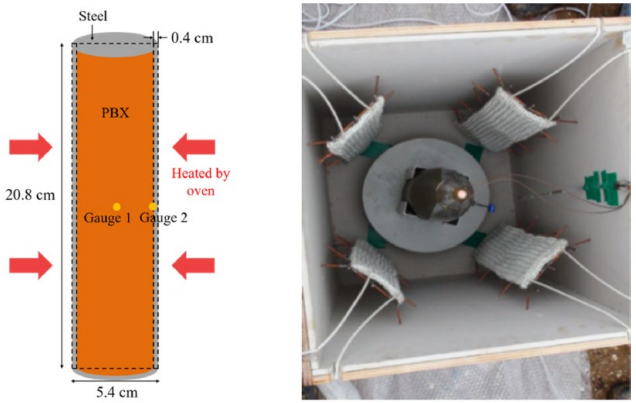
- Test item was the RDX25 fill with steel case [3]
- Heating load was 3.3 °C / hr after 7 hr at 108 °C
- Both RDX & AP reactions considered
  - Heat rate causes RDX to respond before AP
  - Temperature well below what is needed for Al to contribute
- Evaluating “composite” vs “component” representation

RDX25 (20%RDX, 35% Al, 25% AP)





Test Configuration



(a)

(b)

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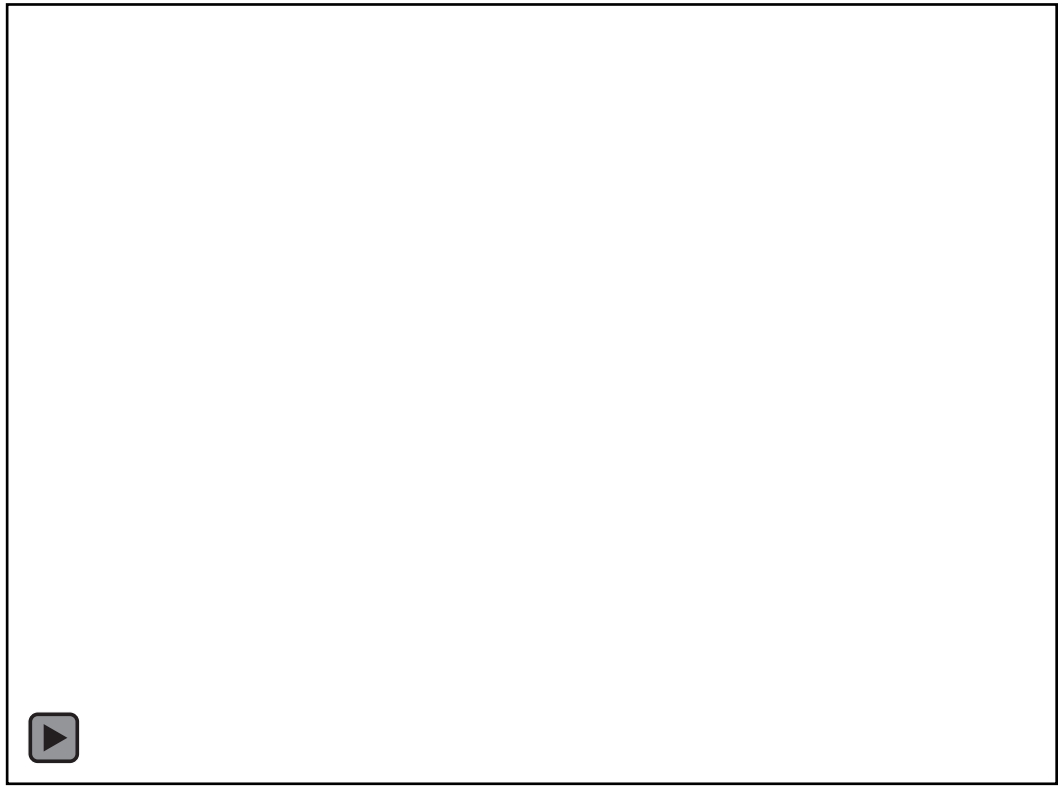
Full-Scale Analysis Example (PBXN-109 Fill)

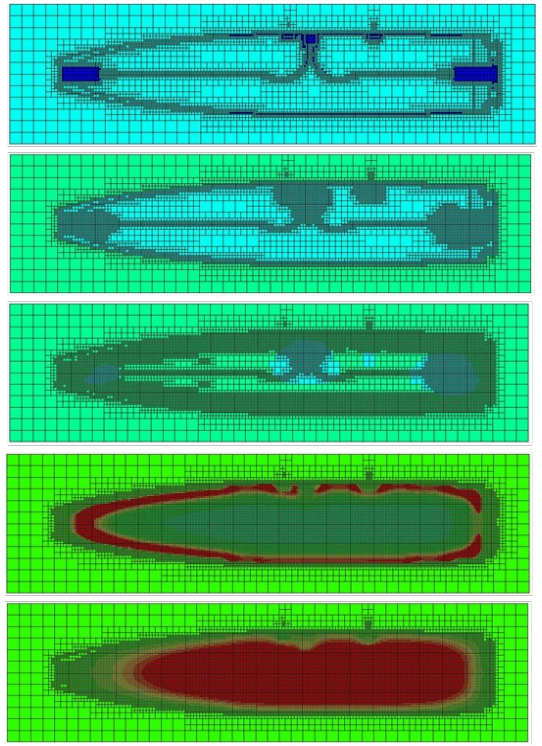
- Test involves engulfing item with heat and elevating load over time
- There is an “induction” process related to the endothermic process
- Implicit/AMR framework allows for efficient analysis

Change in Temperature & Composition



Video

Evolution of Mesh



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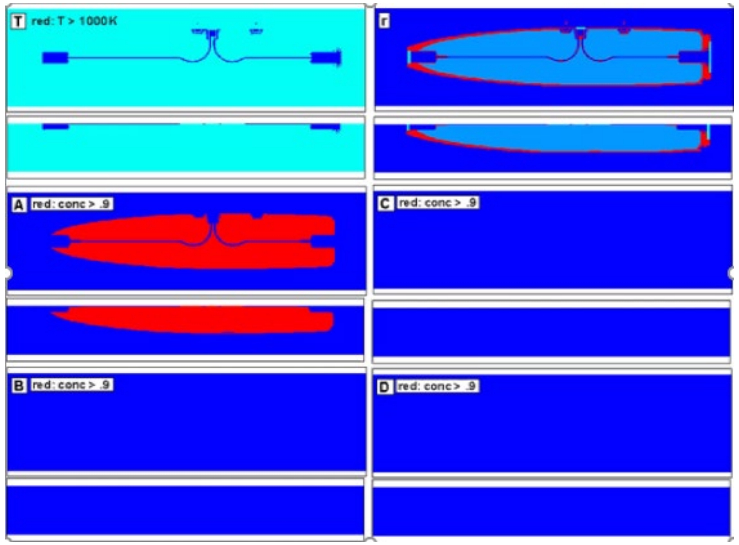
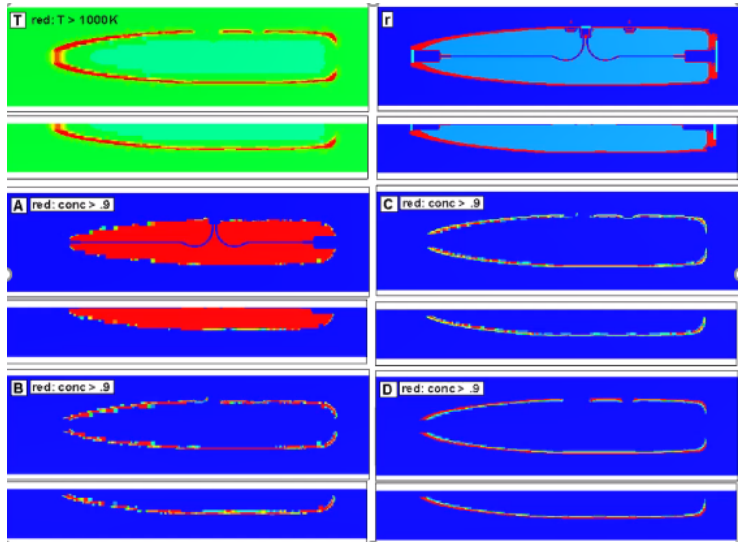
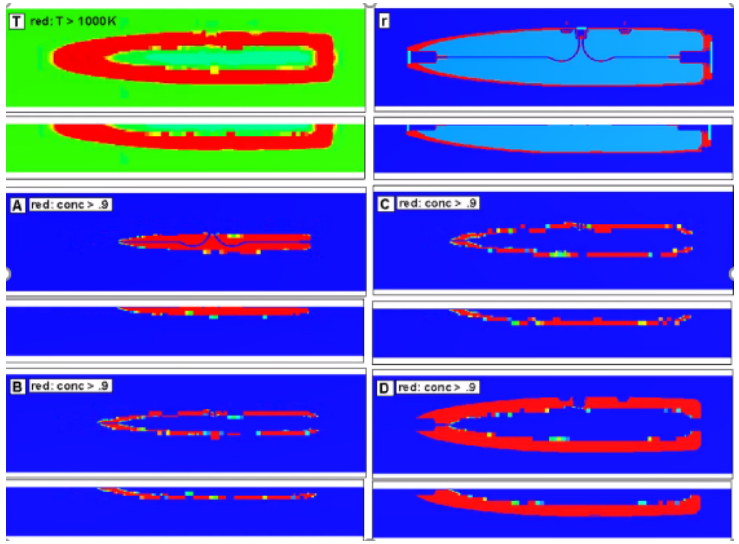
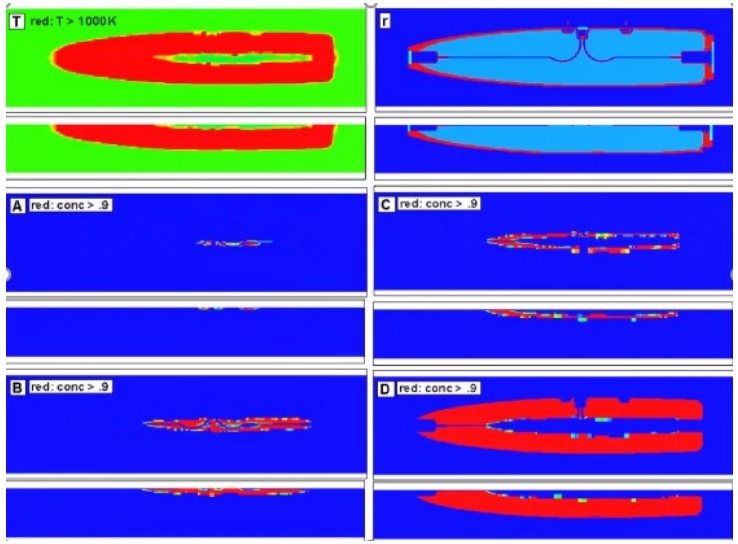
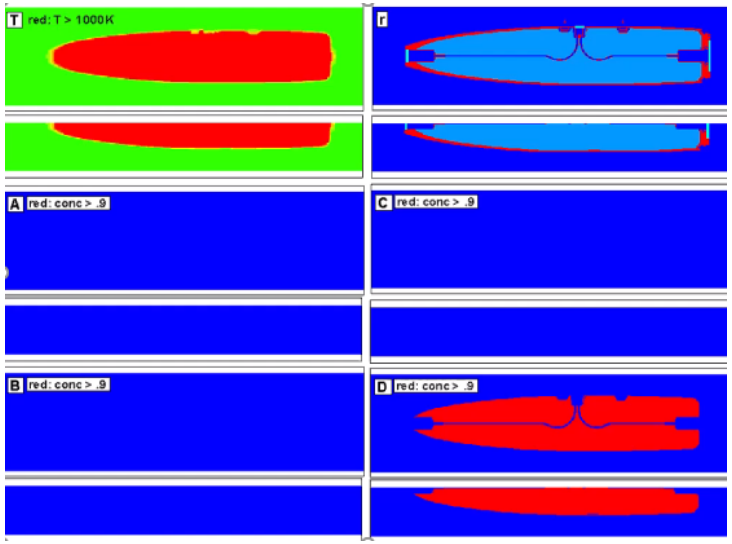
Full-Scale Analysis Example (PBXN-109 Fill) – Still Images

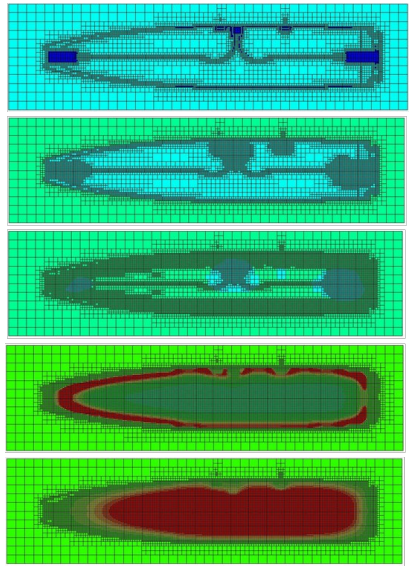












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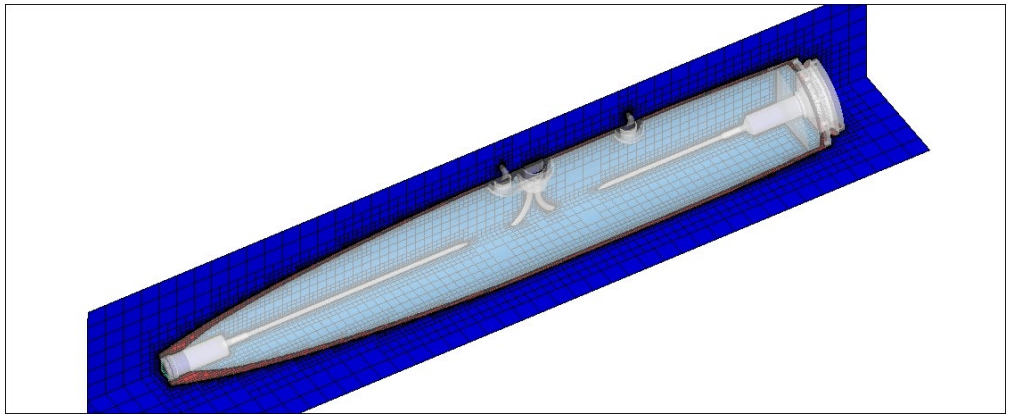
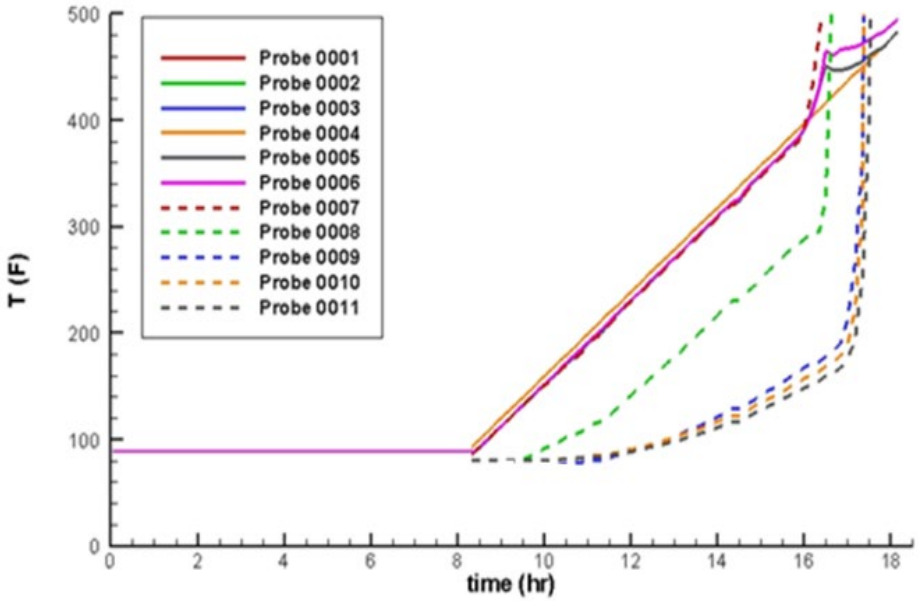
Full-Scale Analysis Example (PBXN-109 Fill)

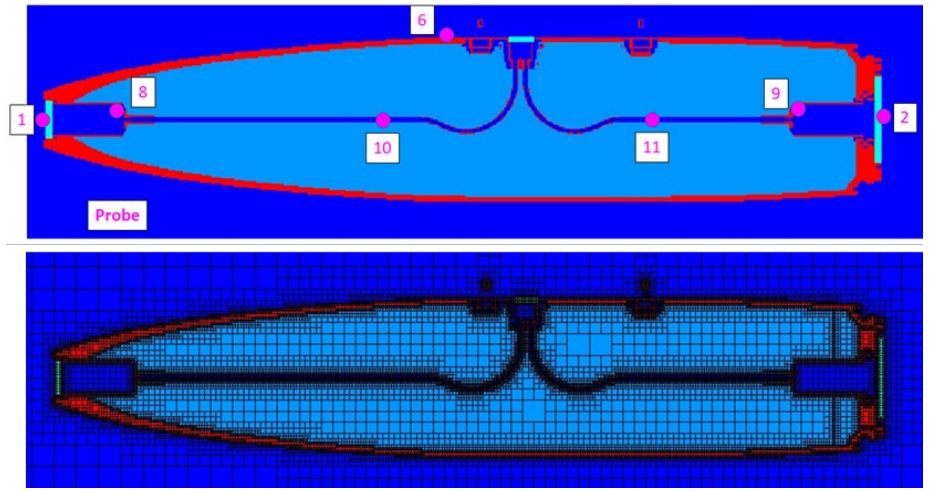
- Predicted “time to explosion” consistent with test data
- Response of the energetic, such as the induction phase, key to overall system response
- 3D modeling framework captures non-uniform response such as <u>difference in front & rear fuze well</u>
  - Early reactions at one end can cause differential forces resulting in billet movement





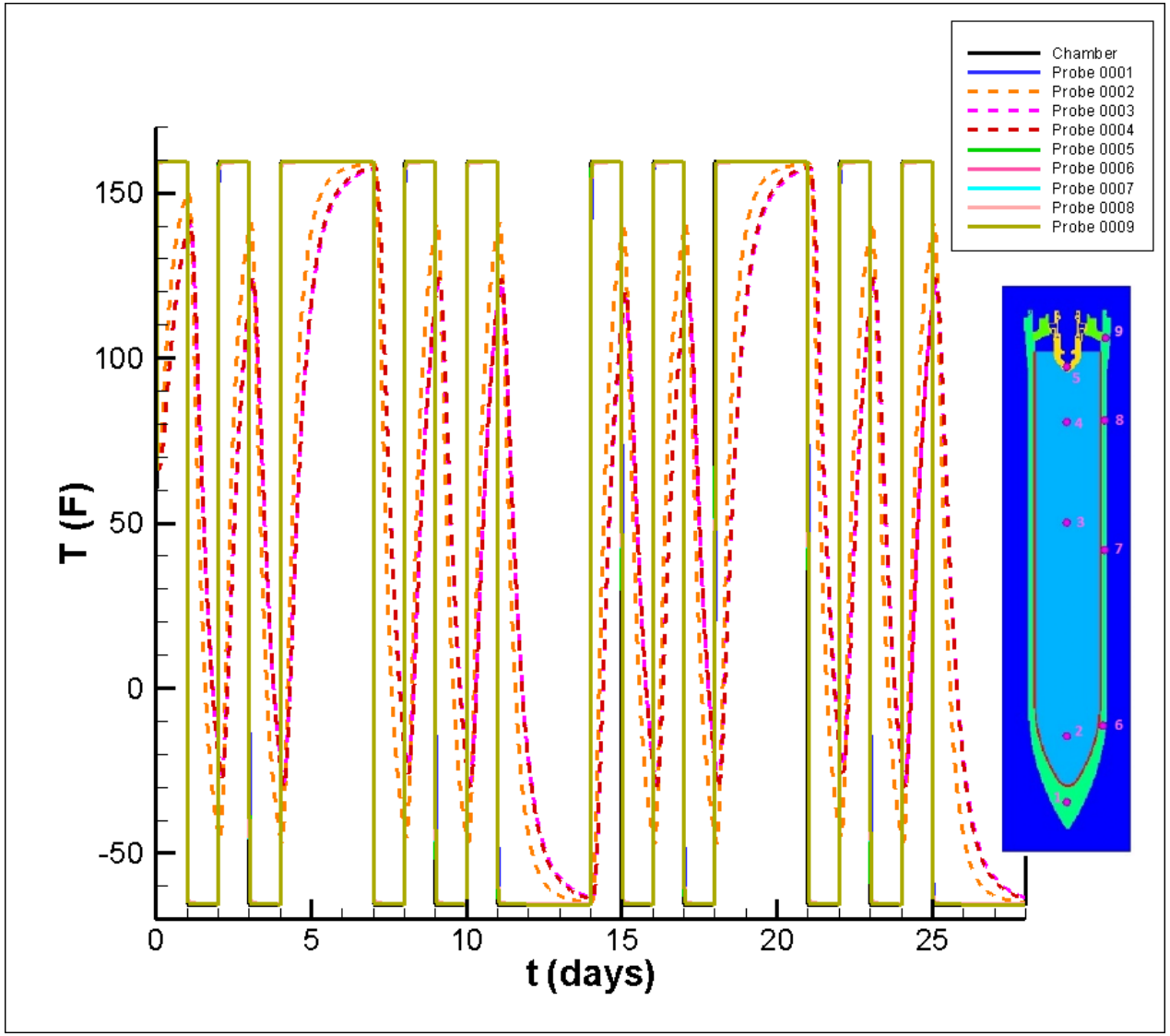
Results consistent with test data

Location of Recording Probes



Long Term Environmental Qual Test (RDX Fill)

- Another slow process that involves heating and cooling
- Performed to meet MIL-STD-2105D & 810G, DoD Test Method Standard, Hazard Assessment Tests for Non-Nuclear Munitions
- Munition exposed to 28-day temperature cycle of hot & cold
- Example of full-scale munition test
- Note - response of internal fill slower than what is probably thought to happen



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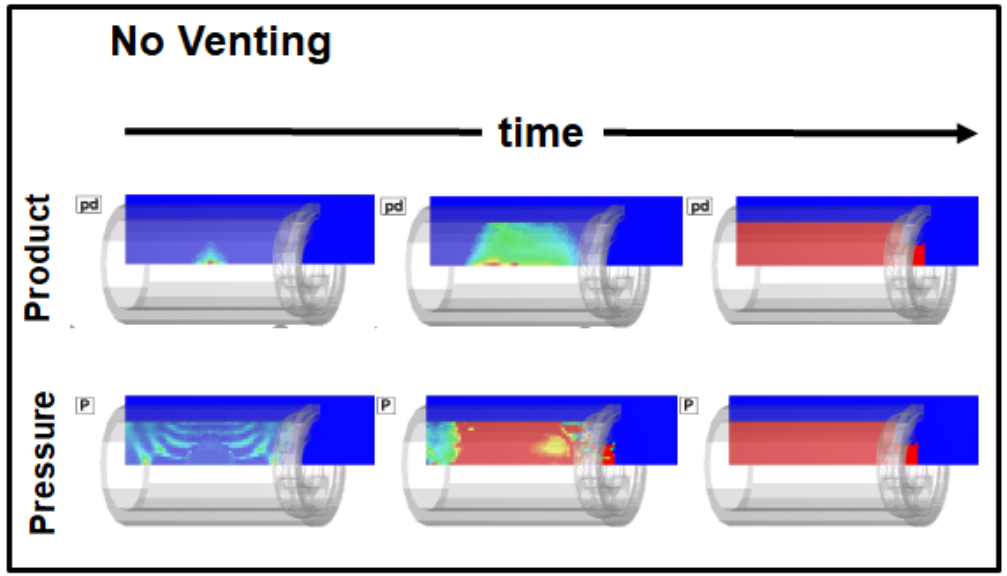
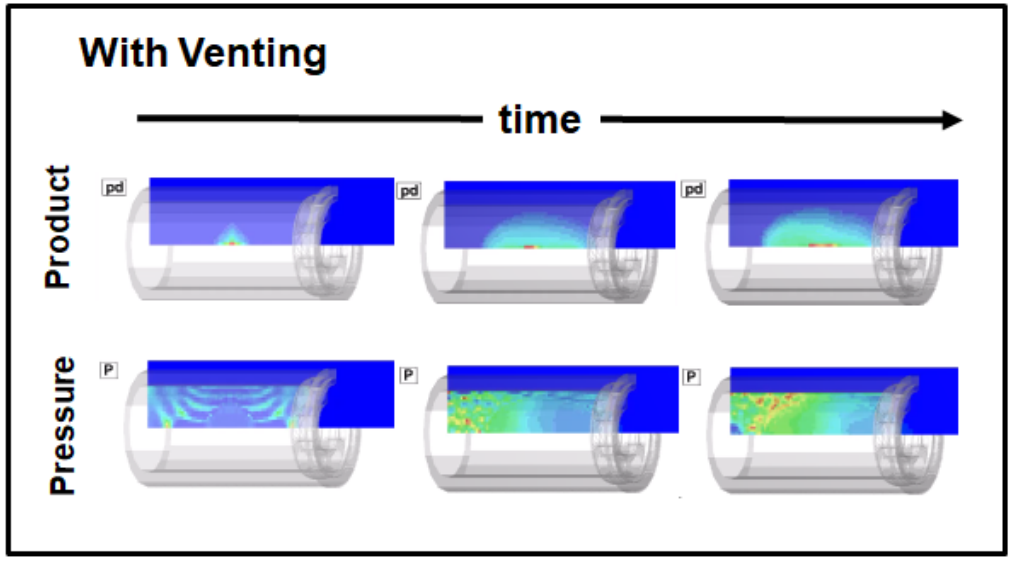
Fast Cookoff Example

- Heating process is modeled as in the slow cookoff scenario
- Response after ignition is modeled – requires solution of full set of governing equations
- Reaction model transitions to a pressure-dependent burn rate model[4]

$$V = aP^n$$

- Solution captures the feedback process from confinement to the reaction rate





[4] Yoh, et al, UCRL-JRNL-207203, Oct 2044 *Journal of Applied Physics*

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Conclusions

- Tremendous potential for leveraging digital engineering in the IM design process
  - Requires tools that capture key phenomena in weapon-scale scenarios
  - Robust and efficient numerical approaches key to have tools that integrate into the design and evaluation process
- Scenarios range from slow cookoff to detonations - robust modeling tools needed
  - Multi-material code with variety of reaction models addresses the phenomena
  - AMR / Implicit approach has proven efficient & promotes integration with design process
- Challenges exist when addressing composite energetics
  - Working theoretical and experimental processes to address this issue
  - Potential for additional useful information collection during qual tests

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Naval Surface Warfare Center Dahlgren Division

Barrel Heating and Cook Off in Powder Guns

Presented by

Jon Yagla, PhD

Senior Member, International Ballistics Society

Integrated Engagement Systems (E) Department

WELCOME

Insensitive Munitions and Energetic Materials Technology Symposium

Indianapolis, Indiana

October 2022

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Barrel Heating in Hot Guns

- Hot guns can be very dangerous.
- If a cartridge is allowed to remain in a hot gun, it may explode.

I will discuss:

- Barrel heating during action time
- Barrel heating during blowdown

- Concurrent barrel cooling

- Heat transfer to a cartridge loaded into a hot gun
- Time until cook off

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Important Lessons Learned IM Test Development

Liquid Fuel Fire Computer Simulation

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RÉPUBLIQUE FRANÇAISE
MINISTÈRE DE LA DÉFENSE

Fast-Cook-Off Test :

Liquid Propane Gas vs Kerosene Pool Fire

Fabien Chassagne (DGA/DT/CAEPE)

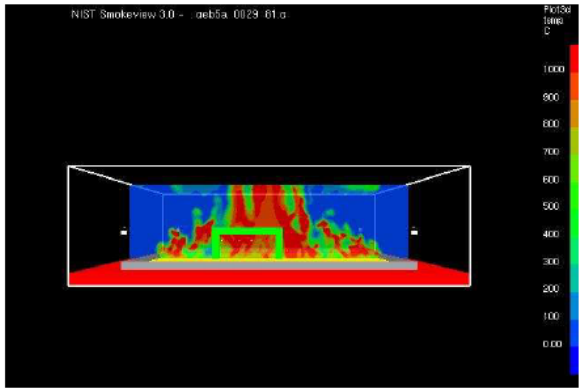
DGA
DÉLÉGATION GÉNÉRALE POUR L'ARMEMENT

Fire dynamics simulation

- Numerical code : FDS (Fire Dynamics Simulator) developed by the NIST (USA)
- Well-adapted to simulate hydrocarbon fire (Low Mach number flow)
- 3D, multi-species, Large Eddy Simulation (LES), Radiative heat transfer modeling by Finite volume method

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 & \text{(mass)} \\ \dfrac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho Y_i \mathbf{u}) = \nabla \cdot (\rho D_i \nabla Y_i) + \dot{m}_i''' & \text{(species)} \\ \rho\left(\dfrac{\partial}{\partial t} + (\mathbf{u} \cdot \nabla)\right)\mathbf{u} + \nabla p = \rho \mathbf{g} - \nabla \cdot \bar{\tau} & \text{(momentum)} \\ \dfrac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h \mathbf{u} = \dfrac{Dt}{} - \nabla \cdot \mathbf{q}_r + \nabla \cdot k \nabla T + \sum_i \nabla \cdot h_i \rho D_i \nabla Y_i & \text{(energy)} \end{cases}$$

Conservation equations



Example of Kerosene Fire

"Multi-species" includes solid phase carbon particles (JJY)

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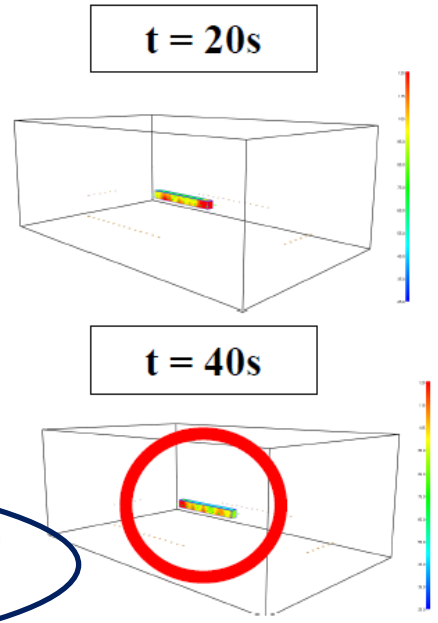
We Found that 90% of the Heating is Radiation from Carbon Particles

- Calculated **heat exchanges** between the munitions and the flames

Time-Averaged Heat Flux (kW/m²)	LPG Fire	
Incident Heat Flux Φinc	104,1	
Radiative Heat Flux Φrad	84,2	89,7%
Convective Heat Flux Φconv	9,6	10,2%
Net Heat Flux Φnet	93,9	

Heat flux is mainly due to radiation ($\varepsilon_{munitions}$ = 0.9) but is not uniformly applied to the munitions



Radiation heat flux is 90%

Convection heat flux is 10%

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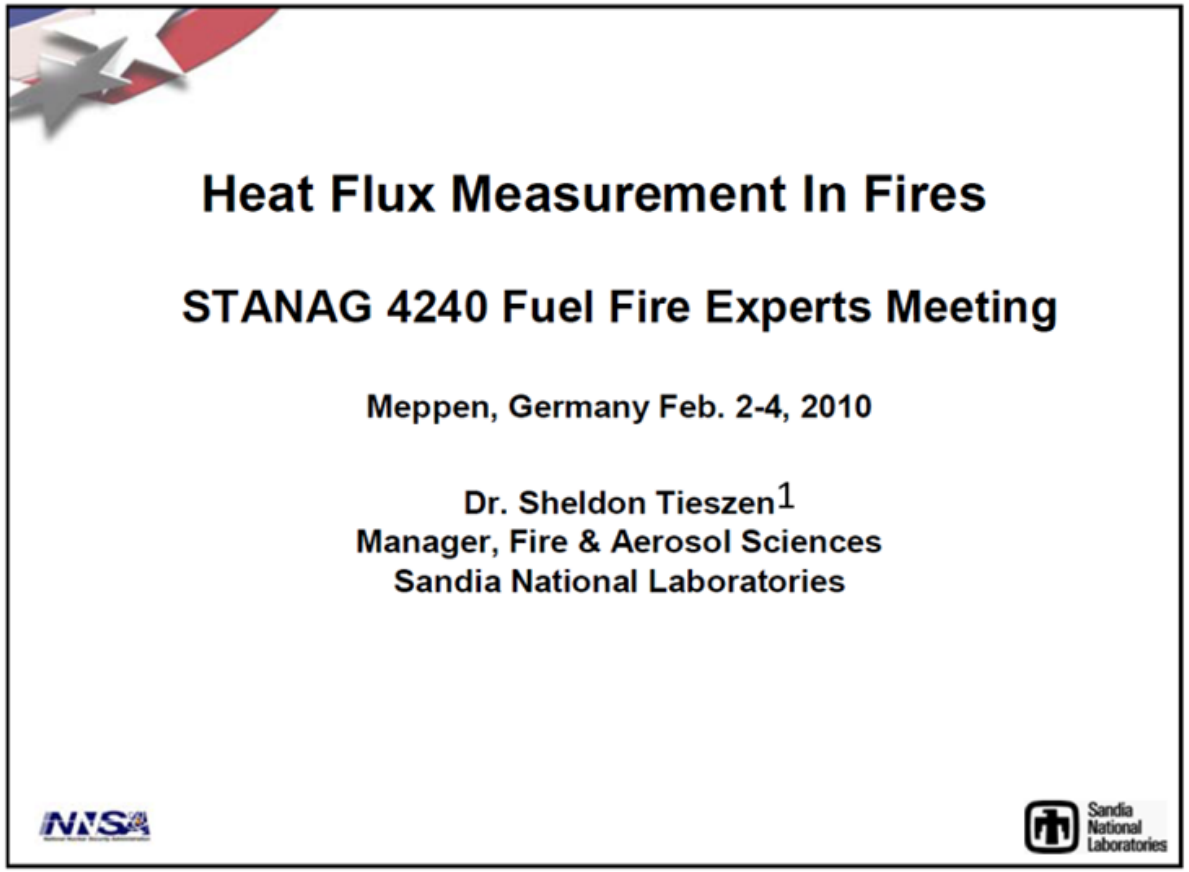
We Learned that the Fraction of Carbon Particles is *Very Small*

We Learned The Mass Fraction Of Carbon Particles Is ***Very Small***



1. Dr. Sheldon Tieszen, PhD; Manager, Fire and Aerosol Sciences. *Heat Flux Measurement in Fires*; STANAG 4240 Fuel Fire Experts Meeting; Meppen, Germany, 2–4 February 2010

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Soot Production
Laminar Flames

Table 1. Peak Soot Concentrations in Laminar, Low-Strain Steady Diffusion Flames

fuel	flame	peak fv reported	Reference	Method	assumption	current best estimate of fv
methane	79 mm high coannular	3×10^{-7}	[64]	HeNe extinction	$K_e = 4.9$ (D&S)	1.7×10^{-7} ($K_e = 8.5$)
propane	85 mm high coannular	6×10^{-6}	[64]	HeNe extinction	$K_e = 4.9$ (D&S)	3.5×10^{-6} ($K_e = 8.5$)
ethylene	91 mm high coannular	13×10^{-6}	[64]	HeNe extinction	$K_e = 4.9$ (D&S)	7.5×10^{-6} ($K_e = 8.5$)
ethylene	88 mm high coannular	10×10^{-6}	[65]	Ar-ion extinction (514 nm)	$K_e = 4.9$ (D&S)	5.8×10^{-6} ($K_e = 8.5$)
ethane	88 mm high coannular	3×10^{-6}	[65]	Ar-ion extinction (514 nm)	$K_e = 4.9$ (D&S)	1.7×10^{-6} ($K_e = 8.5$)
acetylene	6 mm high coannular (smoke pt)	15×10^{-6}	[66]	path-ave HeNe extinction	$K_e = 3.5$ (L&T)	6.2×10^{-6} ($K_e = 8.5$)
ethylene	75 mm high coannular (smoke pt)	6×10^{-6}	[66]	path-ave HeNe extinction	$K_e = 3.5$ (L&T)	2.5×10^{-6} ($K_e = 8.5$)
propane	150 mm high coannular (smoke pt)	4×10^{-6}	[66]	path-ave HeNe extinction	$K_e = 3.5$ (L&T)	1.6×10^{-6} ($K_e = 8.5$)

- **Jet Fuel ~ 6 ppm Propane ~ 1.6-3.5 ppm**
- **Peak Soot Concentration of Jet Fuel ~ 3 x Propane (all else equal).**

Sandia National Laboratories

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Fast Cook Off Lesson on Radiation

Two Burners Worked – Radiation from carbon particles met the requirement. Stoichiometric fires w/o Carbon did not.

Liquid Injection

Meppen, Germany

China Lake, USA

Pre-Mixed Injection

't Harde, Netherlands

Bofors, Sweden

Gaseous Injection

Dahlgren, USA

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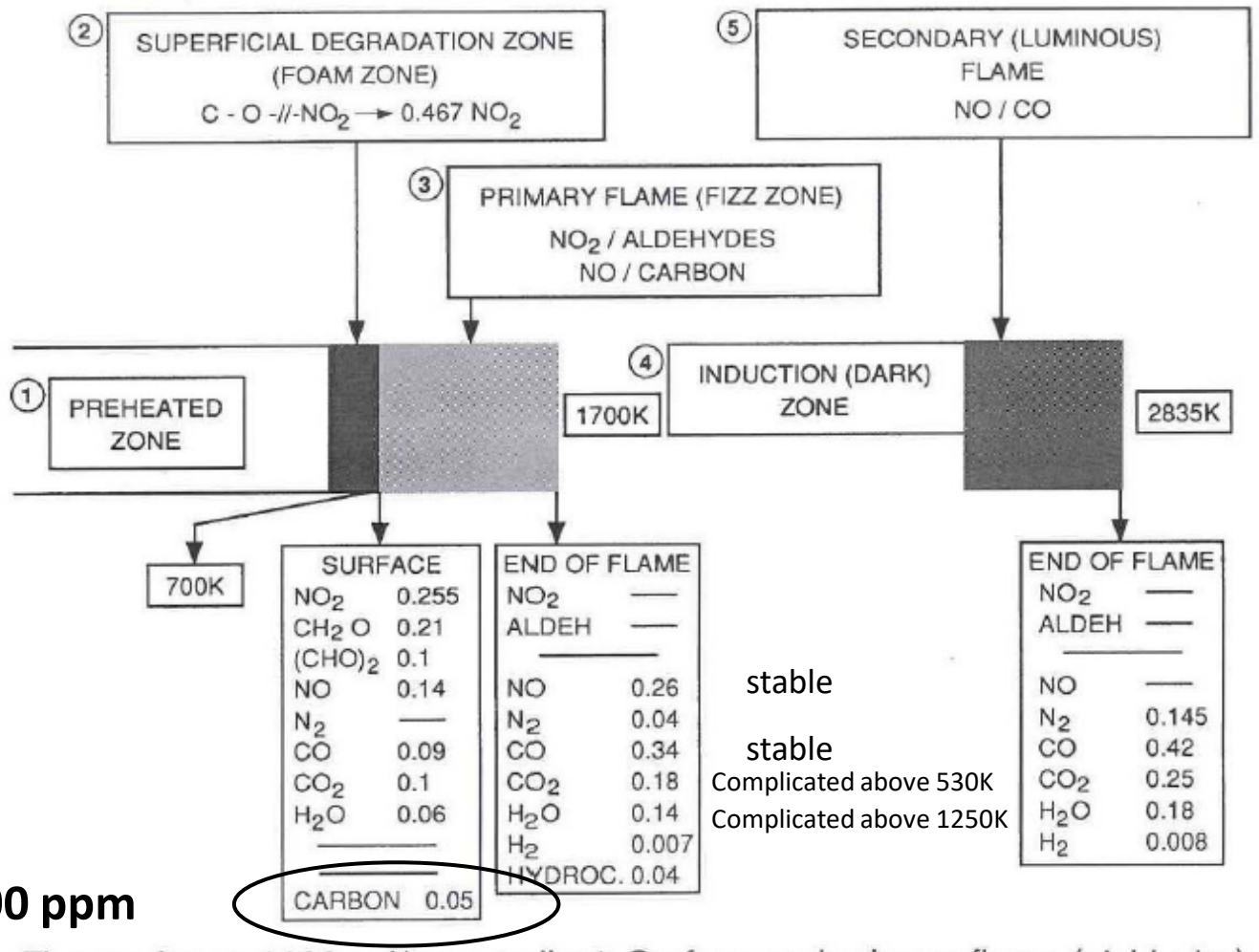
In the NATO "Science of Cook Off Workshop"

Combustion of Solid Propellants

G. Lengellé, J. Duterque, J.F. Trubert
Research Scientists, Energetics Department
Office national d'études et de recherches aérospatiales (ONERA)

This paper showed there was free carbon in low concentrations in propellant combustion.



Carbon: 0.05, 5%, or 50,000 ppm

Figures for an 1100 cal/g propellant. Surface and primary flame (at 11 atm) mass fractions from gas analysis

Figure 5: Various Zones of the Combustion of a Double Base Propellant.

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Conclusions for Gun Barrel Heating

- There are ample carbon particles entrained at T_{gas} for gas radiation emissivity = 1.0.
- The powder flame temperature, T_{flame}, will add additional radiation at the flame temperature.
- The flame temperature, T_{flame}, may heat the carbon particles and add additional radiation at the flame temperature.
- **Action time** Temperature will be flame radiation plus gas radiation
- **Blowdown** Gas radiation plus convection

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Propellant Heating from a Single Shot in a 30mm Machine Gun

Total Heating = Action time (while projectile is in the gun) + Blowdown time

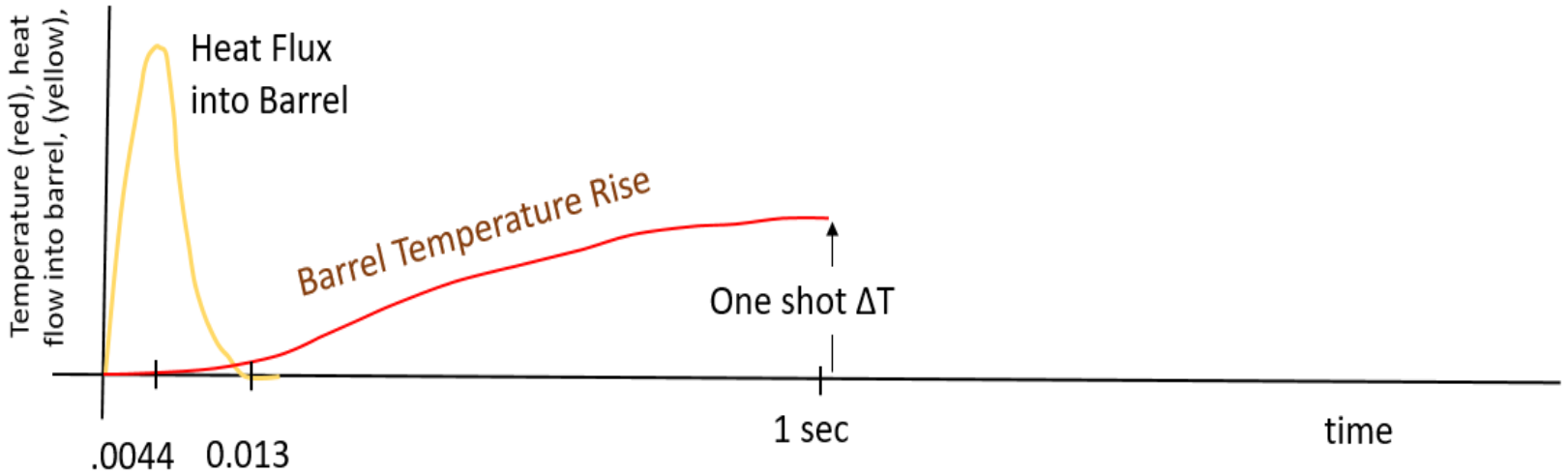
This is data for 30mm

t_A = .0044 seconds, Intense barrel heating due mainly to radiation during action time

t_B = .013 Barrel heating during blowdown due to radiation and convection

$t_A + t_B$ = 0.017 Total barrel heating time

t_{RoF} = Rate of fire, 1 second between shots for 30mm



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Mechanical Heating

Engraving

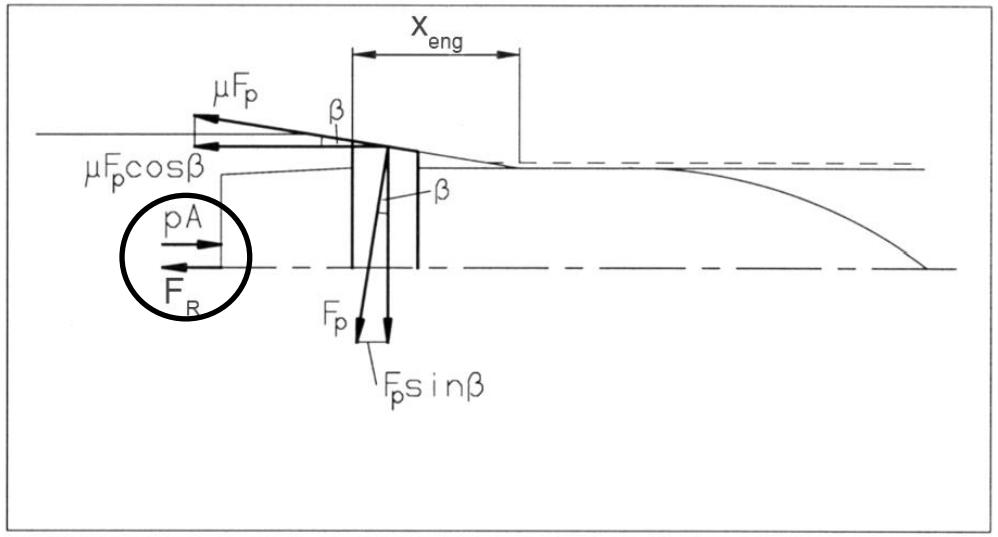

Fig. B. 3. Initial Engraving Geometry (β = half angle of the forcing cone, x_{eng} = engraving length).

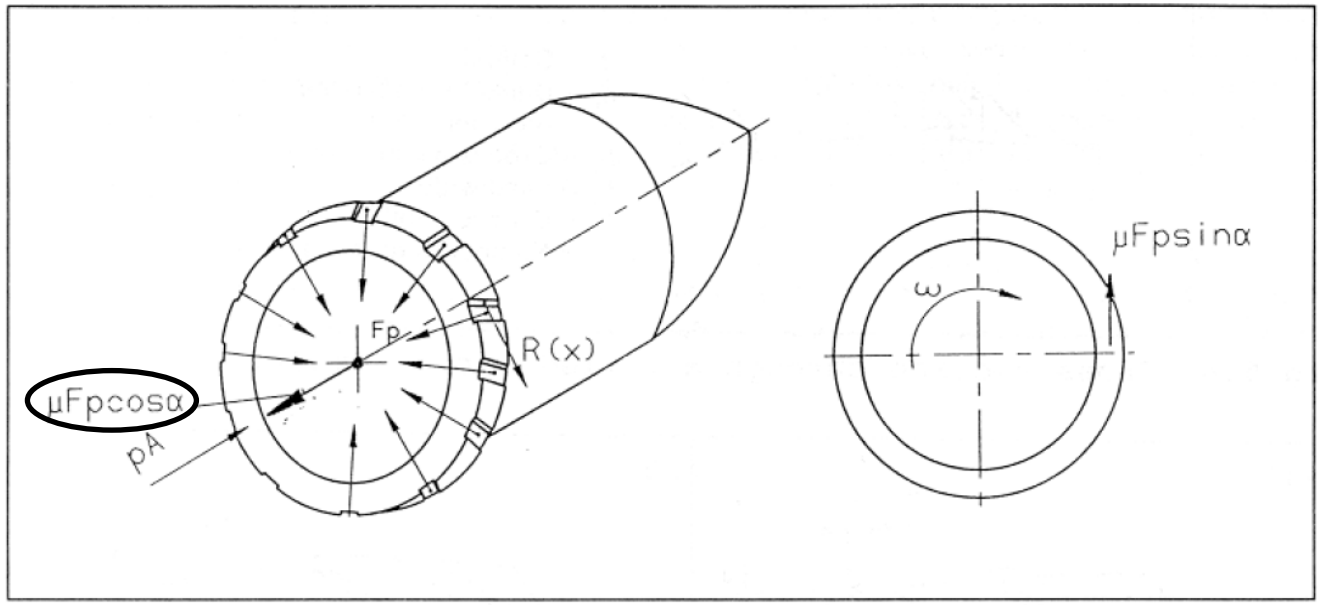

Fig. B. 5. Definition of the pressing force $F_P(x)$ and its components [2].

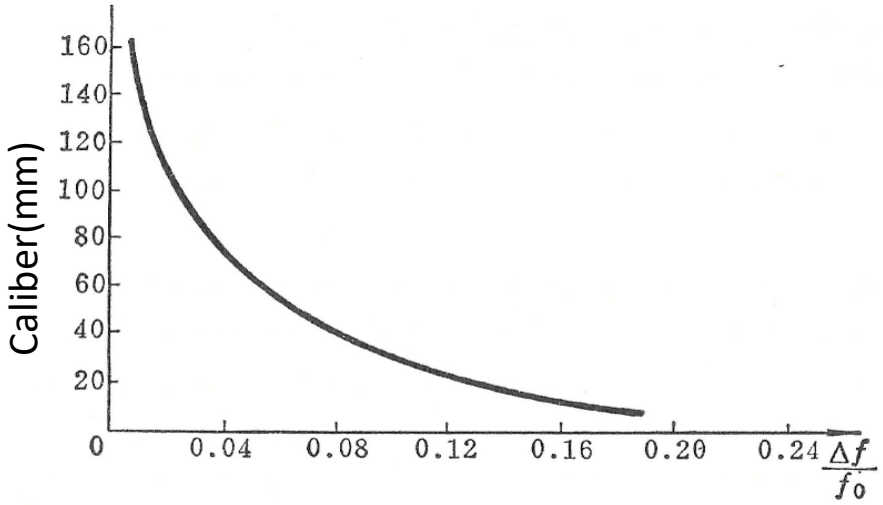

Fig 2.5 The heat loss $\frac{\Delta f}{f_0}$ vs the caliber

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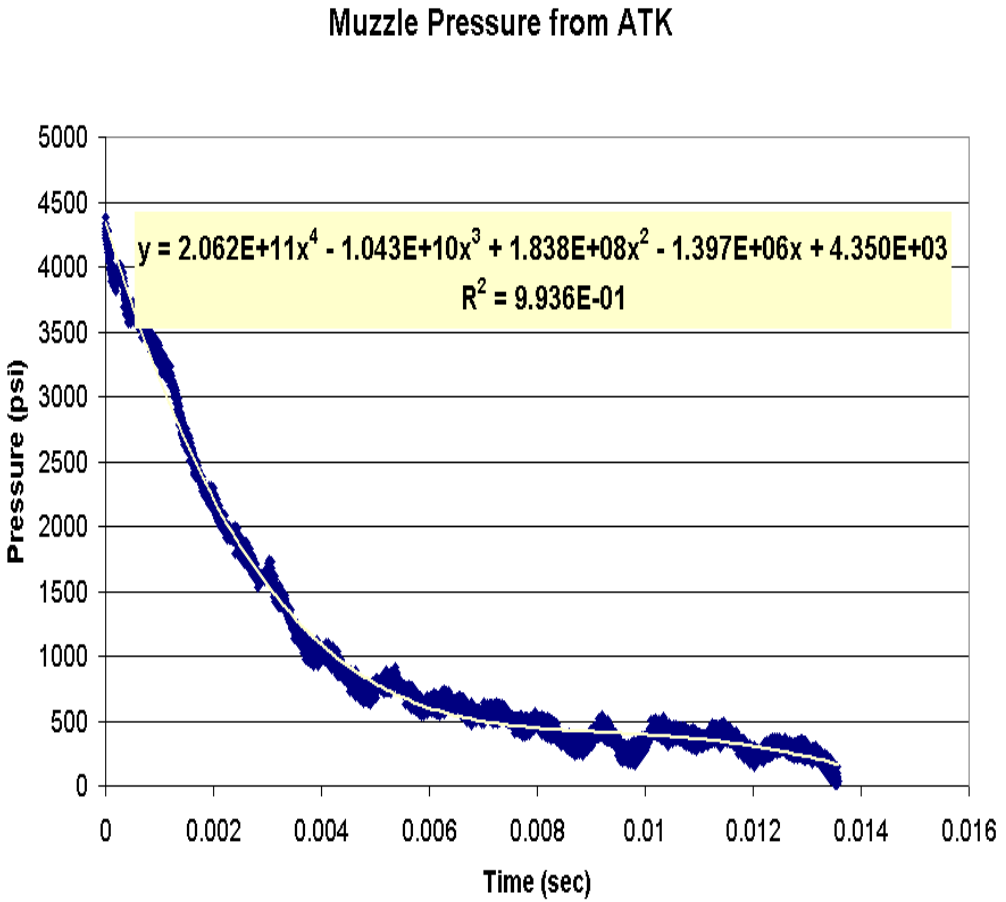
Blowdown

Blowdown in Various Stages



$$p_f / p_i = [1 + t / \tau]^{2\gamma/(1-\gamma)}$$

Barrel and gas characteristic time $\tau =$

$$2(V/AC_i)\{[(2/(\gamma+1)^{(\gamma+1)/(\gamma-1)}]^{1/2}\}/(\gamma-1)$$

Polytropic flow equations to get ρ, T, speed of sound

Compressible flow equations for convection and radiation

1. Yagla, Jon J. *Pressure Vessel Discharge Non-dimensional Equations*, Paper No. 190335551; 28th International Symposium on Ballistics; Atlanta, Georgia, 22–26 September 2014. DTIC AD 1154106

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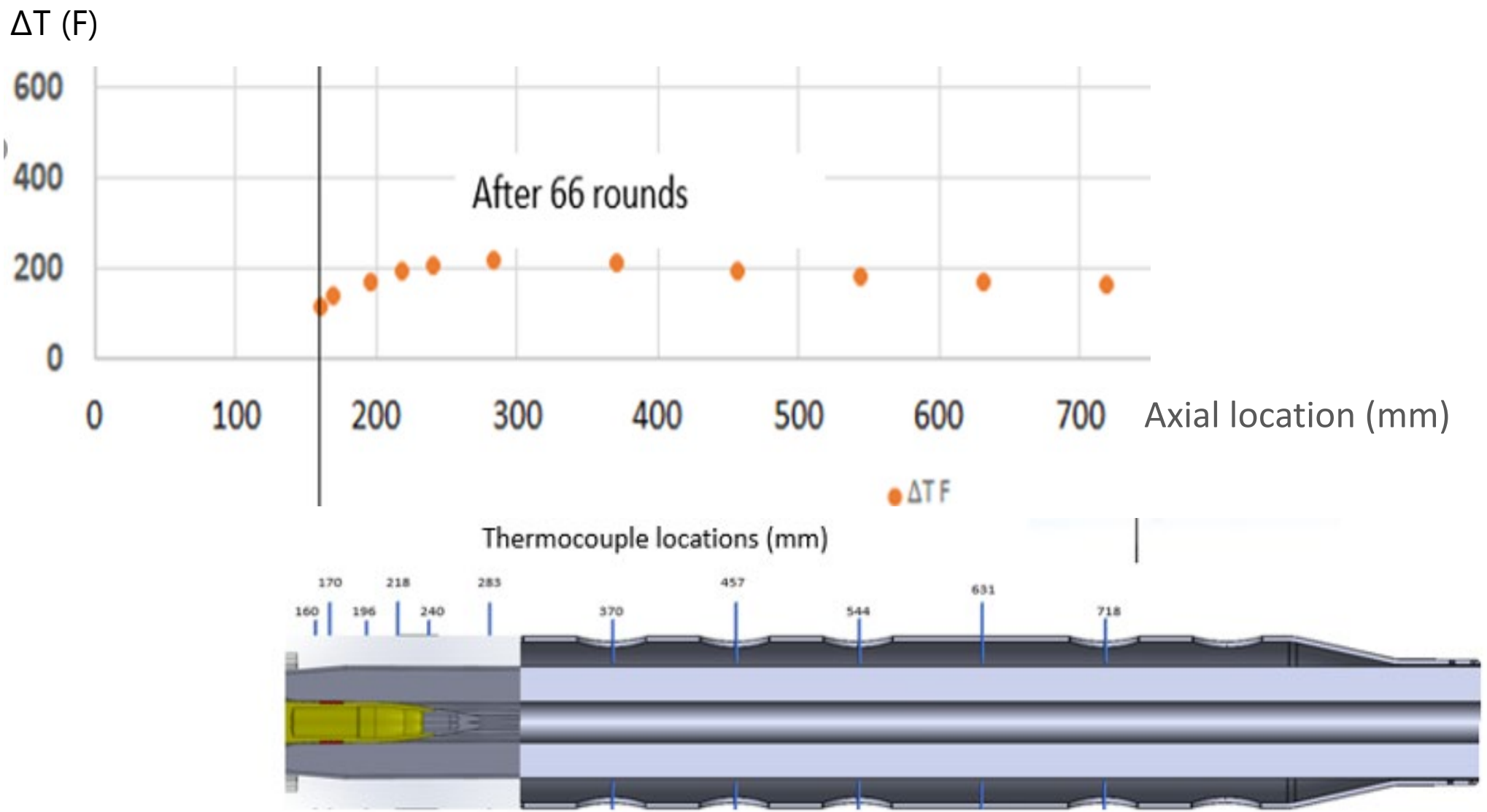
Barrel Temperatures after Many Rounds Fired



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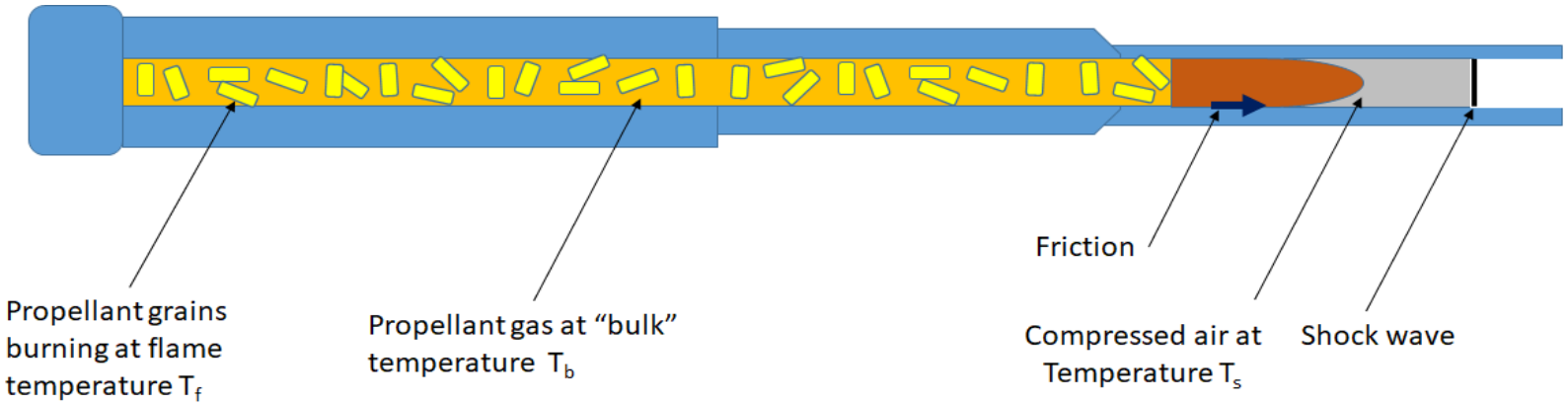
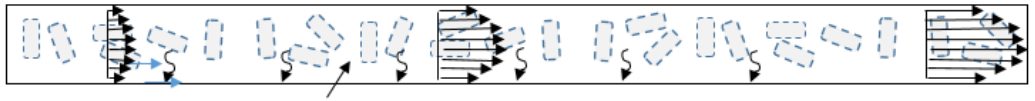
Let's Do the Math: Conventional Gun (Action Time)



T_{bulk} = 2835 K

Convection



Small, < 5% of total heating

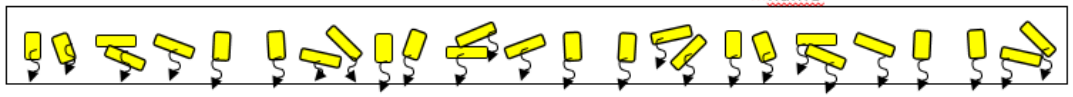
T_{bulk} = 2835 K

Radiation from gas at T_{bulk}

About 30% of the radiation heating

T_{Flame}= 3800 K

Radiation from propellant grains at T_{flame}



About 70% of the radiation heating

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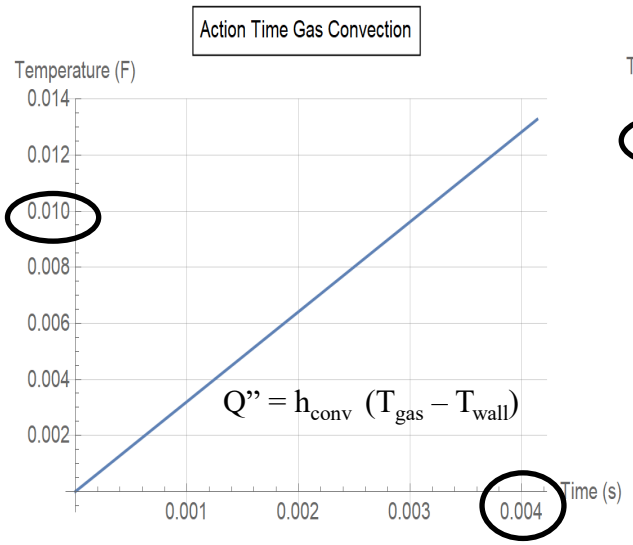
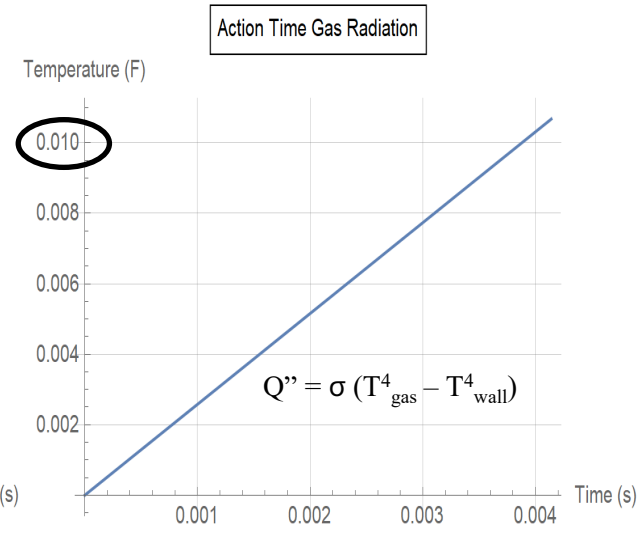
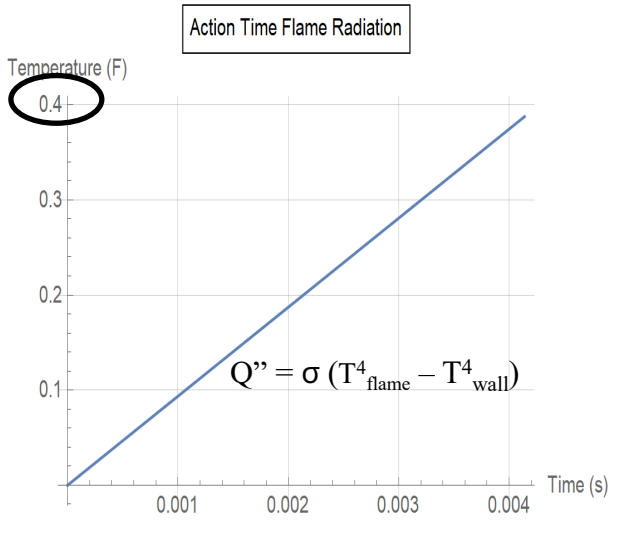
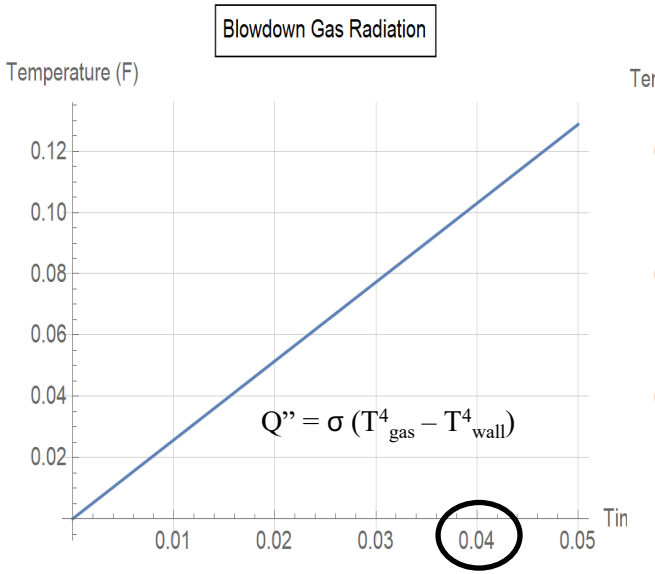
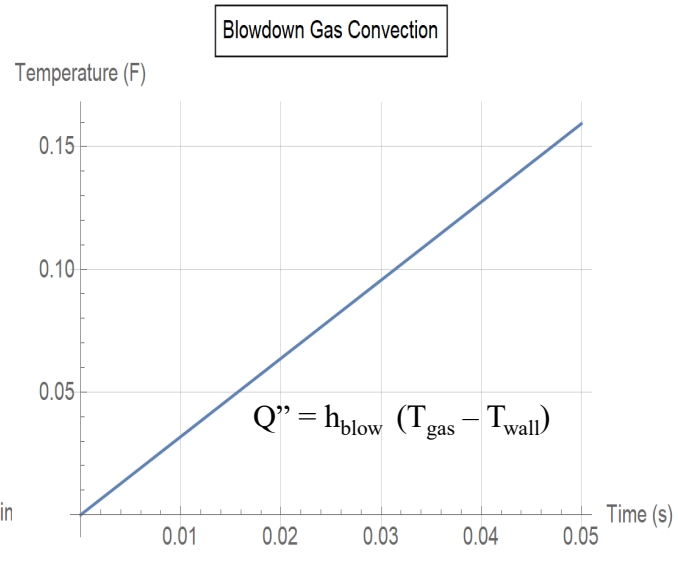
Action Time and Blowdown Gas Dynamic Heating

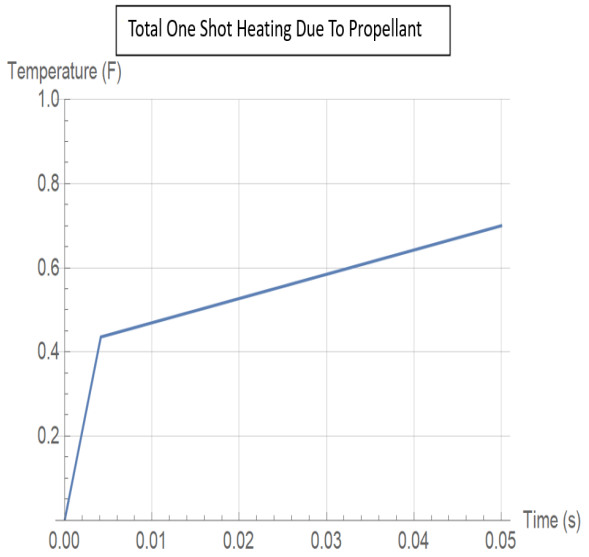












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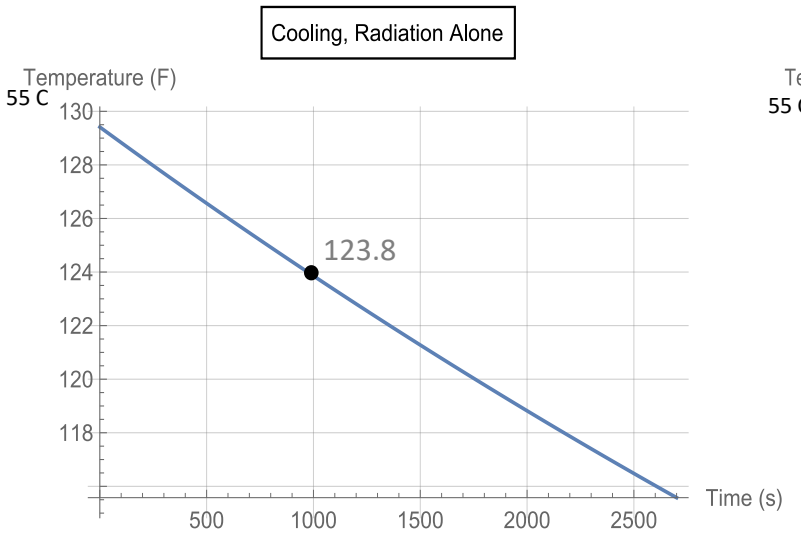
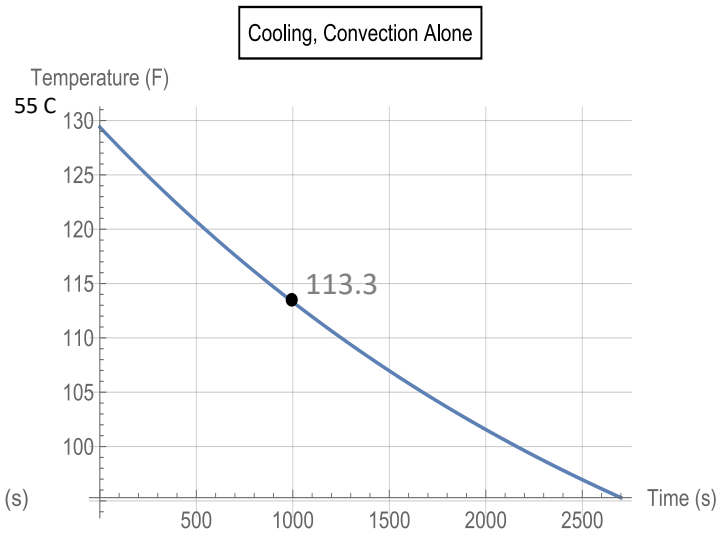
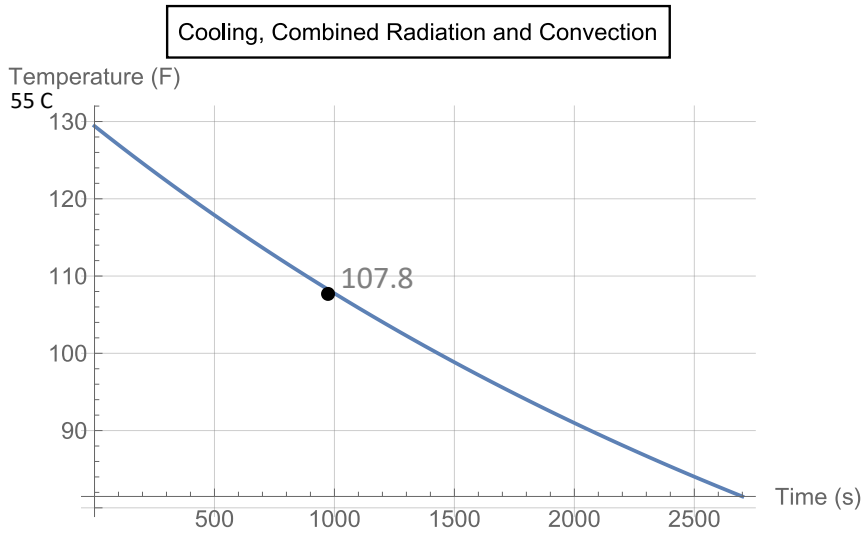
Radiation and Convection Cooling







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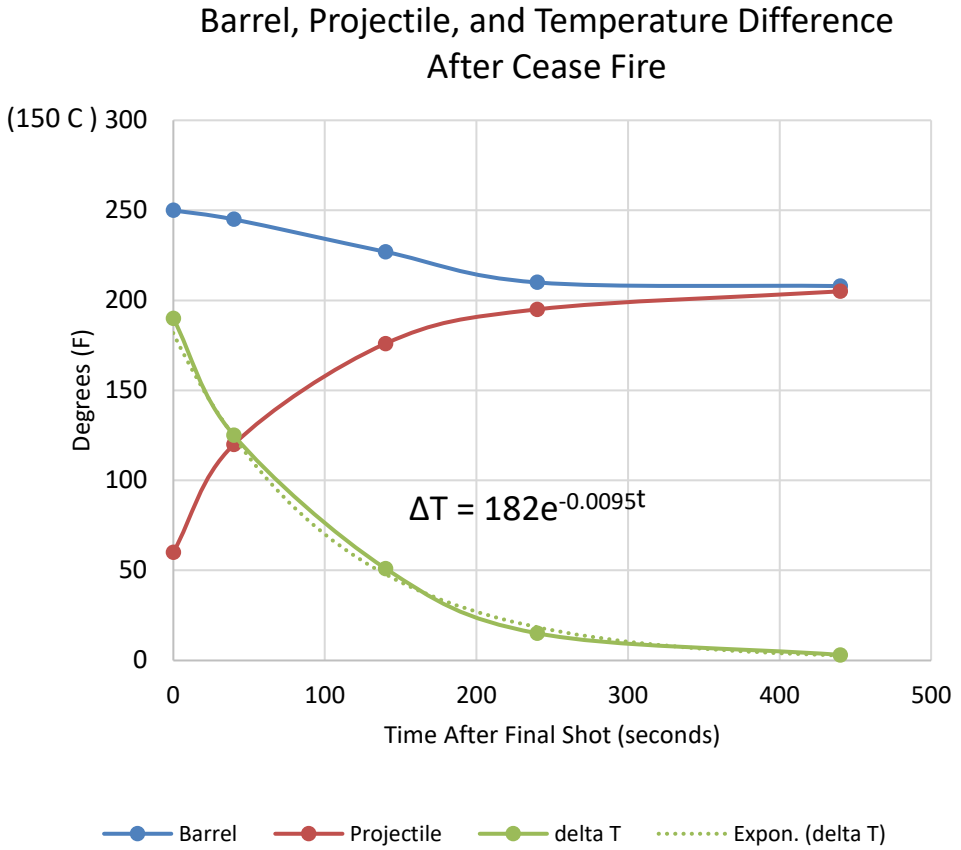
Barrel Heating a Projectile – *See the Poster for Details*

Laboratory apparatus to measure the heat transfer function of the barrel-to-projectile system with a segment of a barrel and instrumented cartridge. The difference between barrel temperature and the projectile temperature allows direct calculation of the heat transfer coefficient as shown on the left.



Experimental data shows the difference between the barrel and projectile in gun firing and cooling follows a curve similar to Newton's Law, an exponential function

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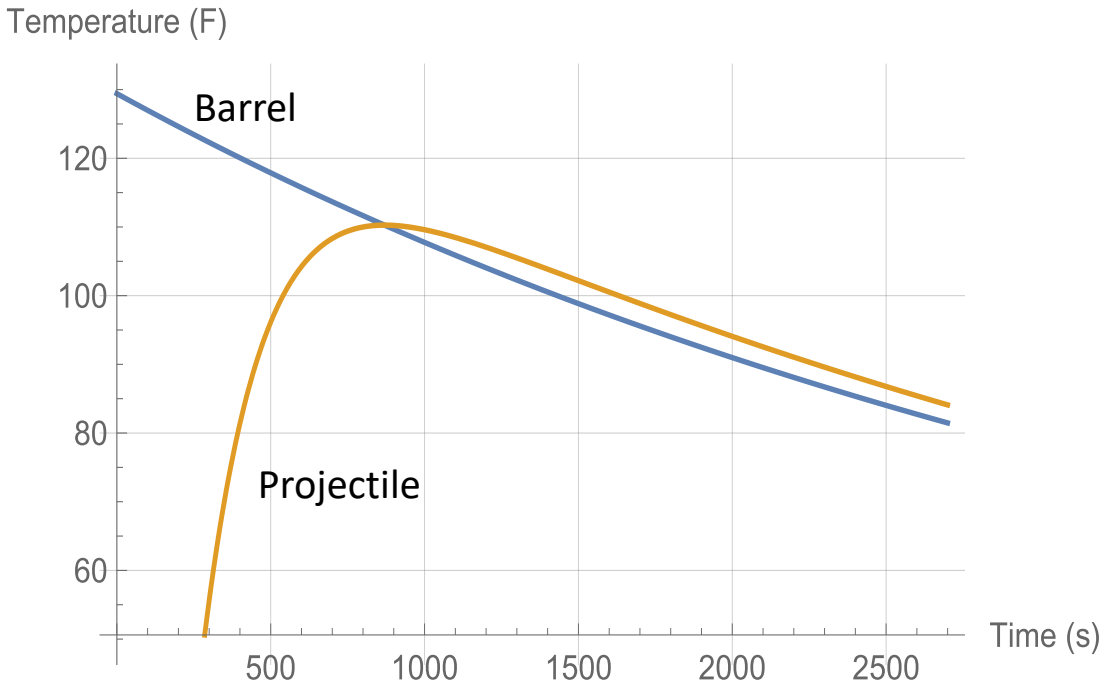
Calculation of Projectile Temperature and Experimental Data

Theory

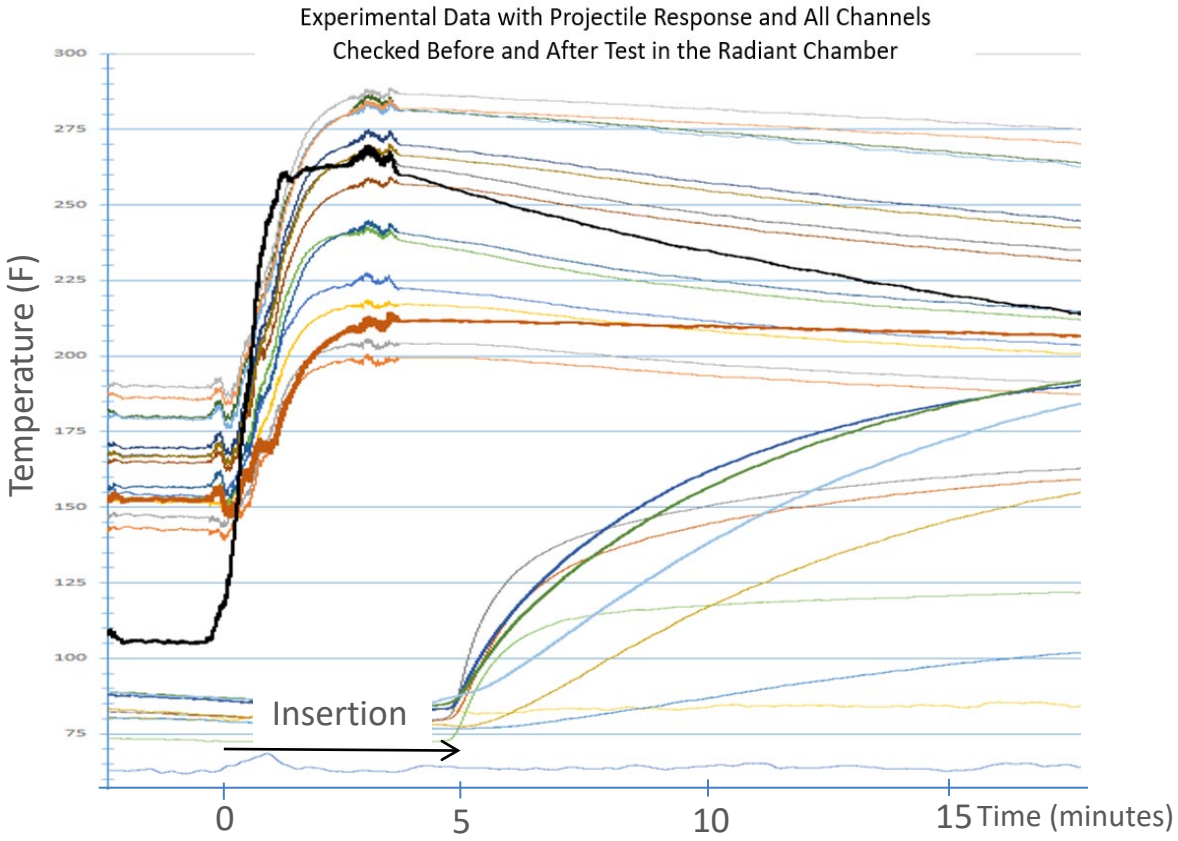
Barrel Cooling and Projectile Heating With Delayed Insertion



It took about 5 minutes to open the breech, insert the projectile and begin recording data

Experiment

Experimental Data, Barrel Above, Cartridge Below



The starting temperatures are staggered because the gun was cooling from previous firings

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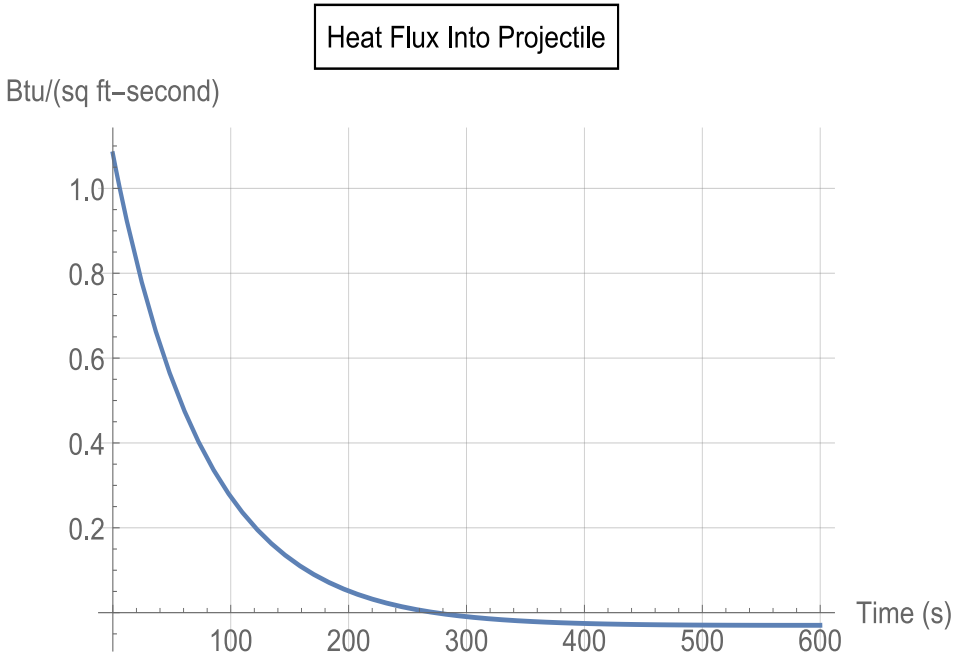
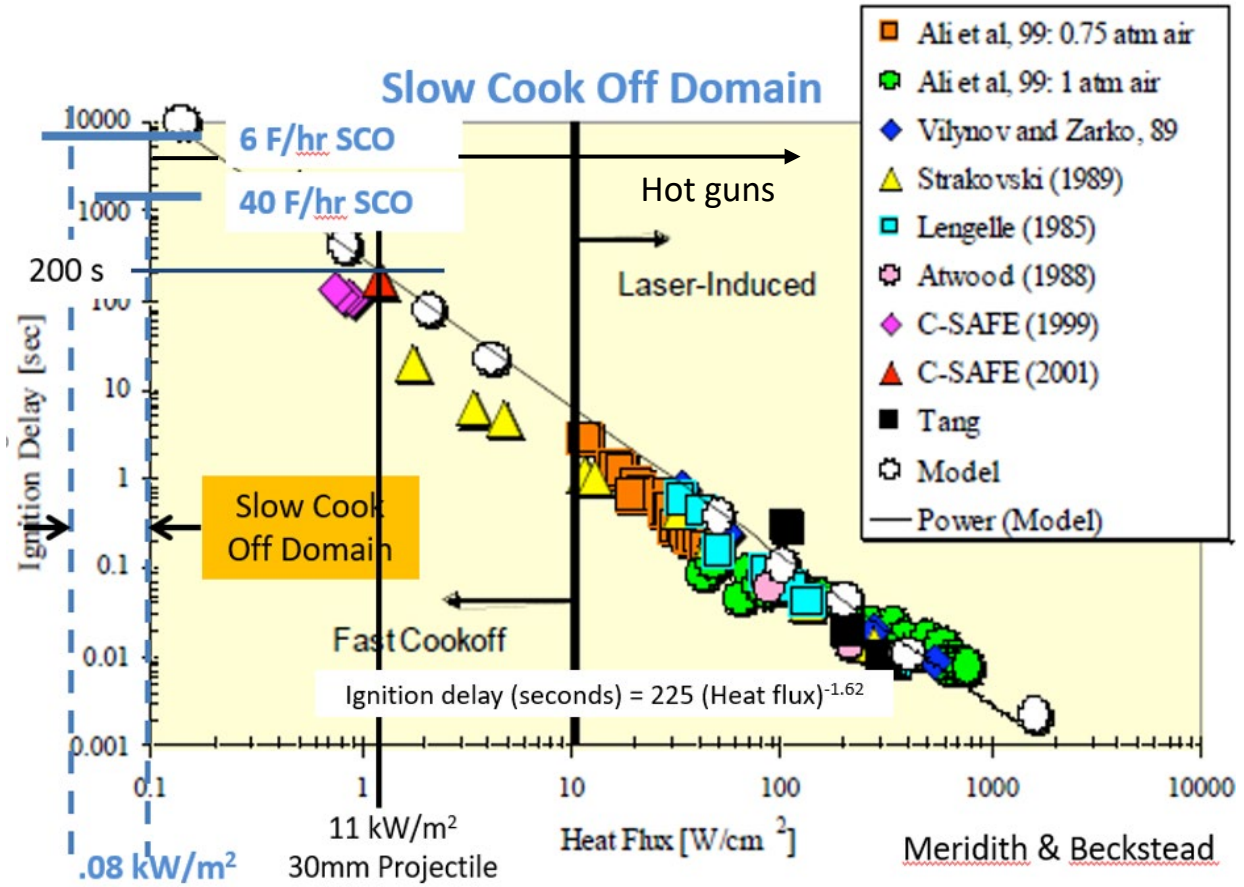
Estimating the Time to Cook Off



The heat flux can be calculated from the derivative (dT/dt) of the projectile temperature curve



Cook-Off

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Summary

- Knowledge from IM test development led to understanding of gun and projectile heating
- Barrel heating is caused by friction, convection, and radiation
- Convection is initially small and increases from 0 to its maximum value at the muzzle
- Radiation is from incandescent flames and entrained carbon
- Radiation can be the dominant heating mechanism in hypervelocity guns
- Barrel heating can be calculated
- Projectile heating and cook off can be predicted

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Kevin Ford
Albert Bauma
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Ephraim Washburn

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Lightweight IM Impact Protection System for Reducing Reaction of Solid Rocket Motors

2022 IMEM Technology Symposium
18-20 October 2022
Indianapolis, Indiana

Andrew Witzig (Lead Author)
Shearwater Technology Inc.
Washington, IL

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Overview:

- Problem Statement / Solution
- Program Overview
- Projectile Defeat Mechanisms
- Rocket Motor IM Protection Systems
- Ballistic Modeling and Simulation
- Motor Reactive Modeling and Simulation
- Testing and Validation
- Conclusions

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Problem Statement / Solution:

Problem Statement:

- As seen in recent global conflicts, Insensitive Munition (IM) technologies provide key tactical and strategic value for protecting personnel and materiel assets in the battlefield.
- Protection of tactical munitions while in storage, in transit, and in the battlefield is critical to mission success.
- Use of insensitive energetics (high explosives and propellants) may not be feasible to achieve performance requirements for existing and future weapon systems.

Solution:

- Novel, lightweight appliques/barriers for mobile missile launchers and transportation protection systems can be used to protect against bullet and fragment impacts in order to lower reactive response to Type V or better.
- Use of lightweight barrier systems as appliques or cannister inserts allow missile systems to use high performance energetics while retaining IM capabilities.

Program Overview:

ATC Materials, Inc. (ATC) successfully completed a Phase II SBIR program under the Army Research Laboratory (ARL). Team members: Shearwater Technology, Inc. and WA Gooch Consulting, Inc.

ATC has a long history of protection system development and production and has produced the Transportation Protection System (TPS) for the Missile Defense Agency (MDA) for in-transit protection of full-up missile rounds.

Program Achievements:

- Development of a modeling and simulation toolset for modeling ballistic performance of applique designs and reactive response of rocket motor.
- Development of a lightweight applique design capable of protecting AP-HTPB motors to Type V response level from **0.50-cal APM2 and FSP impacts at requirement velocities**.
- Development of novel manufacturing techniques to produce applique perforated strike plate.
- Validated applique design performance by conducting two live-fire FSP impact test events that produced Type V or better responses.
- Developed applique is a barrier system for reducing energetic response level and is not full-stop armor. Applique was designed to meet IM requirements of MIL-STD-2105D and associated STANAGs 4496 and 4241.

Phase II Program Resulted in the Development of Design & Manufacturing Methodologies that Can be Used Produce Lightweight, High-Performance Applique & Barrier Systems for IM Protection for a Wide Array of Weapon Systems.

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Rocket Motor IM Protection Systems:

Lightweight protection barriers are not meant to perform as armor that completely arrests the threat projectile.

Instead, the primary design philosophy of the barrier is to:

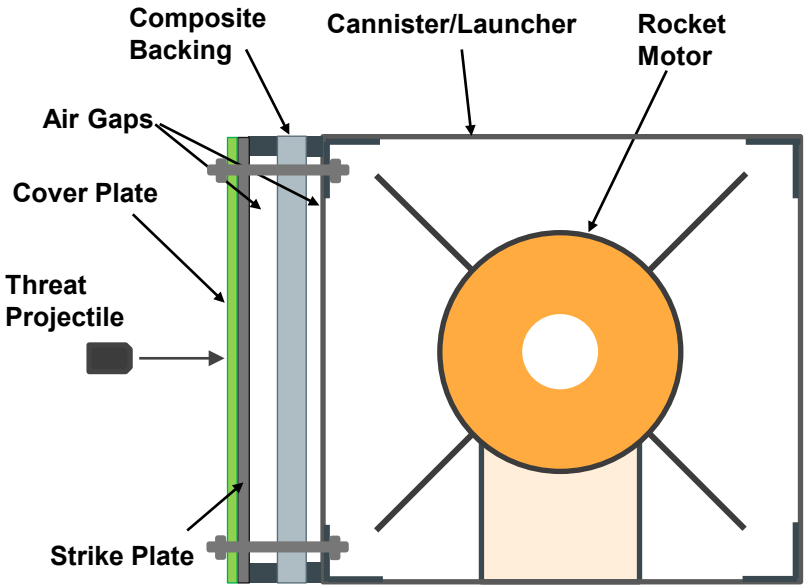
- **Fracture** the incoming threat
- **Spread** and divert debris
- **Capture** energy and momentum prior to motor impact.

Barrier system components & purposes:

- Strike plate – key driver of projectile fracture
- Air gap – allows debris to disperse
- Composite backing – capture debris momentum and strip APM2 jacket

Benefits of Perforated Strike Plate/Composite Backing Architecture:

- Multi-hit performance
- Armor can function as integrated structural component

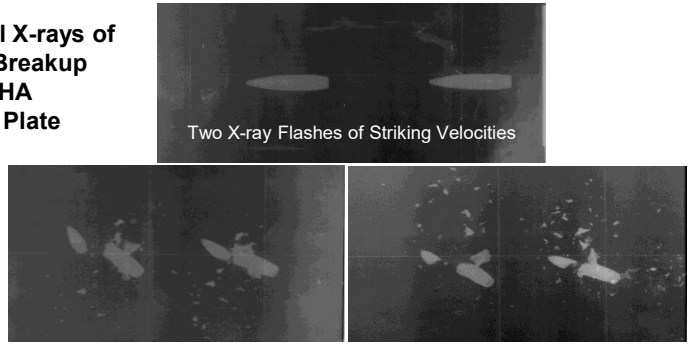


ATC Materials, Inc. Holds US Patent No. 14/661,860, "Lightweight Enhanced Ballistic Armor System" on this Enabling SBIR Developed Technology.

Projectile Defeat Mechanisms

- Primary defeat mechanism is an Ultra High Hard Armor (UHHA) perforated steel plate that induces projectile fracture.
- The strike plate perforations not only lower areal weight, but also, the angular cross-section imparts significant lateral forces on the projectile/fragment to induce further breakup, rotation, and off-axis disbursement of the residual debris.
- For jacketed AP threats the strike plate also strips the jacket from the core reducing the penetrator mass by 40%.

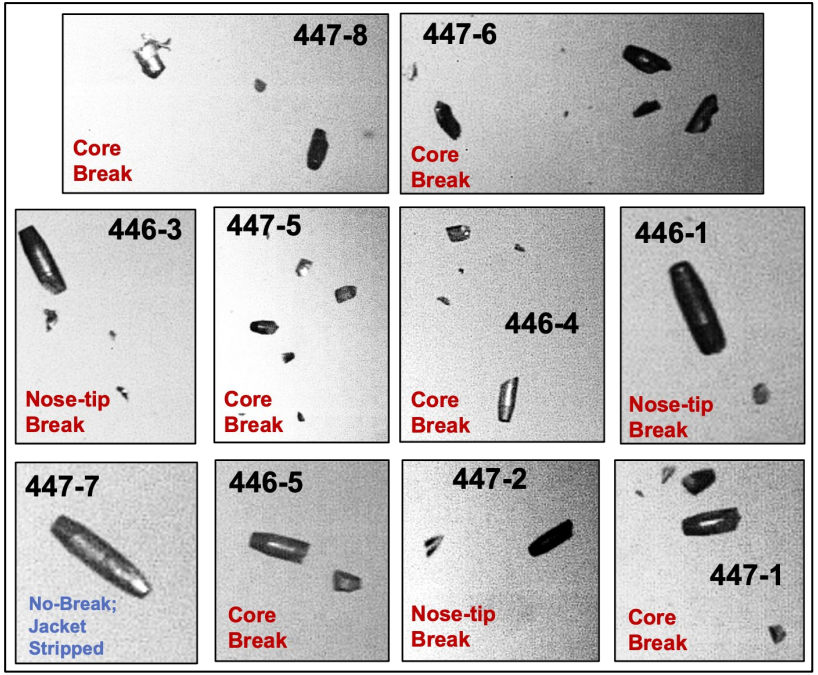
Orthogonal X-rays of Projectile Breakup Exiting UHHA Perforated Plate



Top View X-rays of Projectile

Side View X-rays of Projectile

High Speed Images of Residual Debris From 0.50cal APM2 Ballistic Test Impacts Against ATC Barrier System



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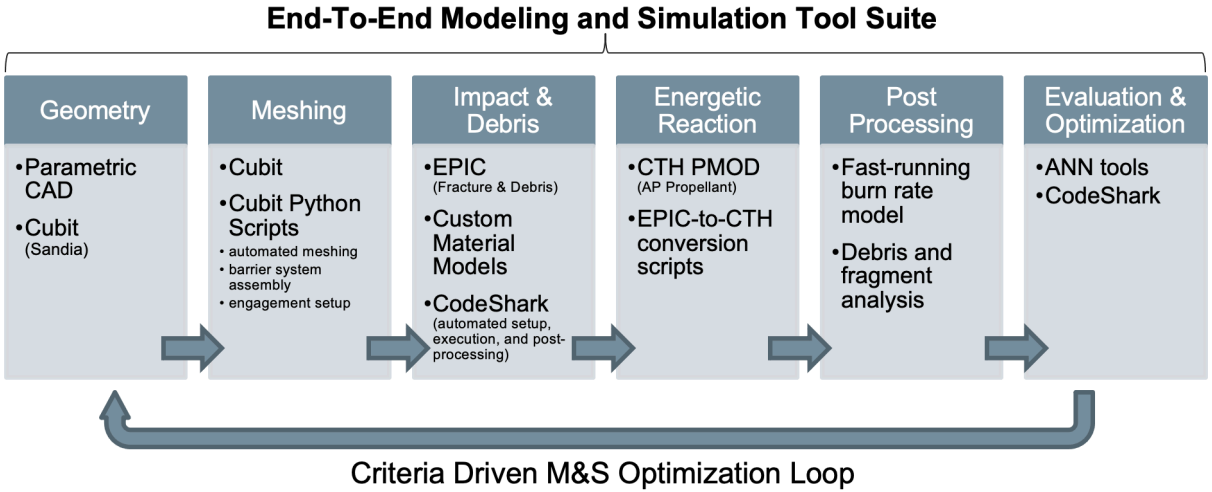
Modeling and Simulation Tool Suite:

- An end-to-end modeling and simulation tool suite was developed for evaluating the performance of protection system designs.
- EPIC18 was used for ballistic impact modeling; CTH was used for modeling reaction response of rocket motor.
- The tool suite allowed for rapid turnaround of design iterations and processed thousands of impact scenarios.



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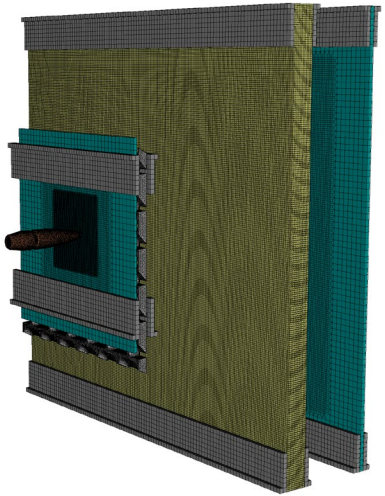
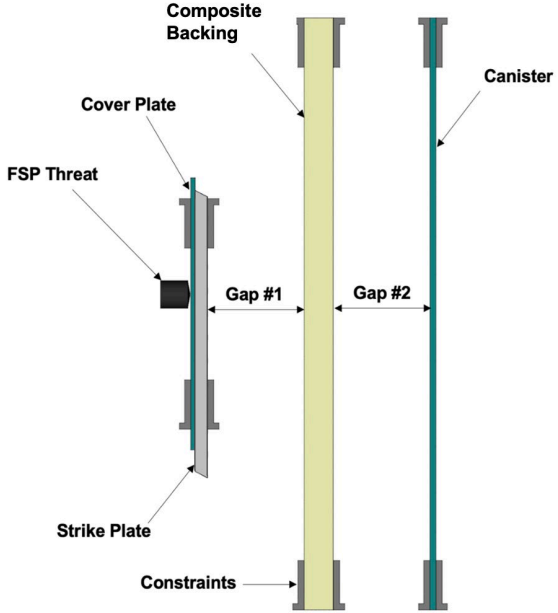
Ballistic Modeling and Simulation Setup:

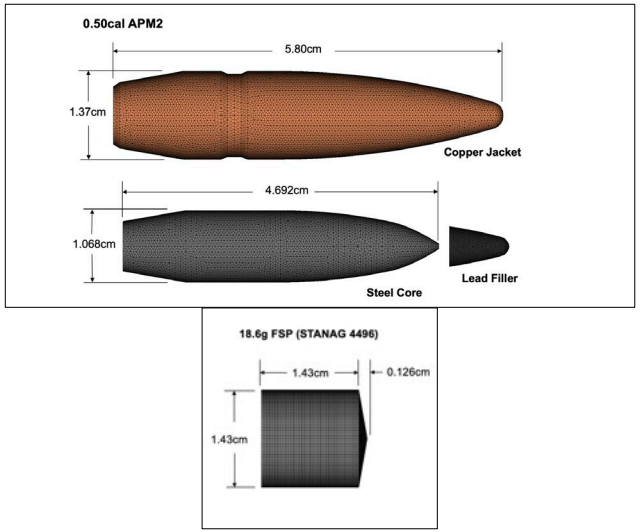
- The geometry/mesh model for the EPIC18 ballistic model for evaluating the barrier system performance is shown in images below. The Mesh was generated using the Cubit (Sandia) software.
- Material Models: Johnson-Cook Strength and Failure; Mie-Gruneisen EOS; Composite used hybrid method with bars for fiber and elements for epoxy matrix. Custom material model developed for UHHA steel strike plate.

Barrier System Geometry/Mesh Model





Threat Geometry/Mesh Model



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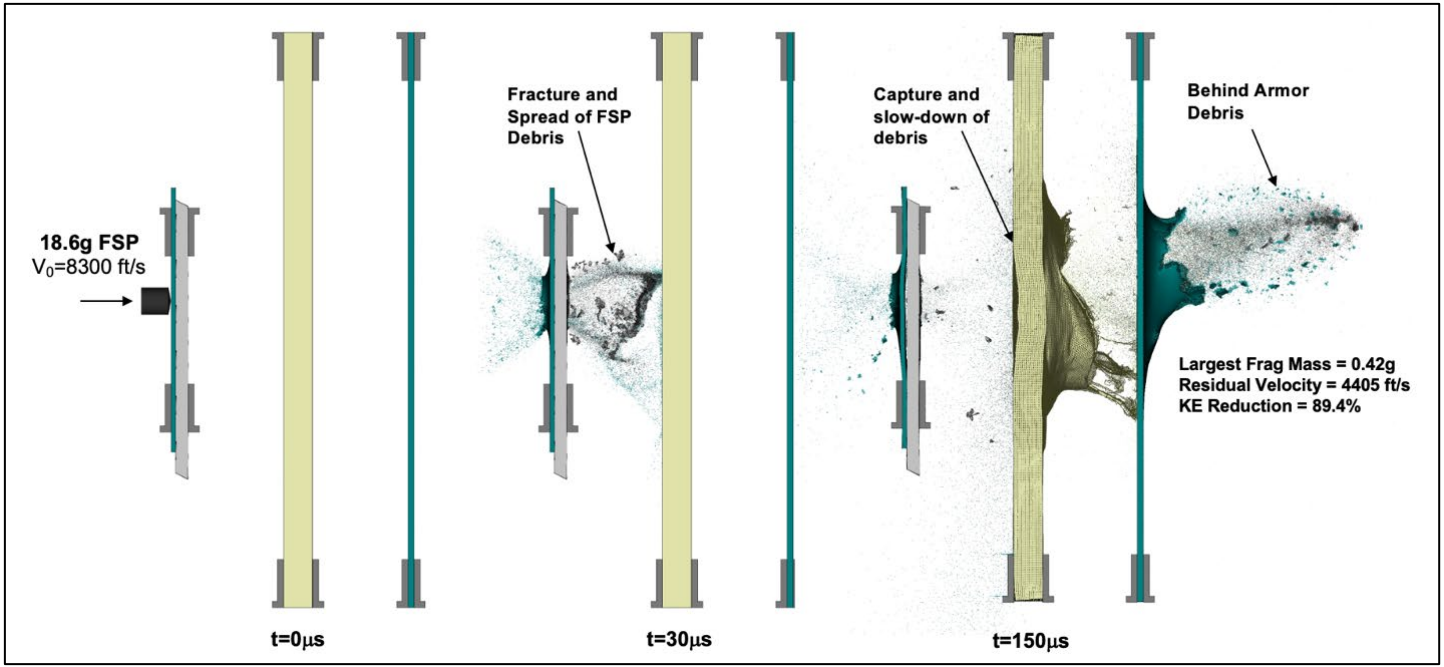
Sample FSP Ballistic Simulation Results:

- EPIC18 was used to simulate an 18.6g FSP impacting the ATC barrier system at 8300 ft/s.
- The FSP is highly fractured by the strike plate and the debris cloud spreads prior to capture by the composite layer.
- In this case the fragment behind armor debris was slowed to 4405 ft/s and reduced KE by 89%.



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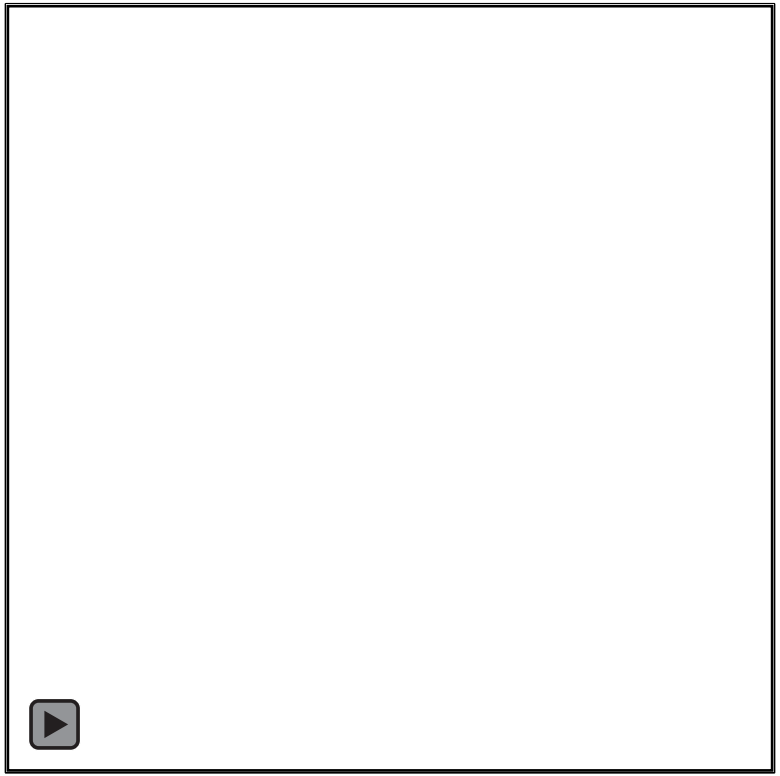
Sample Animation of FSP Impact Simulation:

18.6g FSP impacting the ATC barrier system at 8300 ft/s.



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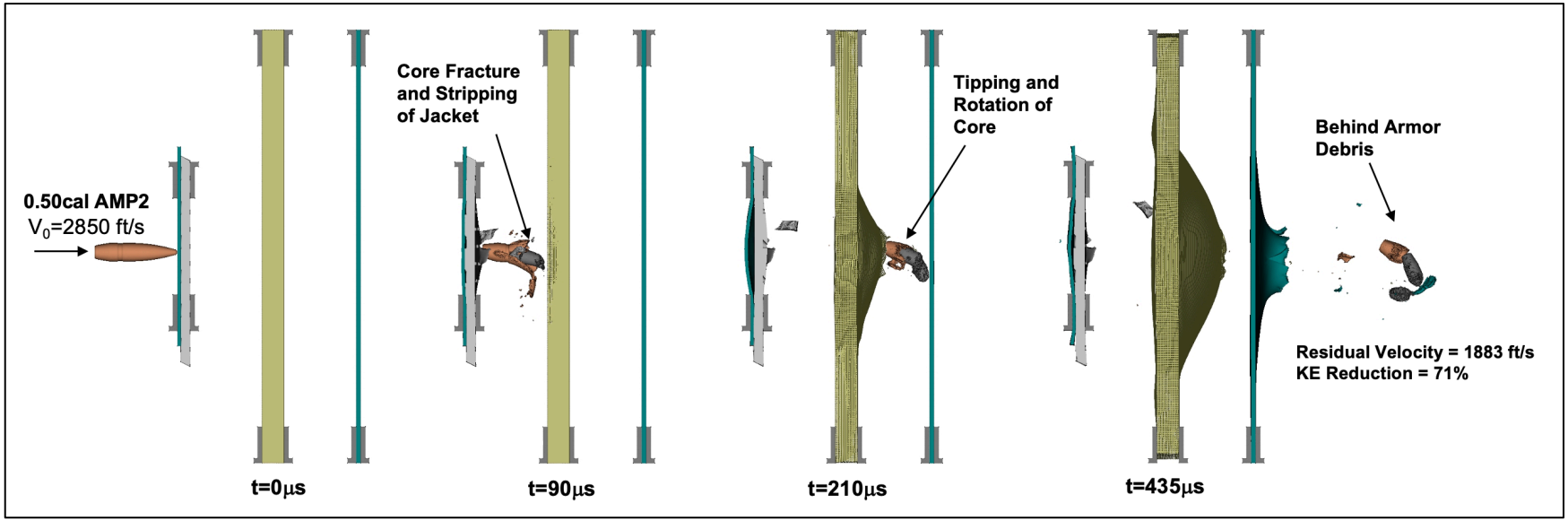
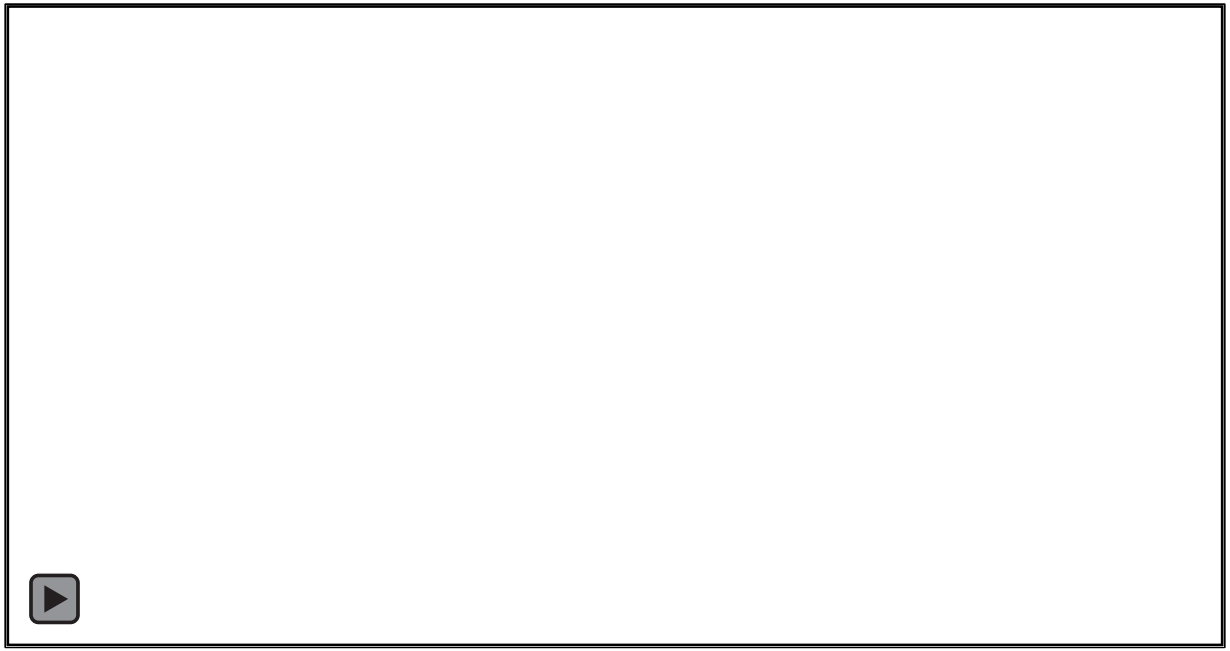
Sample 0.50cal APM2 Impact Simulation Results:

- EPIC18 was used to simulate a 0.50cal APM2 round impacting the ATC barrier system at 2850 ft/s.
- The AP core is fractured, and the jacket is stripped away from the core debris.
- In this case the fragment behind armor debris was slowed to 1883 ft/s and reduced KE by 71%.



Sample Animation of 0.50cal APM2 Impact Simulation:

0.50cal APM2 projectile impacting the ATC barrier system at 2850 ft/s.



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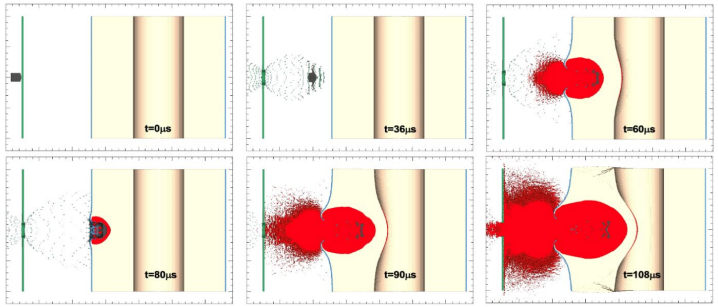
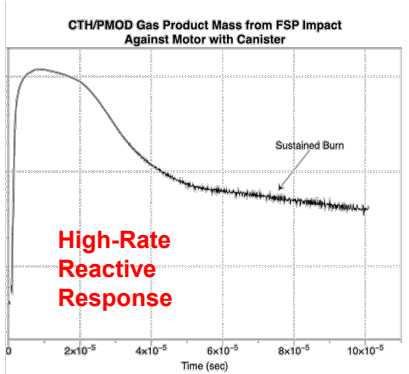
Rocket Motor Reaction Modeling:

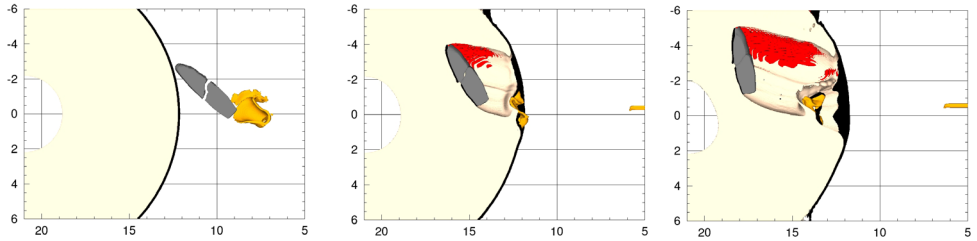
- CTH PMOD Reaction Model was used to model AP-HTPB rocket motor reactive response to impact stimulus.

FSP Impact at 8300 ft/s – Canister Only / No Protective Barrier





Single 50cal APM2 Impact – Post Armor Debris Converted from EPIC

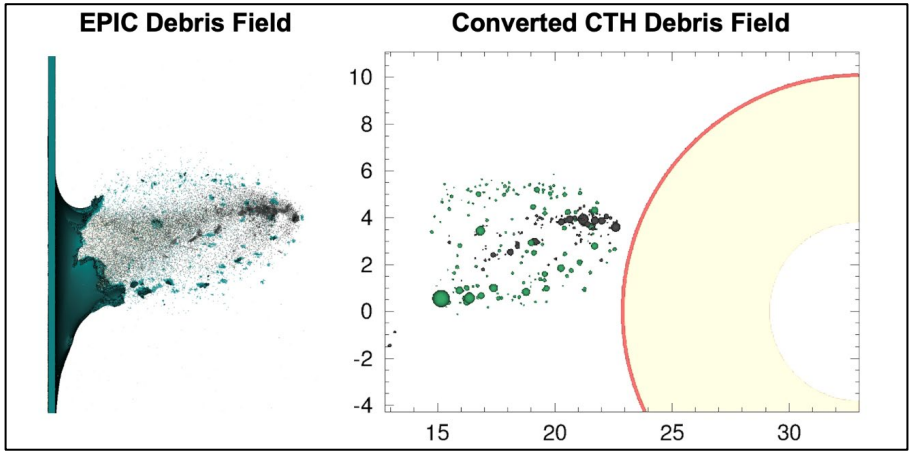


Low-Rate
Reactive
Response

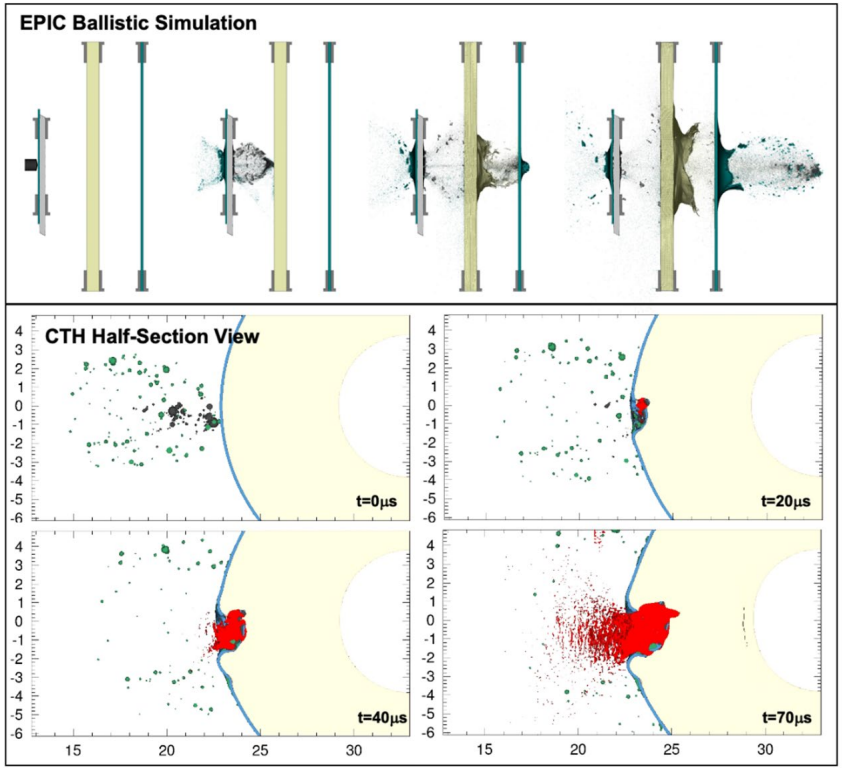
Debris Cloud Conversion to CTH:

EPIC debris fields predictions from FSP impacts were converted to CTH by inserting spherical fragments of equivalent material composition, mass, position, and velocity vectors into the CTH numerical domain.

The position state of the debris cloud was scaled back in time to ensure that the cloud tip was positioned ahead of motor just prior to impact.

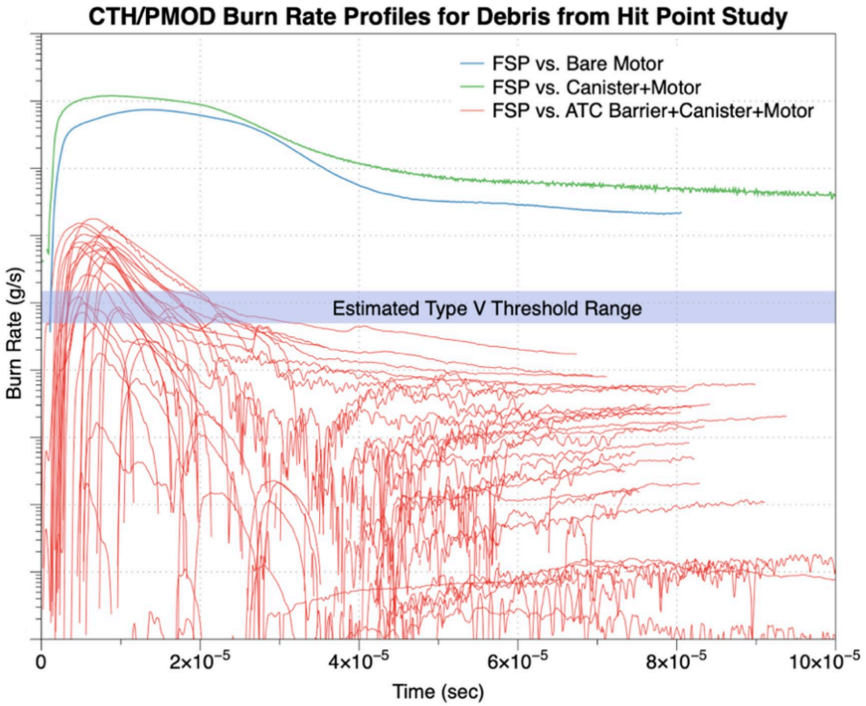


FSP Ballistic Impact Simulation Converted to CTH for Reactive Modeling



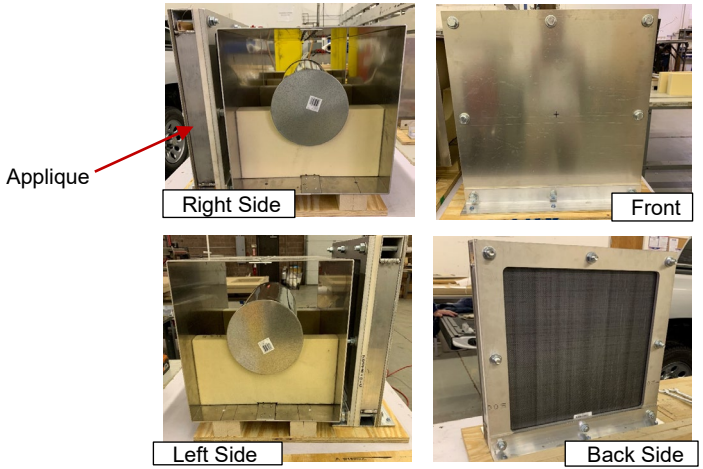
Reaction Rate Threshold Estimation:

- Consumption times of the live-fire surrogate rocket motor on the order of 10's of seconds and were estimated to be Type V reaction outcomes.
- A numerical hit-point method was used to sample the barrier system strike plate perforation pattern to obtain a range of reaction rate data for the system. These simulations included the coupled EPIC18/CTH 3D modeling methodology.
- All hit locations measured for FSP at 8300 ft/s yielded sustained burn rates below the estimated Type V thresholds.



NTS Live Fire Test Series:

- Two full-scale live rocket motor tests were conducted at NTS Camden, AK
- The final IM design was an externally mounted IM applique designed to provide a Type V response from rocket motor under STANAG impact conditions.
- The live rocket motor testing was conducted with two IM fragment impact tests at 8300-fps as this threat exhibited the worst impact conditions and is a primary threat to missile system.



Fabrication of Test Array with Applique and Canister

Aluminized HTPB Surrogate Rocket Motor Fabricated by R3 Aerospace

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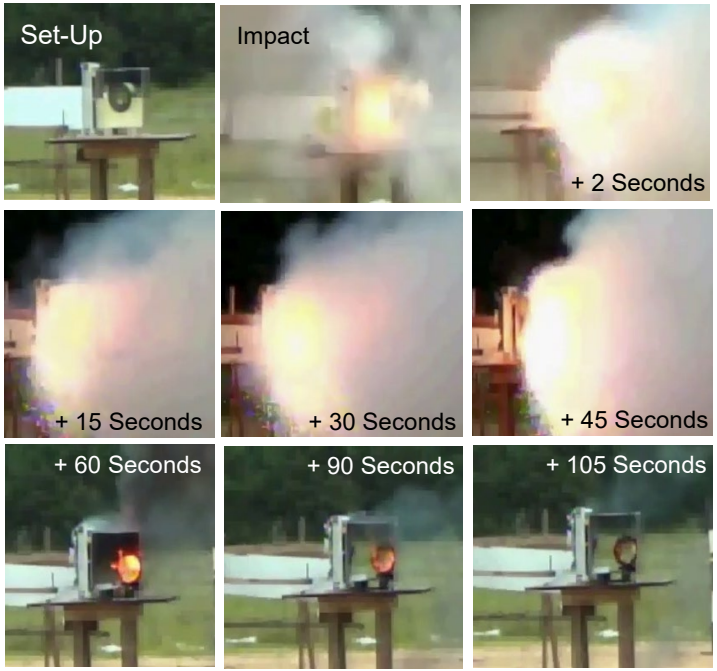
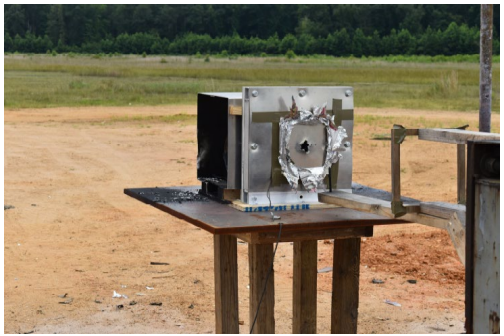
Live Fire Test TS-1: FSP Impact V_0=8515 ft/s

- TS-1 impact velocity was 8515 ft/s and propellant burn time was 57 sec.
- Test stand and canister stayed intact, and motor burned out in-place. Outcome was Type V response.

Test Outcome:
Slow Burn
(Type V Response)





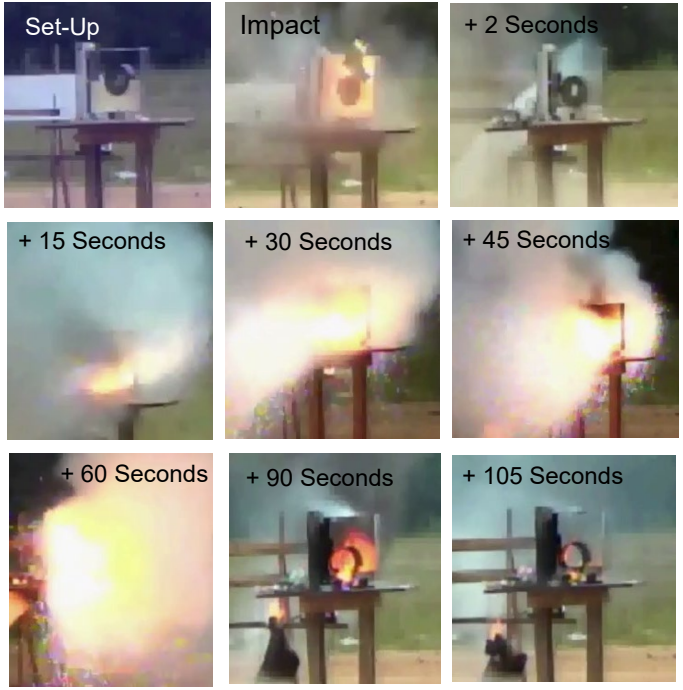
(U) Front side of barrier assembly

(U) Burnt out motor case still intact

Live Fire Test TS-2: FSP Impact V_0=8415 ft/s

- TS-1 impact velocity was 8415 ft/s and propellant burn time was 107 sec. with delayed ignition.
- Test stand and canister stayed intact, and motor burned out in-place. Outcome was Type V response.

Test Outcome: Slow Burn (Type V Response)



Front side of barrier assembly

Burnt out motor case still intact

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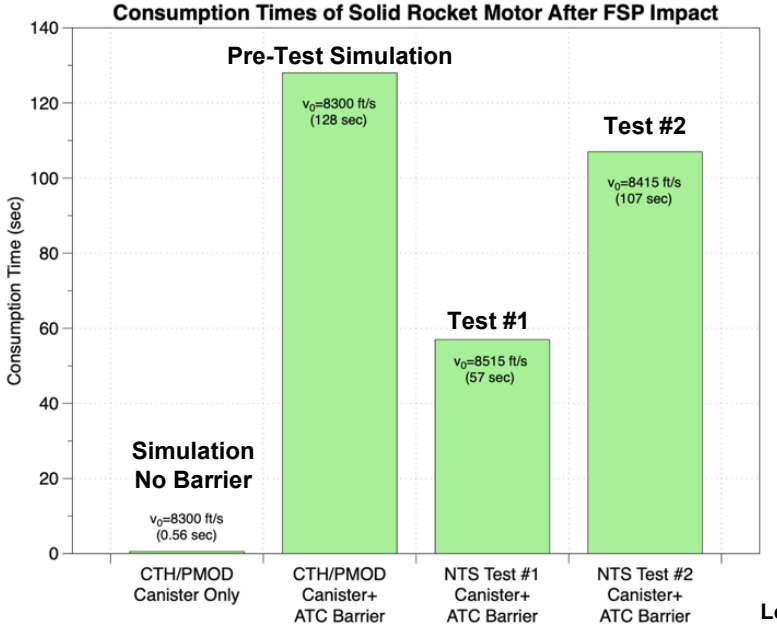
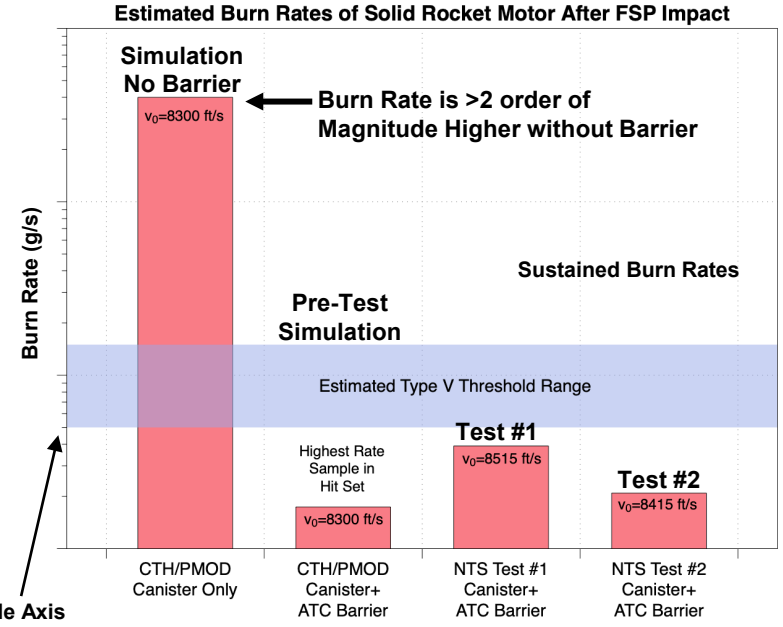
Live Fire Test TS-2 Video:

- 18.6g FSP impact against AP-HTPB rocket motor at 8415 ft/s.

Comparison of Simulation and Test Results:

- Pre-test simulation burn rate and consumption time predictions compared well with test, especially considering that burn rates can span several orders of magnitude.
- Low reaction rates correlate with Type V seen in both tests.





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(U) Final Design Performance Predictions:

- The final design areal density is less than 12 lb/ft^2
- The table below lists performance predictions for the Phase II ATC barrier system base on test and simulation results.

18.6-g STANAG FSP at 8300-ft/s:
KE reduction = 80 - 90%
Probability of Type V outcome = 98%
0.50-Cal APM2 at 2850-ft/s:
KE reduction = 0.60 - 85%
Probability of AP core fracture = 50%
Probability of Type V outcome = 100%

ATC Barrier System Provides High Level of Protection Against AP and FSP Threats for AP-HTPB Propellant Based Rocket Motor

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Follow-On Work:

- While the current Phase II effort has ended, additional funding would allow for further development of the ATC barrier system.

- Additional testing should be performed to:
  1. Identify baseline motor response without a barrier.
  2. Identify motor response with realistic confinement and nozzle aperture.
  3. Provide additional data for validating simulation reaction rate predictions.

- Development and implementation of damage sensitization models for AP-HTBP propellant to support evaluation of multi-hit 0.50cal APM2 scenarios (e.g. triple-fifty tests).

- Continued refinement of strike plate design and manufacturing to further optimize performance and reduced manufacturing costs.

- Investigation of additional of composite backing materials to further reduce system areal density.

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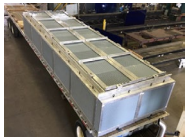
Barriers as an IM Solution

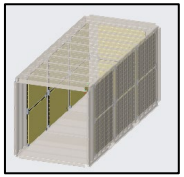
Ballistic barriers decouple performance and safety in energetics allowing for munition enhancement while maintaining IM compliance

Historic view

With barriers as an IM solution

IM compliance…	ATC barriers
…does not address common threats	Meets Type V for “triple-fifty,” and fragment
…is energetic specific	>80% KE reduction likely provides Type V or better for all munitions
…reduces performance	Decouples IM compliance from performance allowing energetic enhancement while maintaining safety
…negatively impacts logistics	Minimal impact and may be integrated directly into future containers, canisters, and launchers





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Summary:

Demonstrated IM Compliance via Ballistic Barriers
ATC Phase II effort successfully developed and demonstrated an armor to provide IM compliance for munitions, solving a major problem for the Army as many current programs are not in compliance with bullet (STANAG 4241) and fragment (STANAG 4496) IM requirements outlined in MIL-STD-2105.

Significant Reduction in Reaction
The Phase II prototype reduced reactions to Type V for a typical rocket motor with aluminized ammonium perchlorate (AP) solid propellant.

Development & Validation of Modeling and Simulation Tool Suite
The team further developed modeling and simulation tools that will allow additional optimization of ballistic barriers for IM compliance for other munitions and energetics.

Ballistic Barriers Enable Performance
ATC's barrier design provides a practical armor system which moves the safety burden from energetics to the ballistic barrier enabling pursuit of greater performance by decoupling energetics and safety.

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

SR Barriers for IMX-104 Filled Artillery Projectiles

Kevin T. Miers, Keyur M. Patel, Jacek Foltynski, Nausheen M. Al-Shehab

2022 Insensitive Munitions and Energetic Materials Technology Symposium

Indianapolis, IN, USA

Presented by Kevin T. Miers, Mechanical Engineer
US Army DEVCOM AC Detonation Physics and Experimental Research Branch
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OUTLINE

- SR Testing and Phenomenology, Item of Interest
- Logistical Analysis
- Computational Considerations
- Barrier Concepts
- Donor Modeling Considerations
- Acceptor Modeling Considerations
- 2D Plane Strain Models
- Constrained Nonlinear Optimization for 2D Plane Strain
- 3D Models
- SR Testing
- Summary and Conclusions; Future Work

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SR TESTING FOR 155MM ARTILLERY PROJECTILES

- Initiation and expansion of donor
- Shock loading and deformation of acceptors
- Various initiation/ignition mechanisms
- Current item of interest: 155mm IMX-104 filled artillery projectiles
- 8 rounds per pallet, multiple pallets
- Projectile known to fail SR in this configuration - Try modeling

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LOGISTICAL ANALYSIS

(https://www.armadainternational.com/2021/01/rethinking-resupply-to-the-forward-line/)

- 155mm artillery usually weighs out before it cubes out
- Removing a single pallet provides ample trade space

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COMPUTATIONAL CONSIDERATIONS

- Modeling performed in LLNL ALE3D code
- Inert materials: Gruneisen EOS, Johnson-Cook Strength, Johnson-Cook Failure
- Air: Gamma law gas
- Donor explosive: JWLB programmed burn with augmented beta burn
- Acceptor explosive: Lee-Tarver Ignition and Growth

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BARRIER CONCEPTS

- Standard mitigation methods: Reduced sensitivity fills, more ductile fills, and barriers/buffers
- Barriers widely studied since at least 1970s
- Metals, plastics, foams, geological materials, etc.
- Some easier to model than others
- Geometry: flat panels, tubes, diamond bars, etc.
- Packaging materials are sunk costs
- Polymer buffers frequently used to attenuate shocks – good place to start

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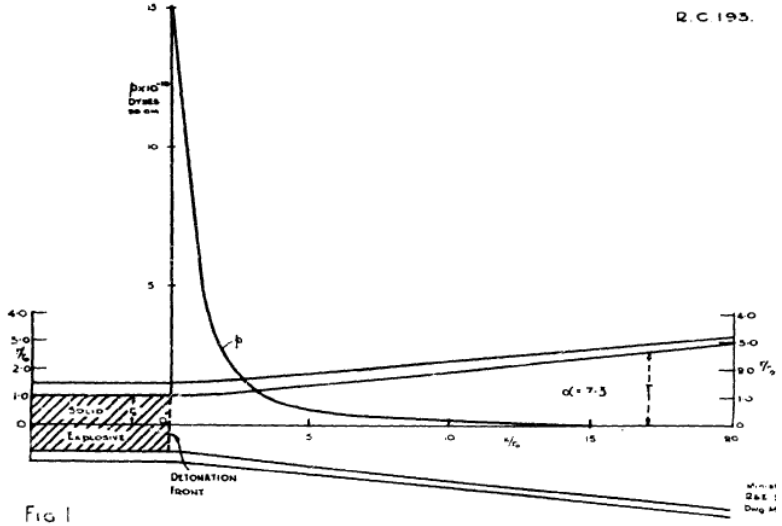
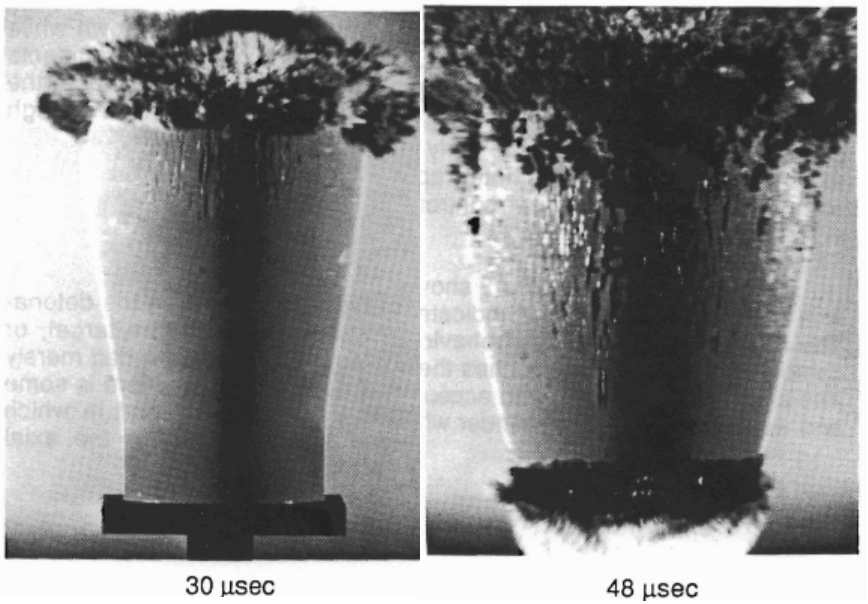
DONOR MODELING CONSIDERATIONS

- Standard mitigation methods: Reduced sensitivity fills, more ductile fills, and barriers/buffers
- Barriers widely studied since at least 1970s
- 2D plane strain: not that physically realistic
- 3D: reactive flow for donor?
- Fragmentation at r/r0 < 1.7, but may behave more like flyer plate in diagonal direction





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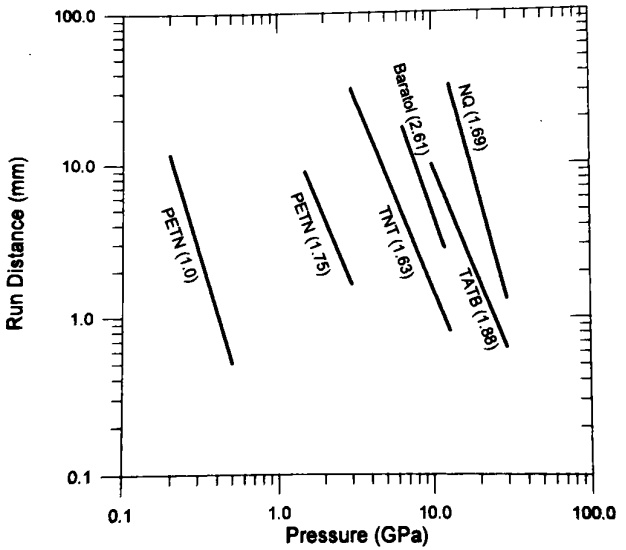
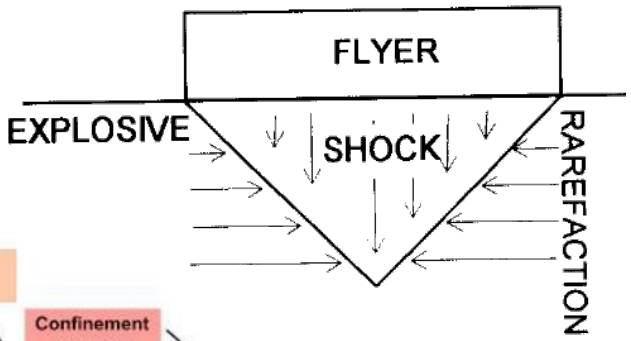
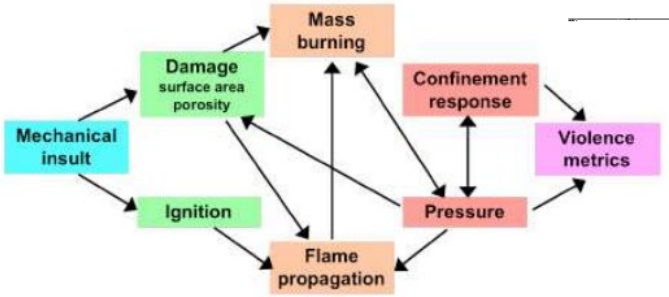
ACCEPTOR MODELING CONSIDERATIONS

- Geometric complexity - need reactive flow modeling
- Lee-Tarver Ignition and Growth
- Rate law; T, P equilibrium for partially reacted states
- Requires very fine zoning (multiple cells through reaction zone)… Try 2D
- Won't address other ignition mechanisms, shock desensitization







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2D PLANE STRAIN MODELS

- Constant volume detonation least unrealistic
- Average wall thickness used
- 50 zones/cm, 2.5M zones
- Need to run to ≥ 200us → approx. 2 hrs wall clock
- The baseline configuration mass detonates

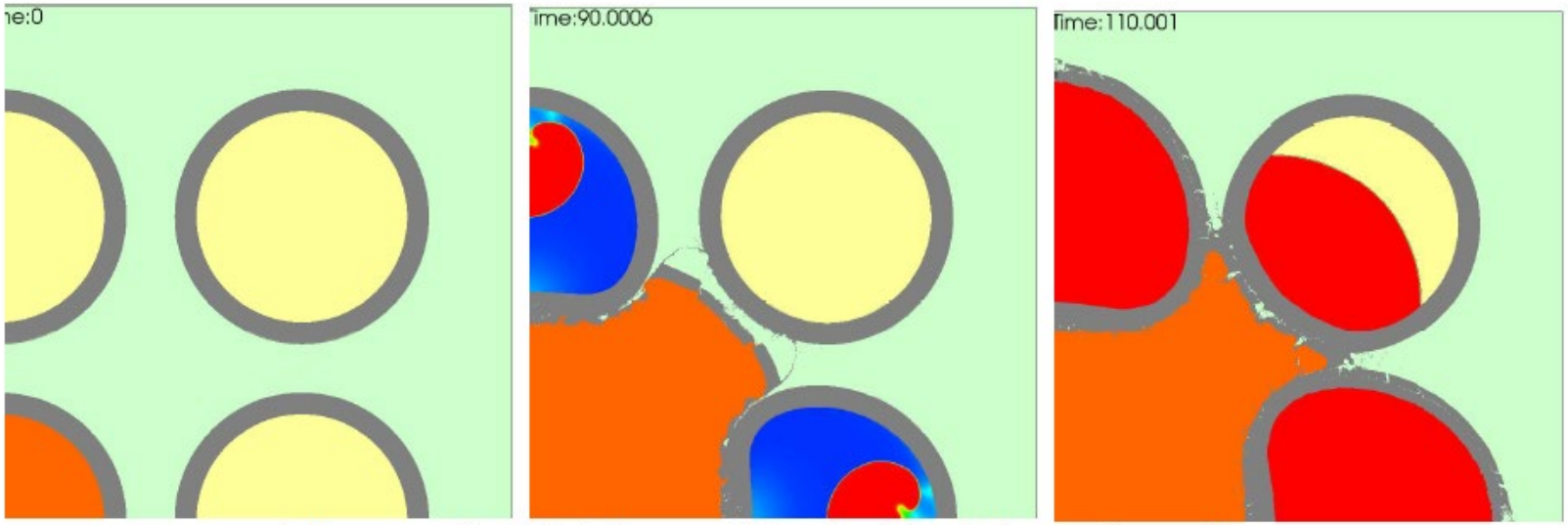

Figure 2. 2D Plane Strain Models – Baseline

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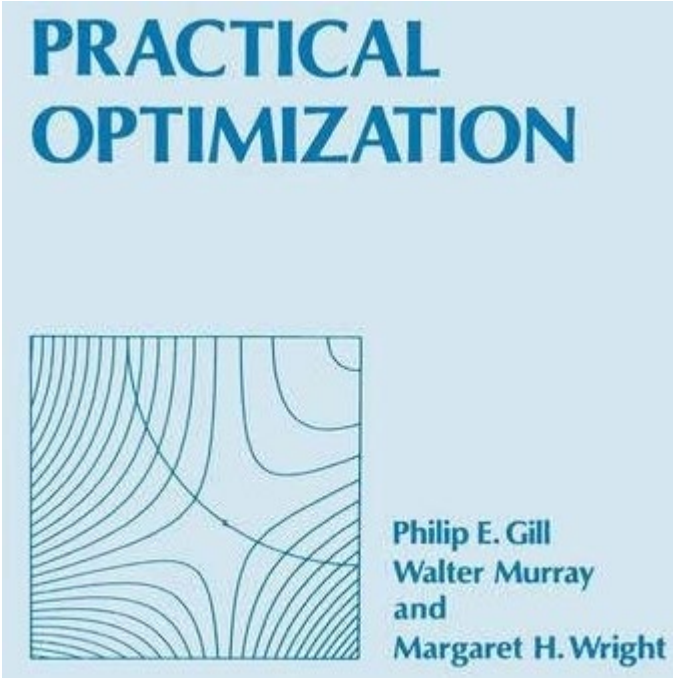
2D PLANE STRAIN MODELS – NONLINEAR OPTIMIZATION

- Various barrier models investigated - long run times
- MATLAB fmincon
- Minimize barrier weight (linear function) subject to:
- Bound constraints: non-negative thickness
- Linear inequality constraint: total thickness less than round spacing
- Nonlinear inequality constraint: F comfortably below 1 in IG model
- Piece of cake?

$$\begin{aligned} \underset{x \in \mathbb{R}^n}{\text{minimize}} \quad & F(x) \\ \text{subject to} \quad & c_i(x) = 0, \quad i = 1, 2, \ldots, m'; \\ & c_i(x) \geq 0, \quad i = m' + 1, \ldots, m. \end{aligned}$$



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2D PLANE STRAIN MODELS – NONLINEAR OPTIMIZATION PROOF OF CONCEPT

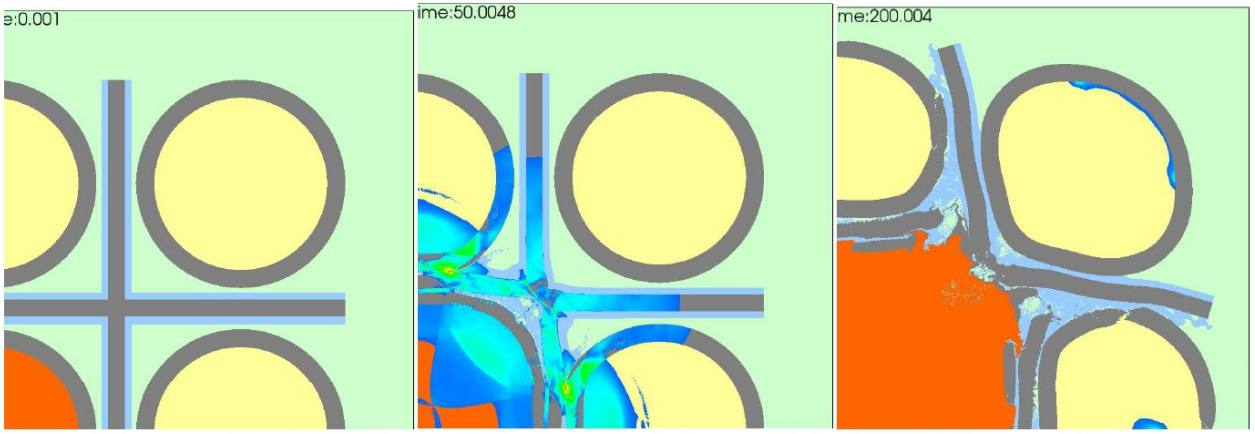

Figure 3. 2D Plane Strain Models – ALE3D Polymer/Steel

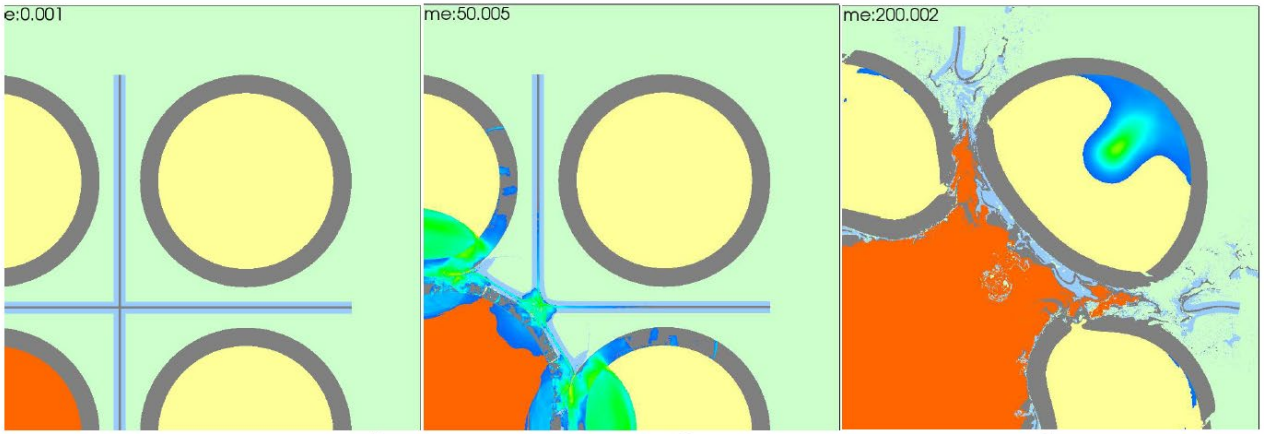

Figure 4. 2D Plane Strain Models – Optimized Polymer/Steel Design

- Initial feasible point, was hard to find
- Looks like a thin plastic buffer will suffice – Try 3D

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3D MODELS

- Reactive flow, 7.5 zones/cm, 40M zones, out to 300us
- Appears the baseline configuration mass detonates, polymer tube configuration does not – Try testing

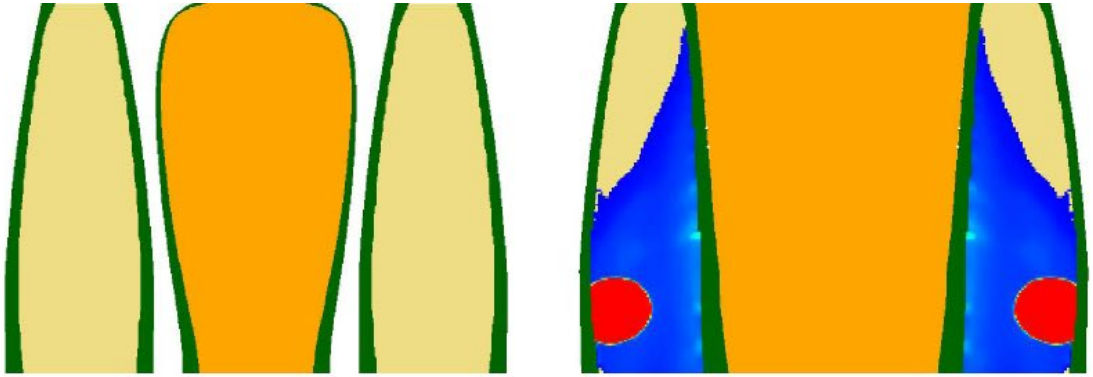

Figure 5. Baseline 3D Model Results

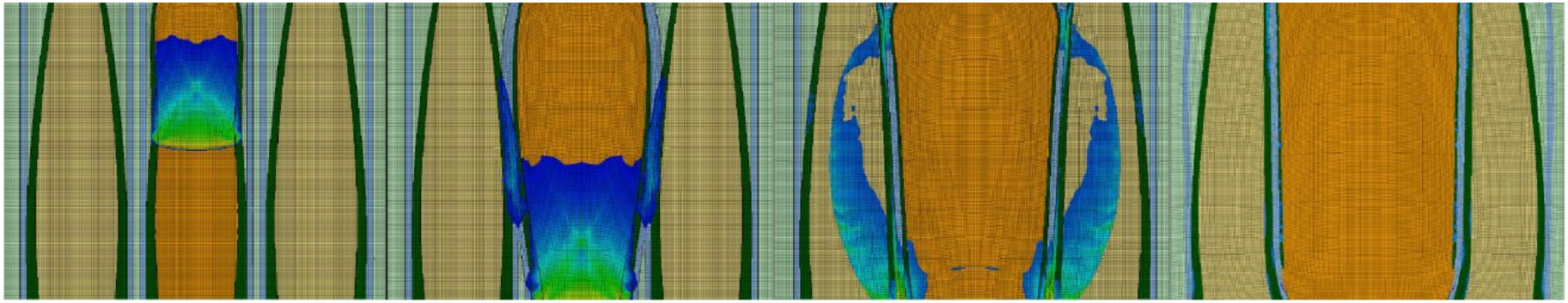

Figure 6. Sample 3D Calculation with Polymer Tube Barrier

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SR TESTING - BASELINE

- 2 pallets adjacent to each other (4 rounds x 4 rounds)

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SR TESTING – POLYMER TUBE BARRIERS

Configuration	Single Projectile	Unconfined SR	Polymer Tubes SR
Overpressure (Relative)	1.0	6.2	0.7

SR pass produces less overpressure than single round!

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SUMMARY AND CONCLUSIONS, FUTURE WORK

- Computationally designed IM barriers to get IMX-104 filled 155mm artillery projectiles to pass SR
- Polymer tube design protects against propagation between pallets and satisfies logistical requirements
  - This design was scored with a passing reaction by the U.S. Army IM Board
  - Stands to be even further optimized!
- Design likely also passes bullet and fragment impact, if any protection needed at all
- Barriers being considered for integration into the packaging
- Other future work – further optimization and demonstration of this and similar concepts, applied to this and similar munitions

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QUESTIONS

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

STEEL FI BARRIERS HARDNESS AND OBLIQUITY EFFECTS

Kevin T. Miers, Daniel L. Prillaman, Eric A. Lynd, Nausheen M. Al-Shehab

2022 Insensitive Munitions and Energetic Materials Technology Symposium
Indianapolis, IN, USA

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OVERVIEW

- NATO IM Fragment Impact (FI) testing
- Penetration mechanics considerations
- High hardness armor steels
- Experimental methodology
- Test Results
- Discussion and preliminary hydrocode models
- Summary and conclusions

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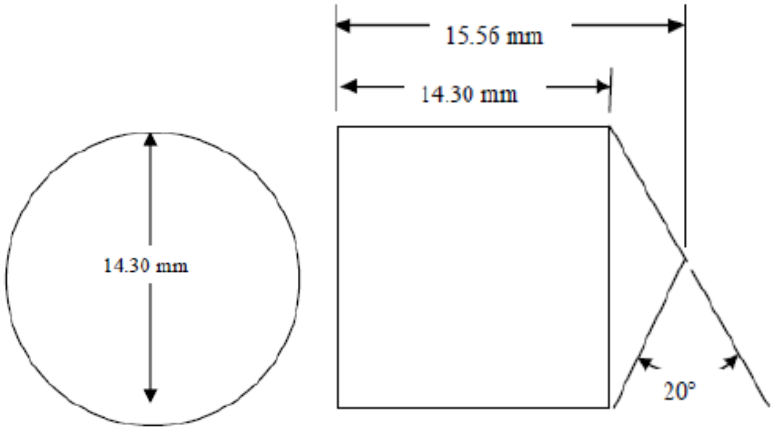
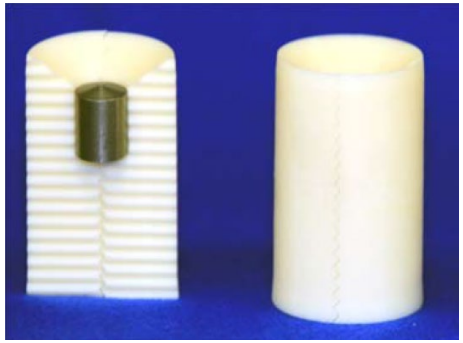
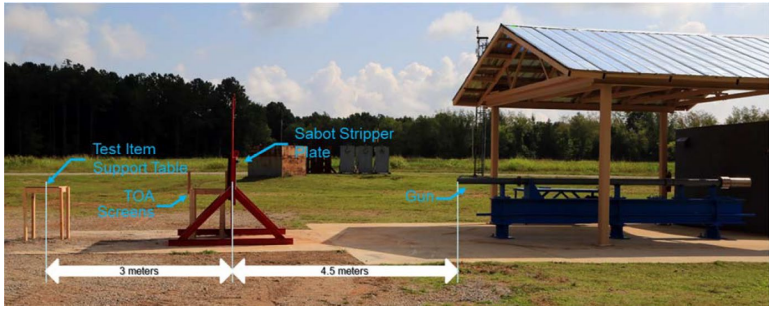
NATO IM FRAGMENT IMPACT TESTING

- NATO standard FI test (STANAG 4496) [1]
  - 14.3mm diameter, 18.6g, L/D~1, 160° conical nosed fragment
  - Mild steel, Brinell hardness <270
    - **New requirement: BHN > 190**
  - 2530±90 m/s impact velocity
  - Aimpoints: center of largest presented area of HE or most shock sensitive location
- Smooth bore 40mm powder gun often used in the U.S. [2]
  - Commercially available, used by various test facilities
  - Powder charge adjusted to obtain correct velocity
  - Replaceable wear section
  - Plastic sabot machined to fit







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NATO IM FRAGMENT IMPACT TESTING (CONT'D)

Steel	Treatment	Yield stress MPa	Yield stress ksi	Tensile stress MPa	Tensile stress ksi	Elongation, %
1020	Normalized	345	50	440	64	36
1040	(air cooled)	370	54	595	86	28
1095		505	73	1015	147	9.5
1020	As rolled	330	48	450	65	35
1040		415	60	620	90	25
1095		570	83	965	140	9

1018 commonly used

(from [3])

HRC	HV	HB(a)	HRA	HRB	Ultimate tensile strength MPa	Ultimate tensile strength ksi
29	294	279	64.7	(104.5)	931	135
28	286	271	64.3	(104.0)	910	132
27	279	264	63.8	(103.0)	883	128
(14)	213	203	…	93.9	676	98
(12)	204	194	…	92.3	648	94
(10)	196	187	…	90.7	621	90

~BHN 270

~BHN 190

Probably need to use higher carbon content steel (>1040)

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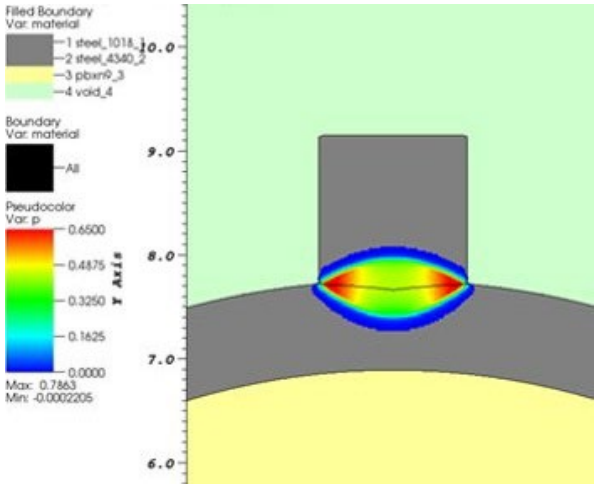
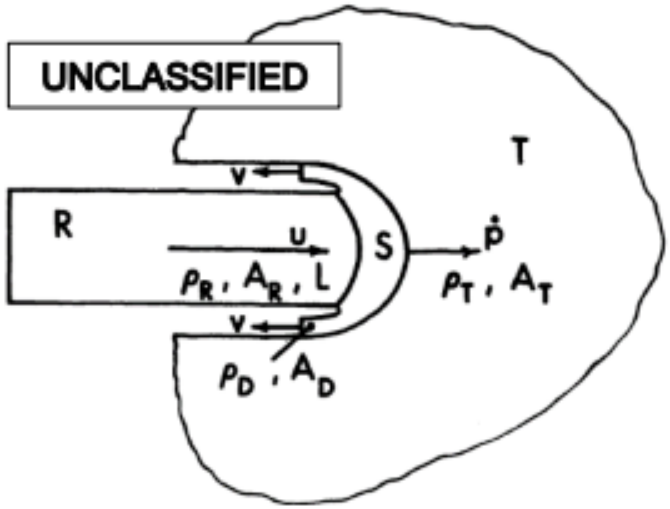
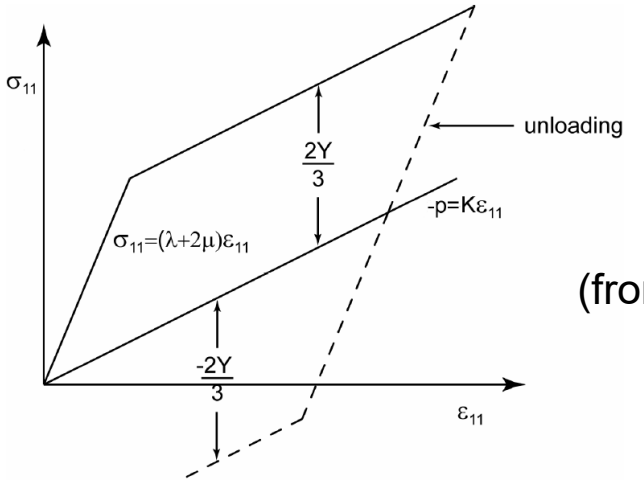
PENETRATION MECHANICS HARDNESS EFFECTS





Note: from BRL-TR-2759.



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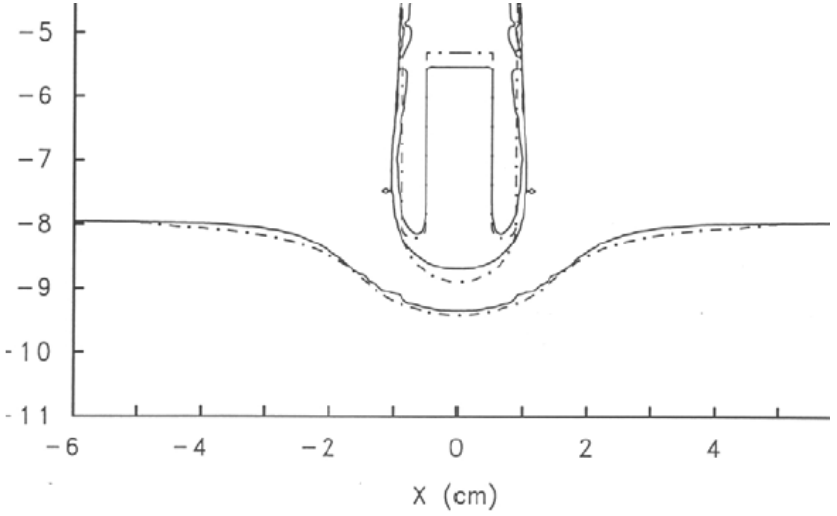

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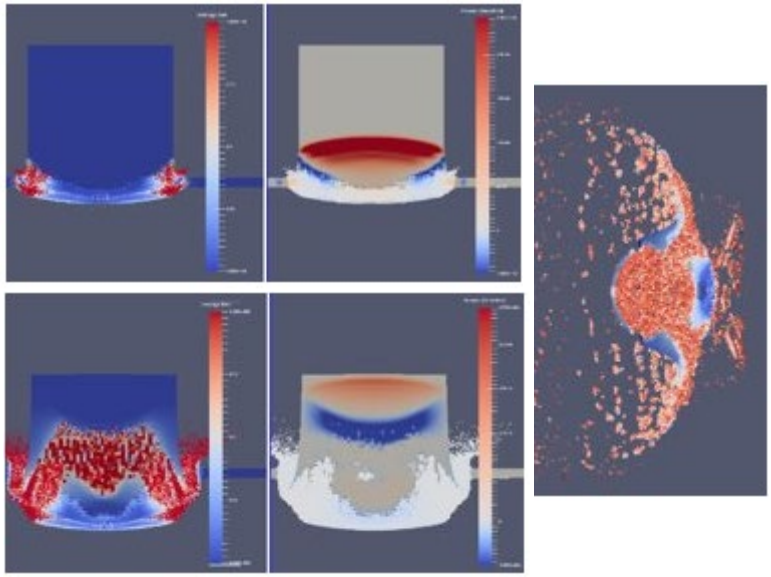
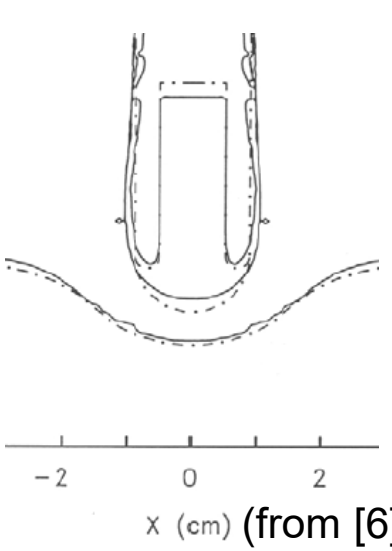
PENETRATION MECHANICS FAILURE EFFECTS





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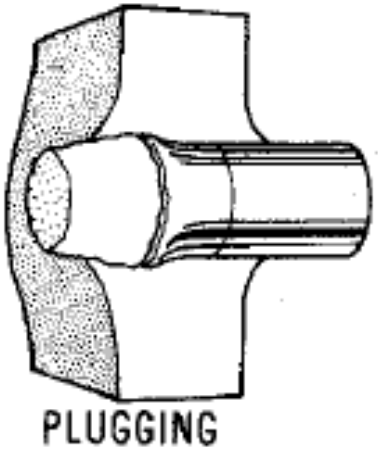

$$P_s = (3\rho_0 c_0 K_c^2 \dot{\varepsilon})^{\frac{1}{3}}$$

Brittle spall strength [4]

$$P_s = (2\rho_0 c_0^2 Y \varepsilon_f)^{\frac{1}{2}}$$

Ductile spall strength [4]

$$s = 2c_K t = 2c_K \frac{\varepsilon}{\dot{\varepsilon}} = \sqrt{\frac{8Y\varepsilon_f}{\rho}} \frac{1}{\dot{\varepsilon}}$$

Grady ductile fragmentation [6]

$$s = \left(\frac{\sqrt{24} K_c}{\rho c_K \dot{\varepsilon}} \right)^{2/3}$$

Grady brittle fragmentation [6]

$$x_0 = (2P_F/\rho\gamma)^{\frac{1}{2}} r/v.$$

Mott fragmentation [12]

$$N(m) = \frac{M_0}{2M_K^2} e^{-\left(\frac{m^{1/2}}{M_K}\right)}$$

Mott distribution [12]

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STEEL ARMOR TECHNOLOGY

- Hardness vs. toughness, ductility
  - Ancillary requirements: cost, structural integrity, manufacturing considerations, multi-hit, environmental
- Heat treatment (quenching and tempering)
- Cast armor
- Rolled homogeneous armor
- Face hardened armor
- High hardness armor
- Ultra high hardness armor
- Metal laminated composites (Dual Hardness)
- Improved metallurgical processing for cast ingots: unidirectional casting, electroslag remelting (ESR)
- Dual hardness ESR

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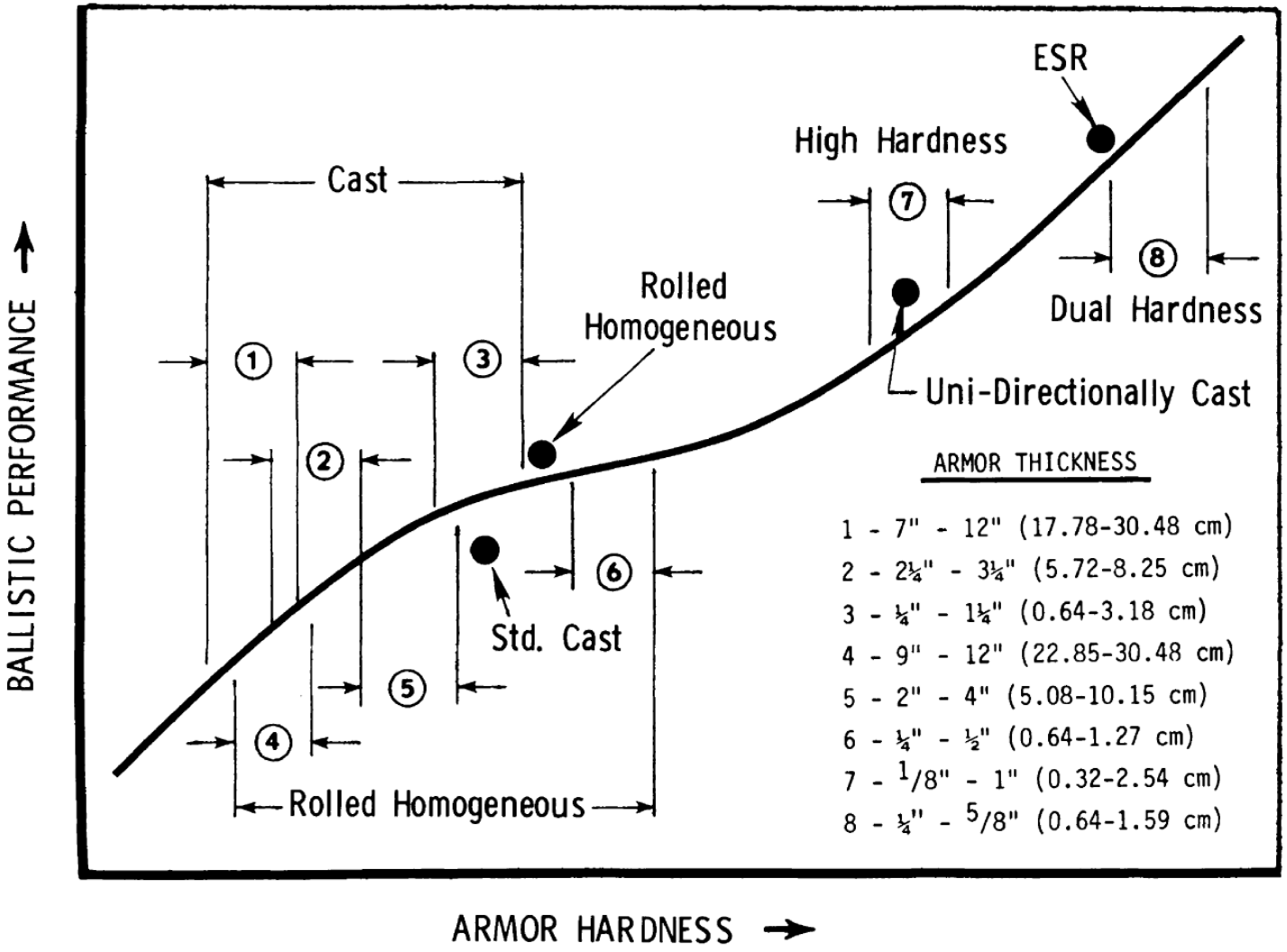
STEEL ARMOR TECHNOLOGY



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EXPERIMENTAL METHODOLOGY

Table 3: Test Matrix

Test No.	Thickness (in)	Material	Obliquity (deg)
RT21-469	0.125	4340 RC38	0
RT21-470	0.250	4340 RC38	0
RT21-471	0.088	4340 RC38	45
RT21-472	0.177	4340 RC38	45
RT21-473	0.125	D2 Tool Steel RC60	0
RT21-474	0.250	D2 Tool Steel RC60	0
RT21-475	0.088	D2 Tool Steel RC60	45
RT21-478	0.177	D2 Tool Steel RC60	45

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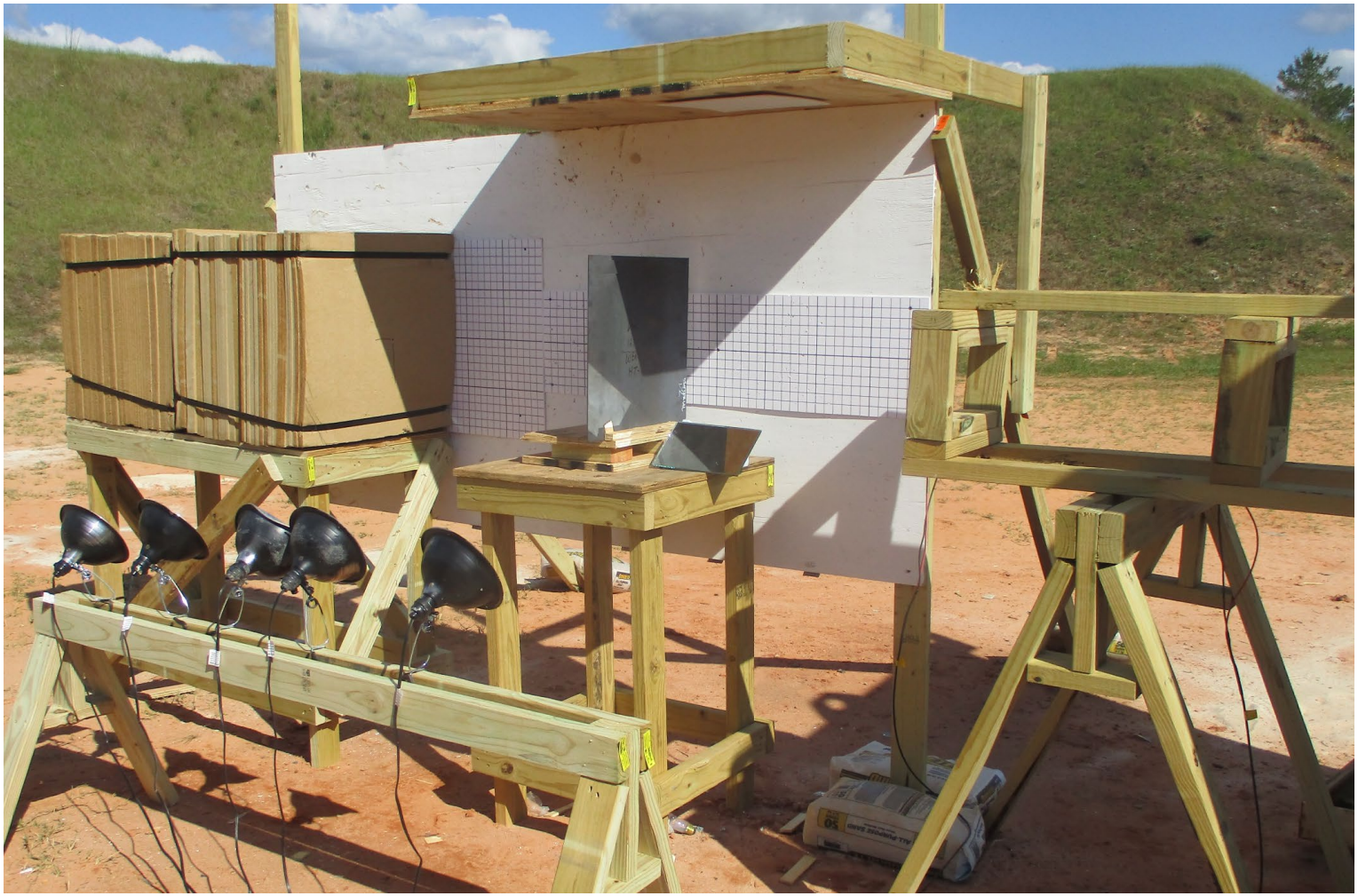
TEST SETUP



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RT469, 0.125”, 4340 RC38, 0 DEG OBLIQUITY

Fig. C1. RT21-469 (0.125”, 4340 RC38, 0° Obliquity) high speed video frames at -100us, 0us, 50us, 100us, 150us, 200us, 300us

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RT469, 0.125”, 4340 RC38, 0 DEG OBLIQUITY

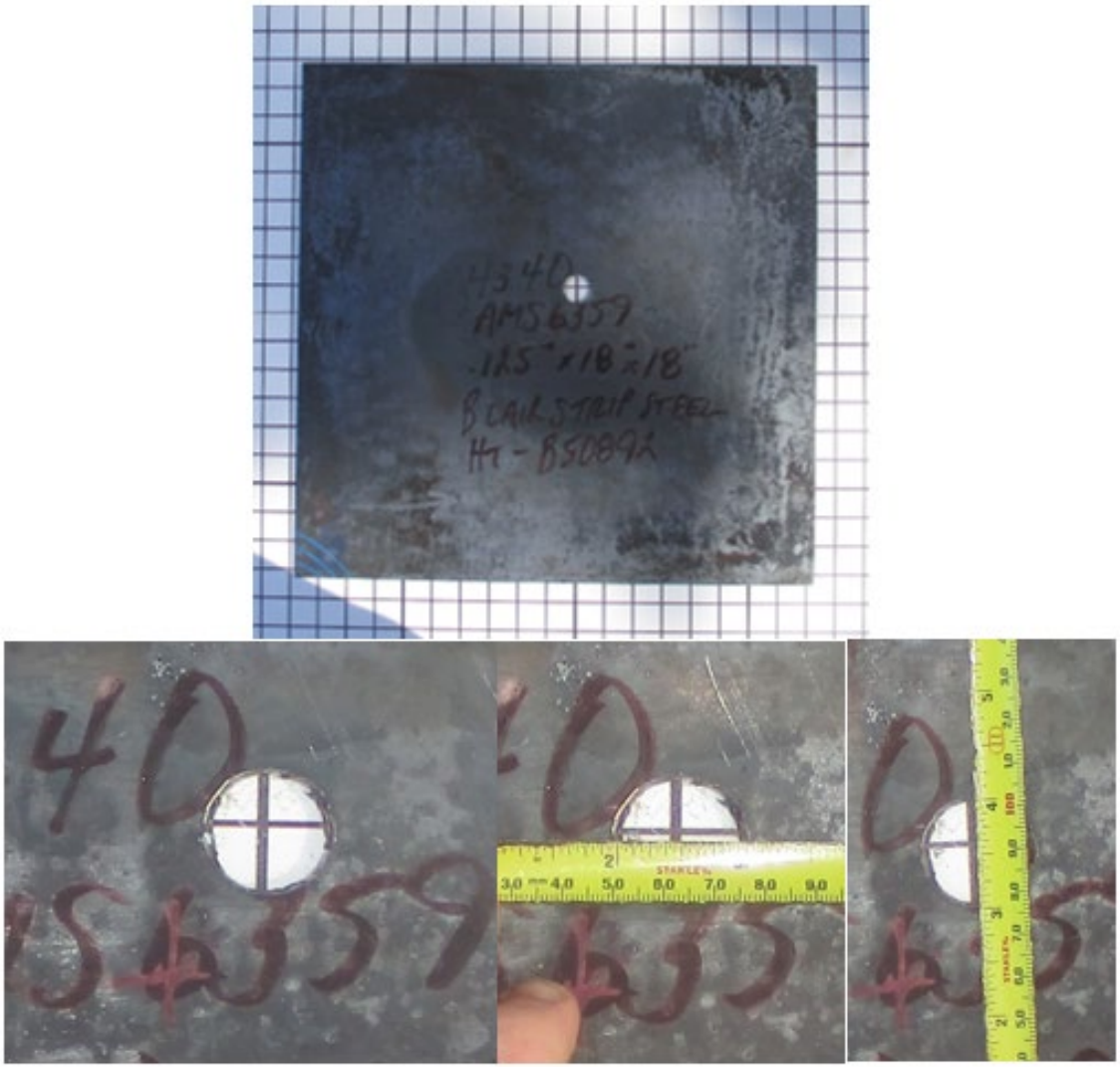

Fig. D1. RT21-469: 4340 RC38 Steel 0.125” Thick, 0 Degrees Obliquity

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RT470, 0.250”, 4340 RC38, 0 DEG OBLIQUITY

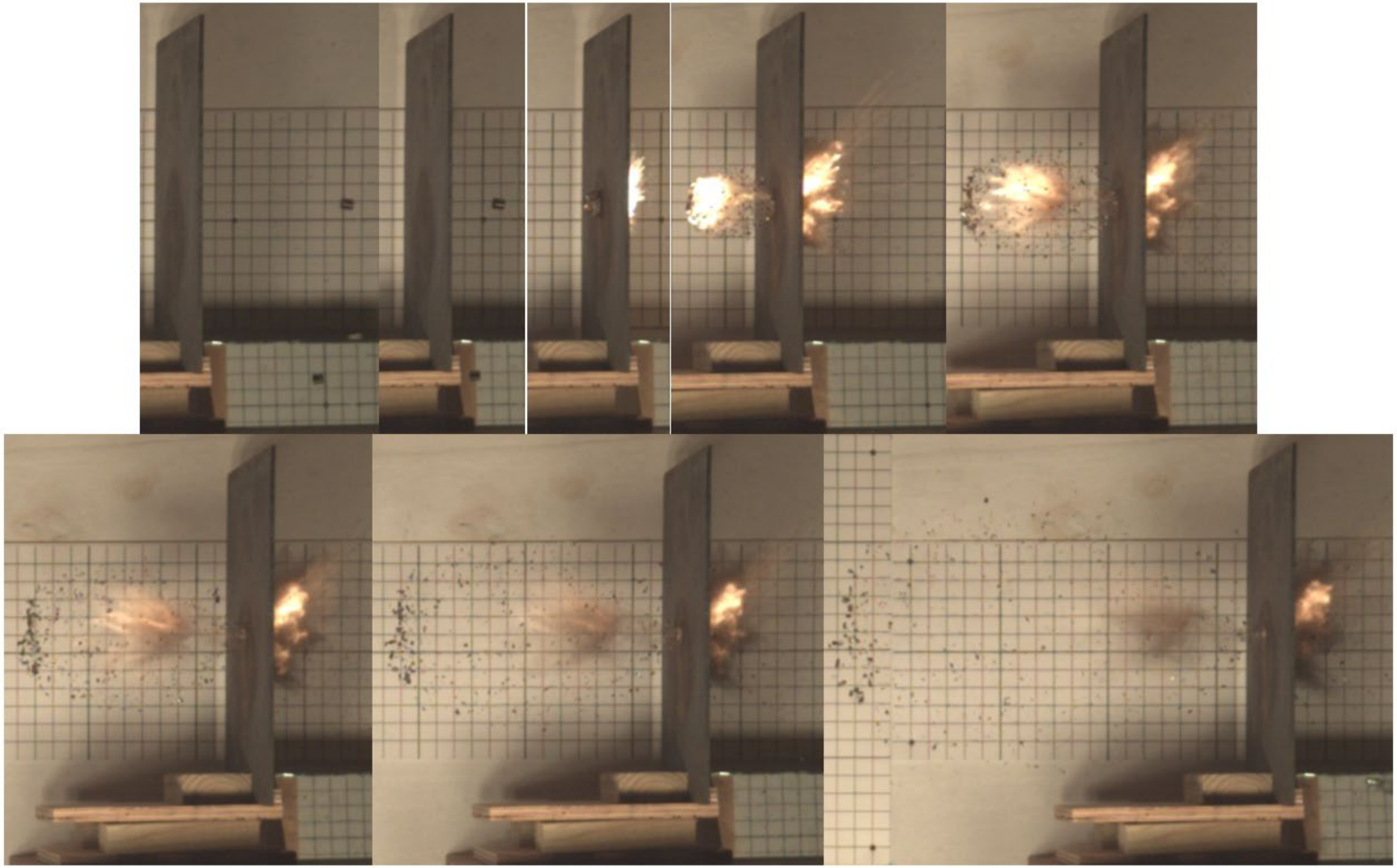

Fig. C2. RT21-470 (0.250”, 4340 RC38, 0° Obliquity) high speed video frames at -100us, -50us, 0us, 50us, 100us, 150us, 200us, 300us

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RT470, 0.250”, 4340 RC38, 0 DEG OBLIQUITY

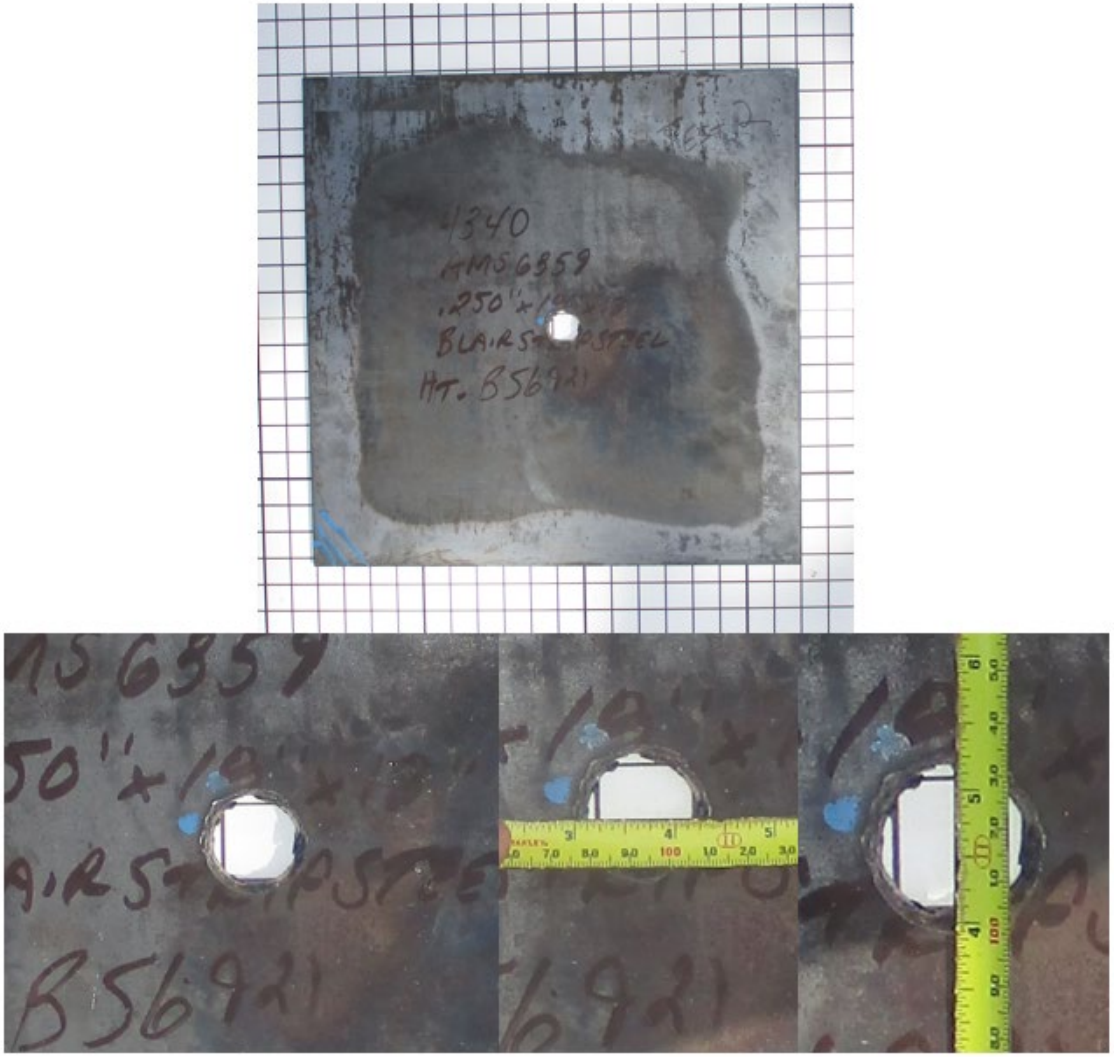

Fig. D2. RT21-470: 4340 RC38 Steel 0.25” Thick, 0 Degrees Obliquity

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RT471, 0.088”, 4340 RC38, 45 DEG OBLIQUITY

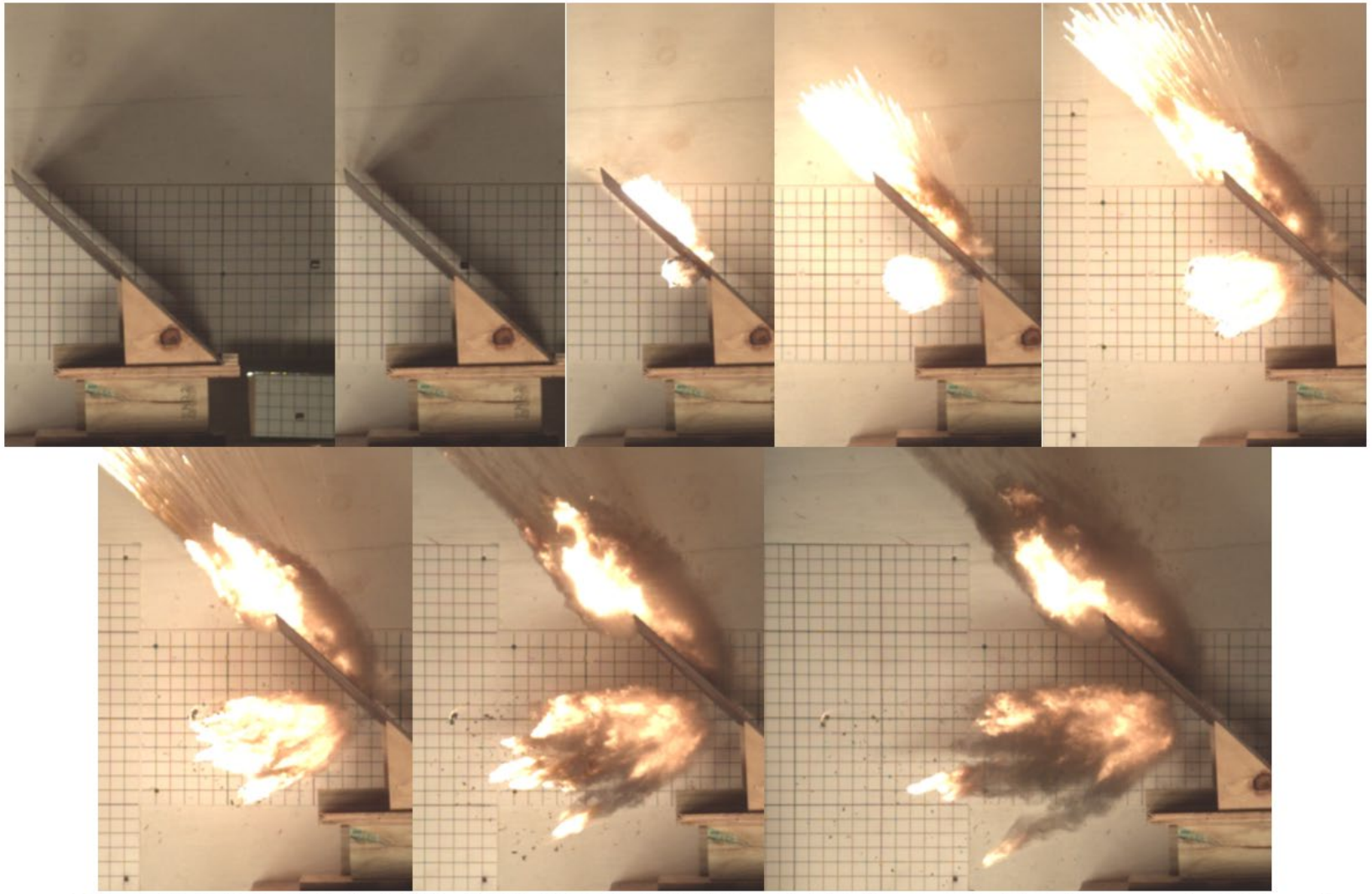

Fig. C3. RT21-471 (0.088”, 4340 RC38, 45° Obliquity) high speed video frames at -120us, 0us, 40us, 80us, 120us, 160us, 240us, 320us

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RT471, 0.088”, 4340 RC38, 45 DEG OBLIQUITY

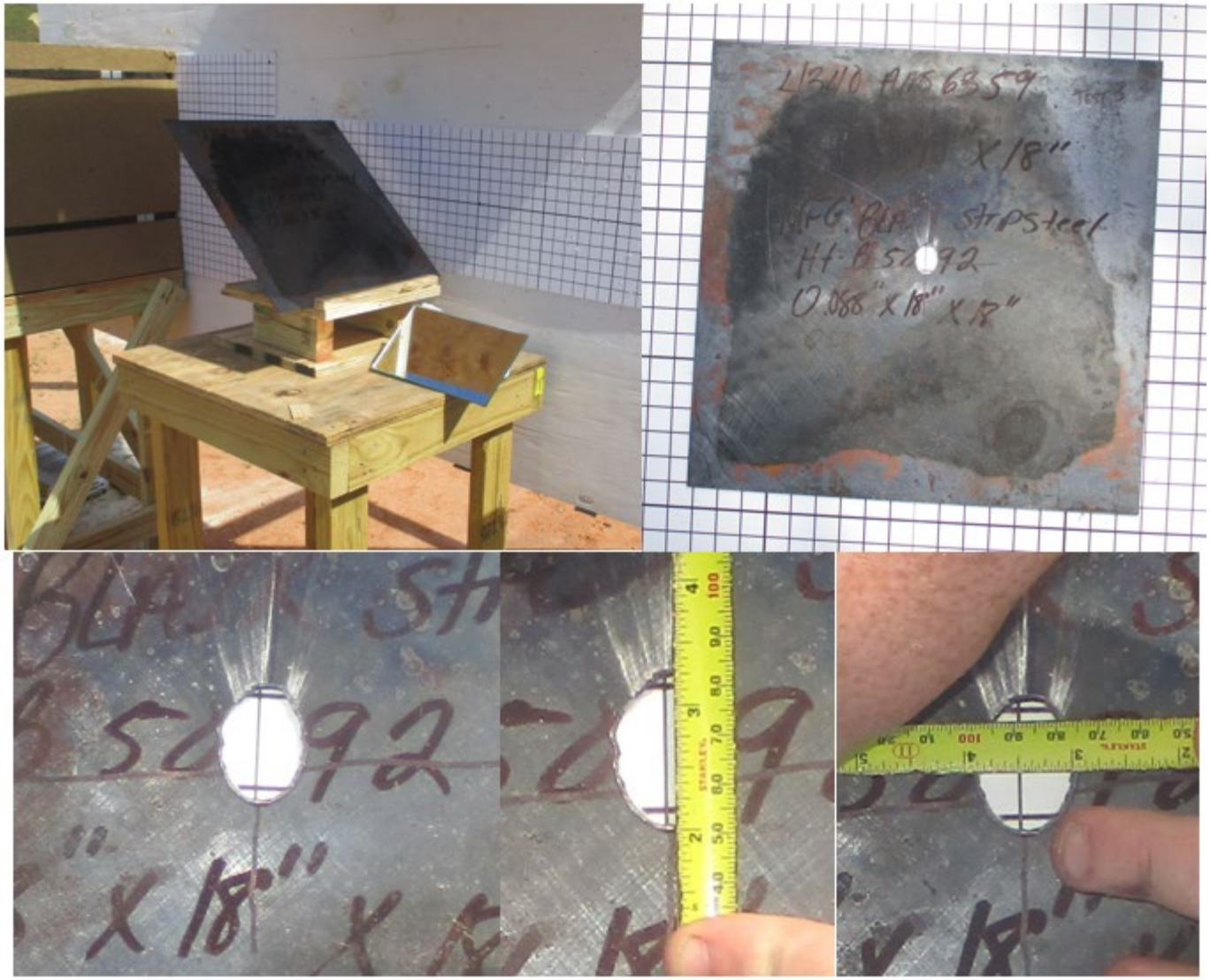

Fig. D3. RT21-471: 4340 RC38 Steel 0.088” Thick, 45 Degrees Obliquity

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RT472, 0.177”, 4340 RC38, 45 DEG OBLIQUITY

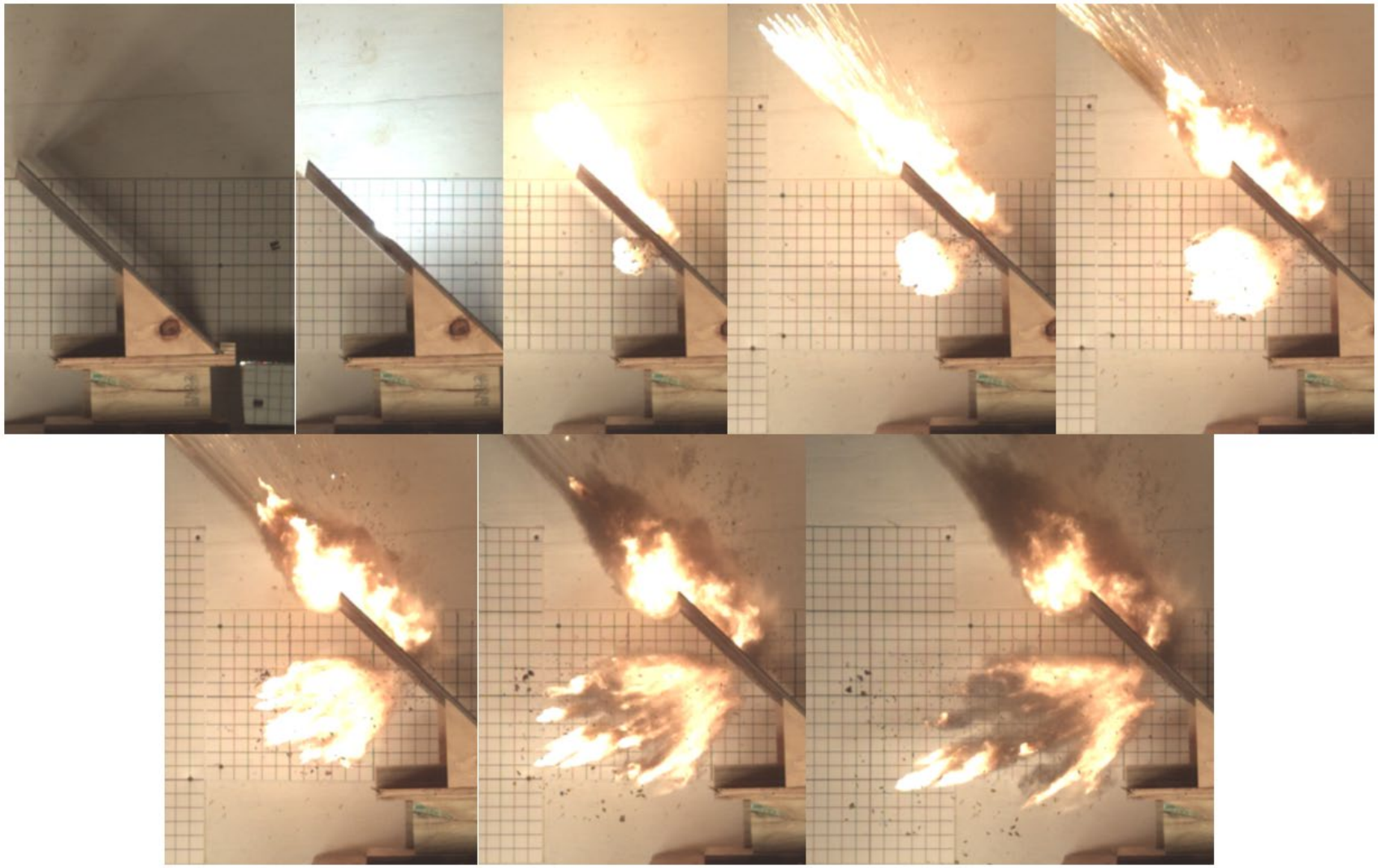

Fig. C4. RT21-472 (0.177”, 4340 RC38, 45° Obliquity) high speed video frames at -120us, 0us, 40us, 80us, 120us, 160us, 240us, 320us

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RT472, 0.177”, 4340 RC38, 45 DEG OBLIQUITY

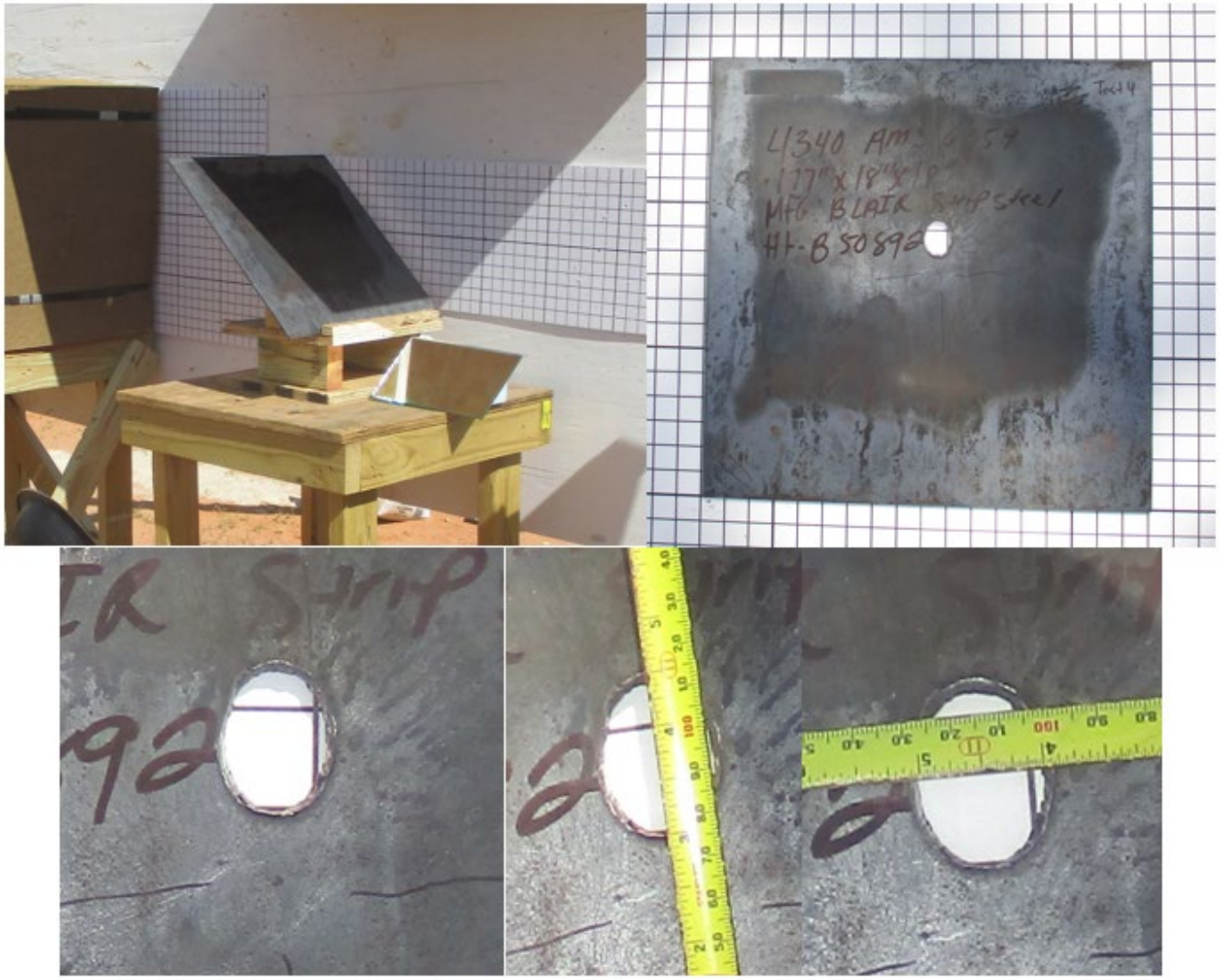

Fig. D4. RT21-472: 4340 RC38 Steel 0.177” Thick, 45 Degrees Obliquity

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RT473, 0.125”, D2 RC60, 0 DEG OBLIQUITY

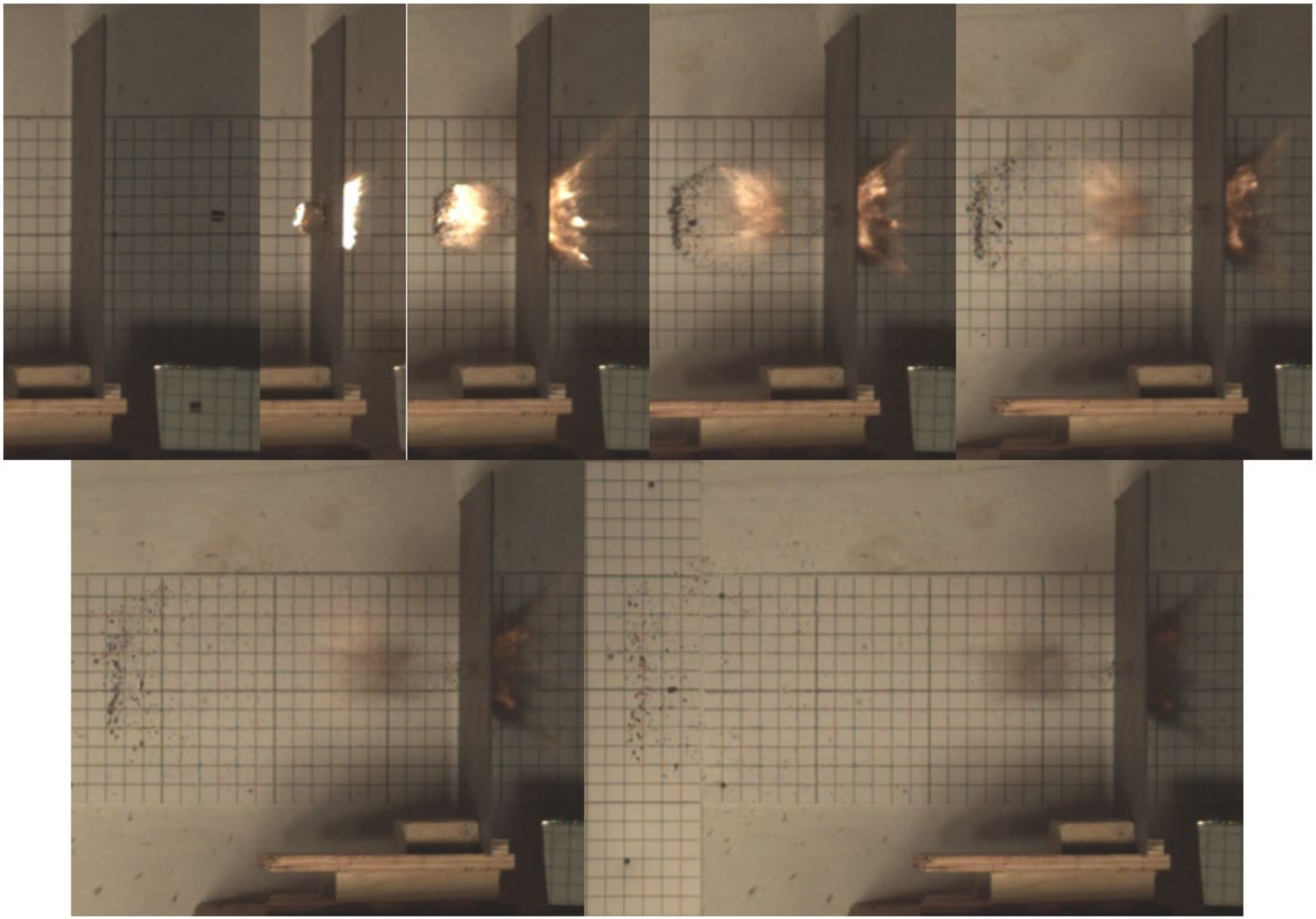

Fig. C5. RT21-473 (0.125”, D2 Tool Steel, 0° Obliquity) high speed video frames at -80us, 0us, 40us, 80us, 120us, 240us, 320us

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RT473, 0.125”, D2 RC60, 0 DEG OBLIQUITY

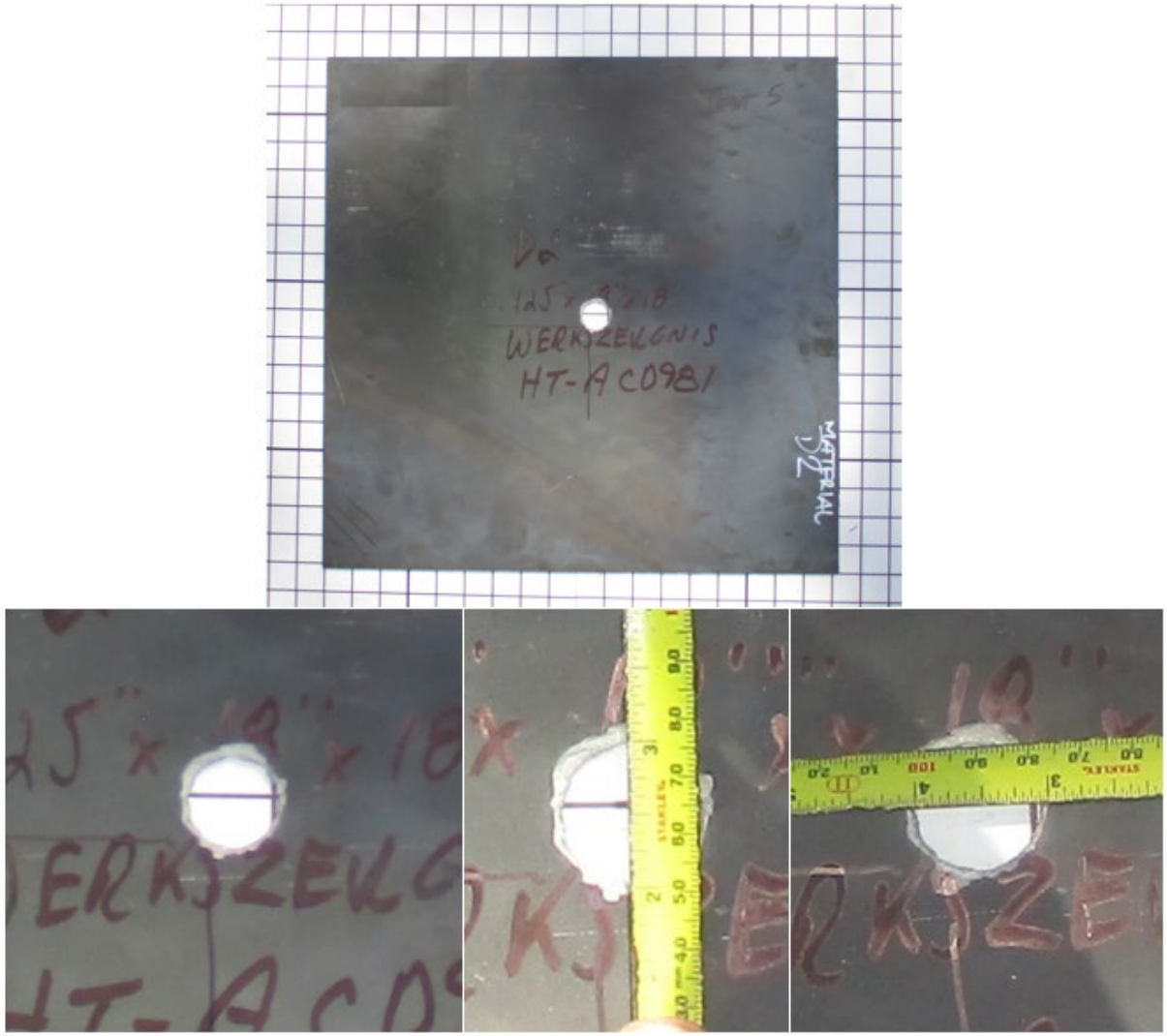

Fig. D5. RT21-473: D2 Tool Steel RC60 0.125” Thick, 0 Degrees Obliquity

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RT474, 0.250”, D2 RC60, 0 DEG OBLIQUITY

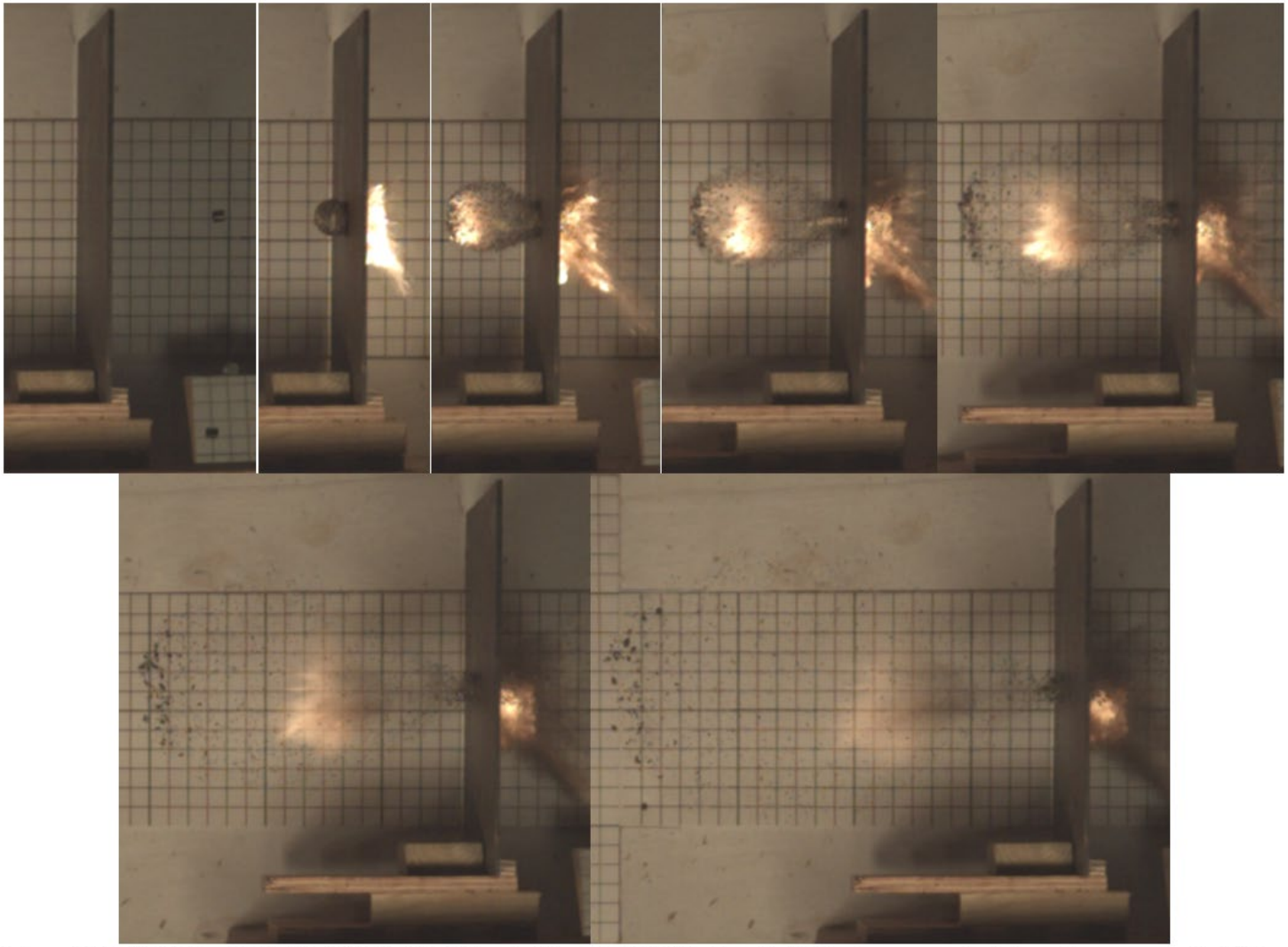

Fig. C6. RT21-474 (0.250”, D2 Tool Steel, 0° Obliquity) high speed video frames at -80us, 0us, 40us, 80us, 120us, 240us, 320us

Distribution Statement A: Approved for public release. Distribution is unlimited.

RT474, 0.250”, D2 RC60, 0 DEG OBLIQUITY

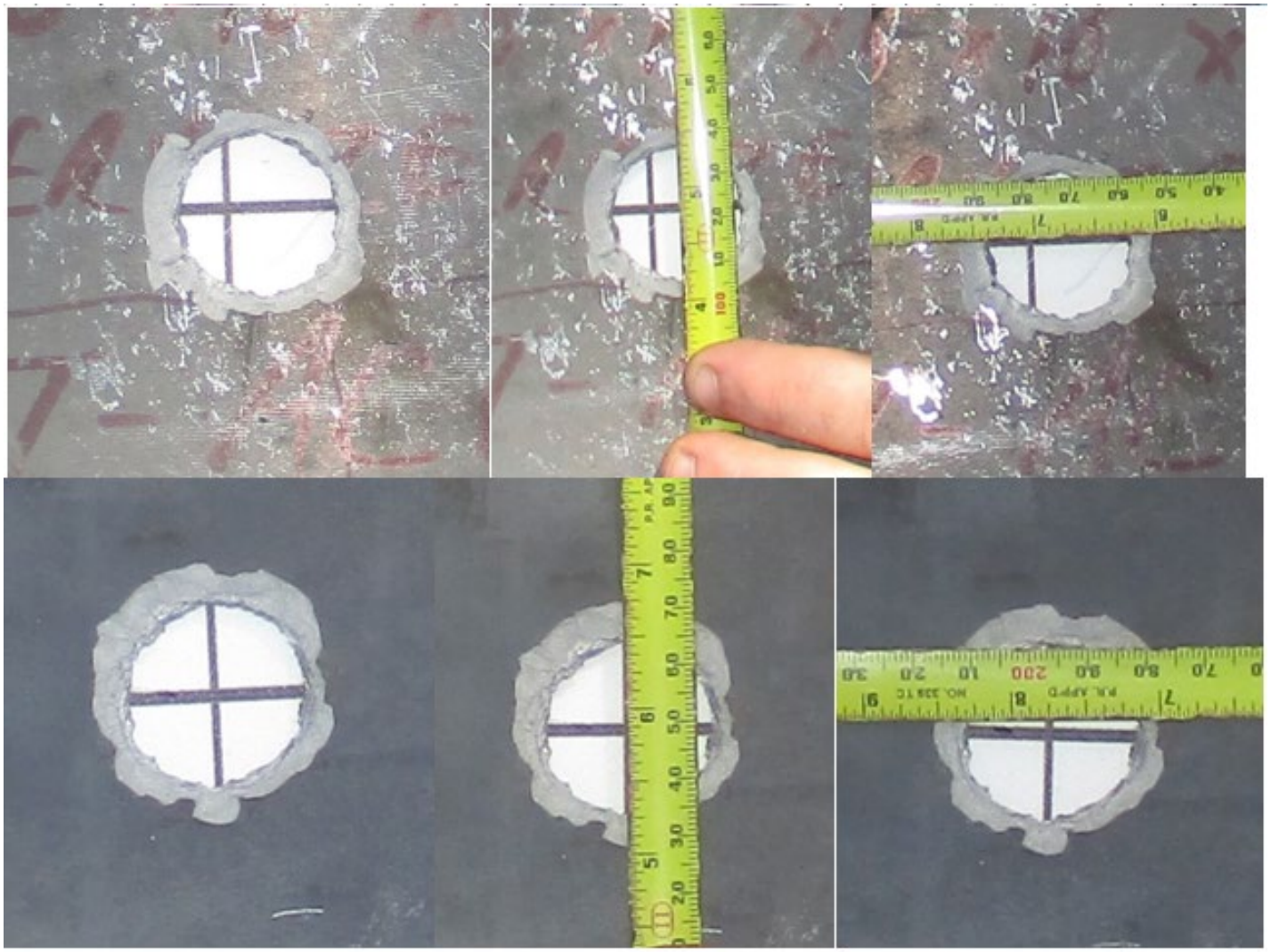

Fig. D6. RT21-474: D2 Tool Steel RC60 0.25” Thick, 0 Degrees Obliquity

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RT475, 0.088”, D2 RC60, 45 DEG OBLIQUITY

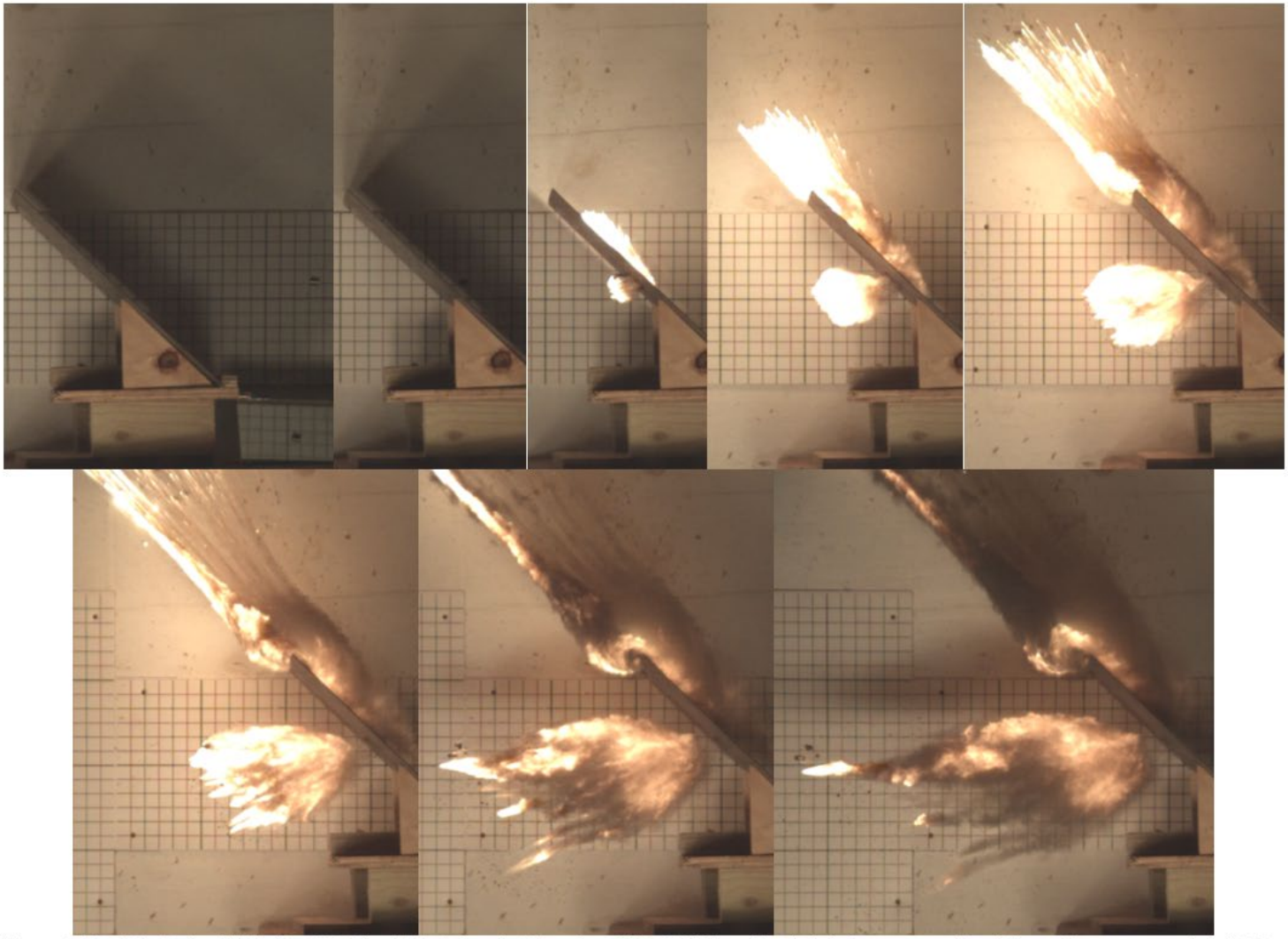

Fig. C7. RT21-475 (0.088”, D2 Tool Steel, 45° Obliquity) high speed video frames at -120us, 0us, 40us, 80us, 120us, 240us, 320us

Distribution Statement A: Approved for public release. Distribution is unlimited.

RT475, 0.088”, D2 RC60, 45 DEG OBLIQUITY

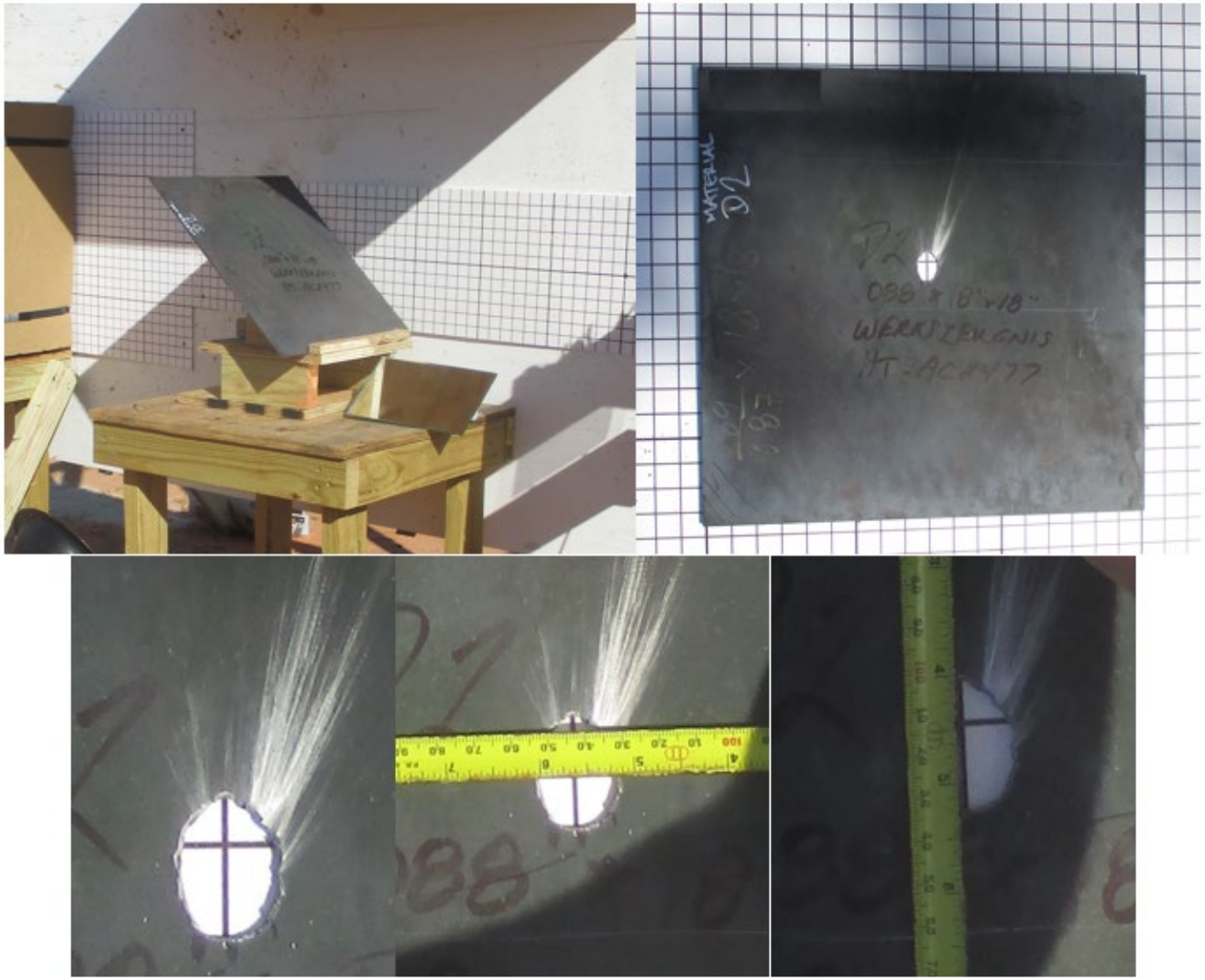

Fig. D7. RT21-475: D2 Tool Steel RC60 0.088” Thick, 45 Degrees Obliquity

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RT478, 0.088”, D2 RC60, 45 DEG OBLIQUITY

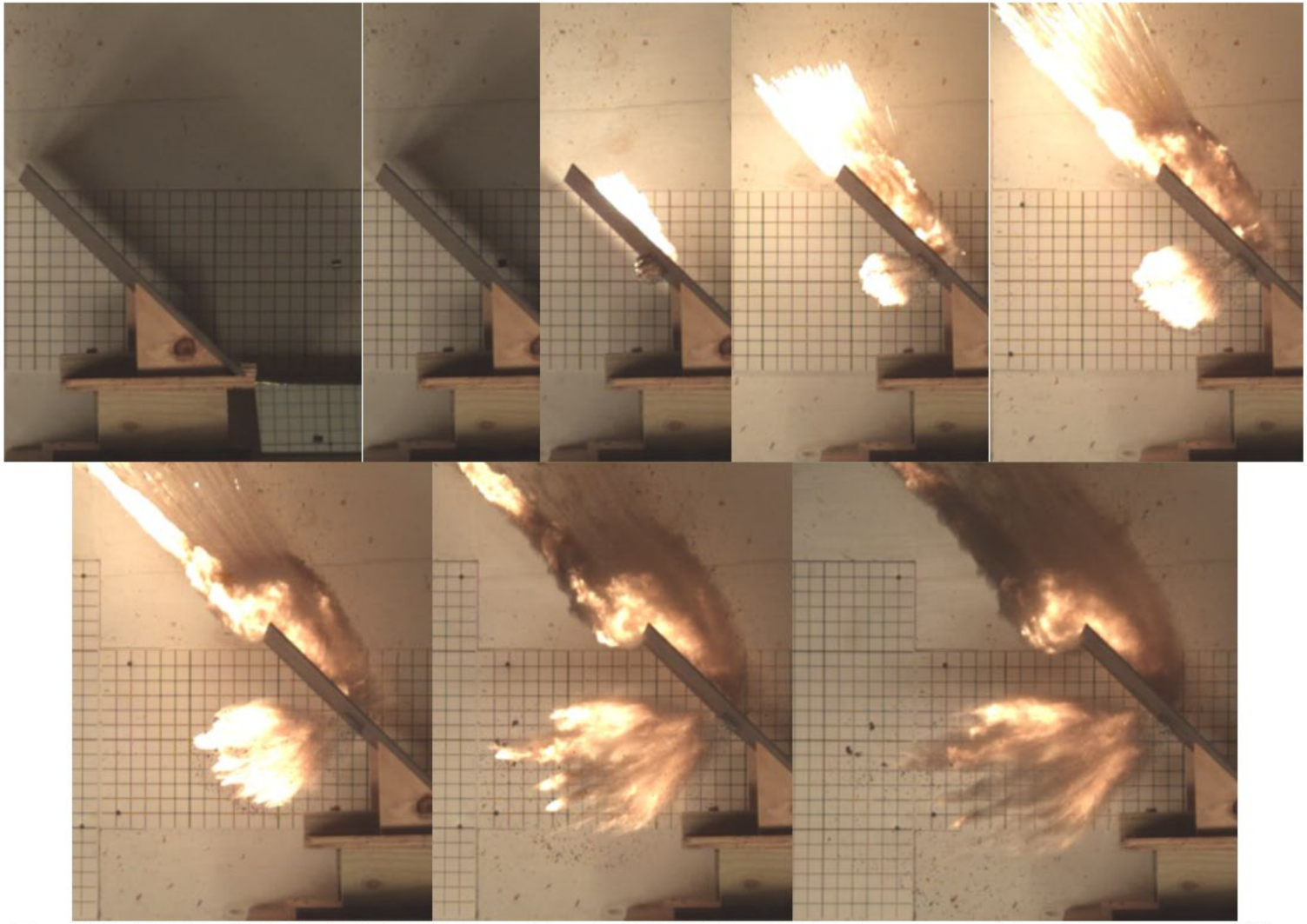


Fig. C8. RT21-478 (0.177”, D2 Tool Steel, 45° Obliquity) high speed video frames at -120us, 0us, 40us, 80us, 120us, 160us, 240us, 320us

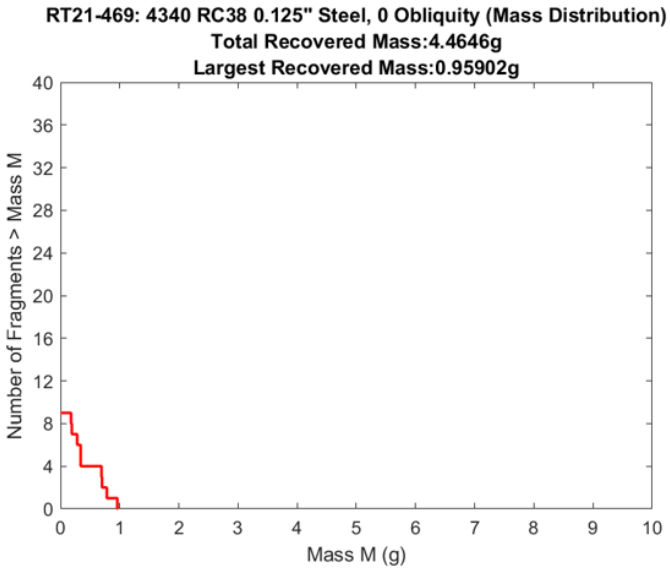
Distribution Statement A: Approved for public release. Distribution is unlimited.

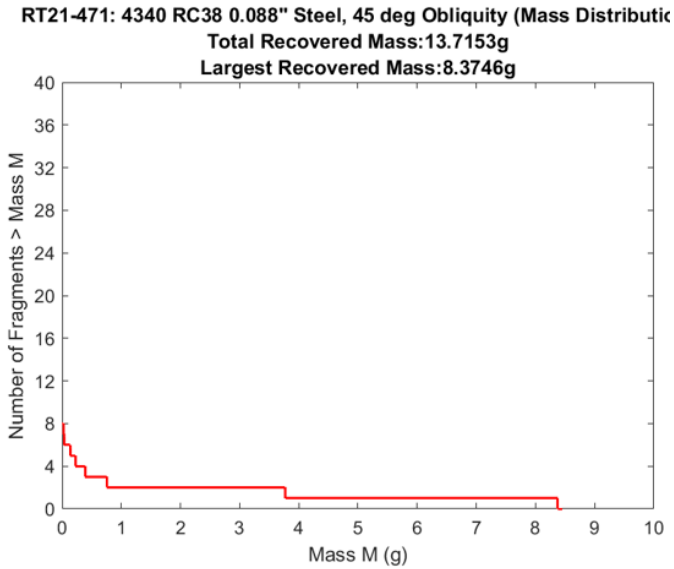
RT478, 0.088”, D2 RC60, 45 DEG OBLIQUITY

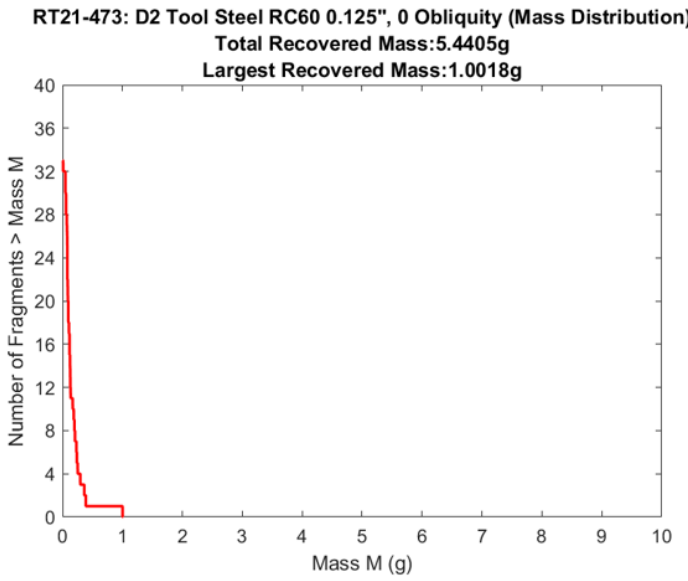
Fig. D8. RT21-478: D2 Tool Steel RC60 0.177” Thick, 45 Degrees Obliquity

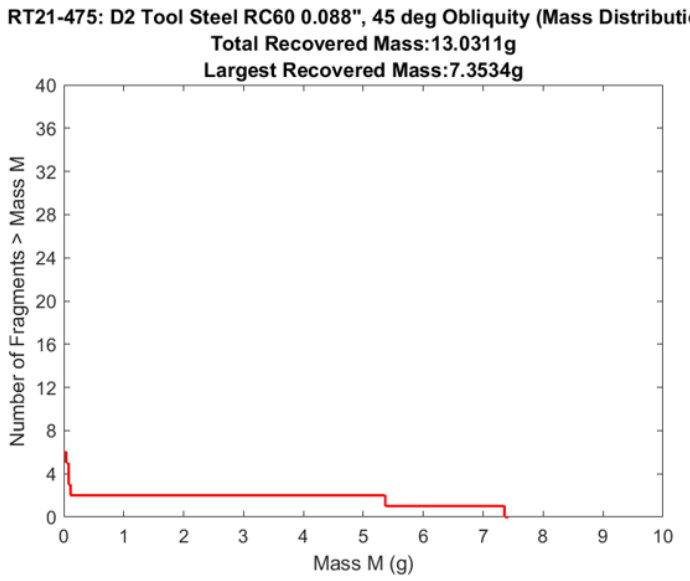
Distribution Statement A: Approved for public release. Distribution is unlimited.

TEST RESULTS – THIN STEEL BARRIERS









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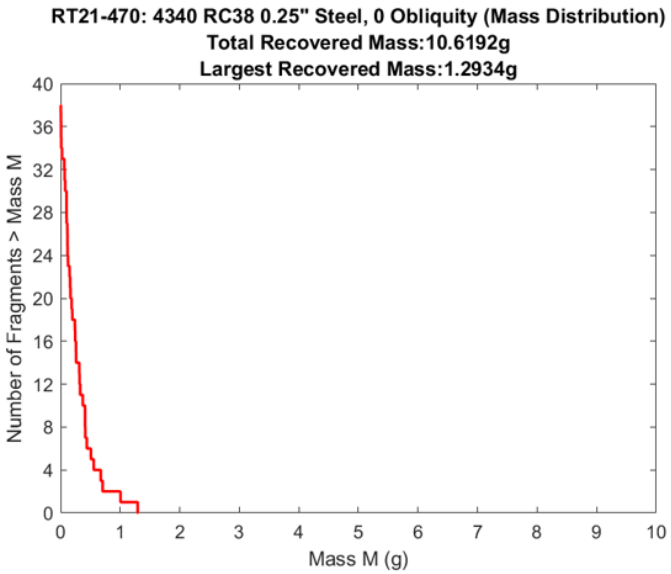
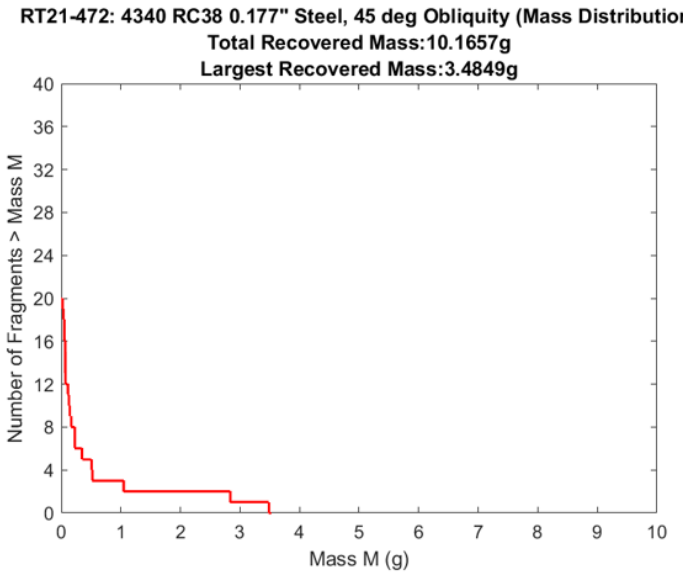
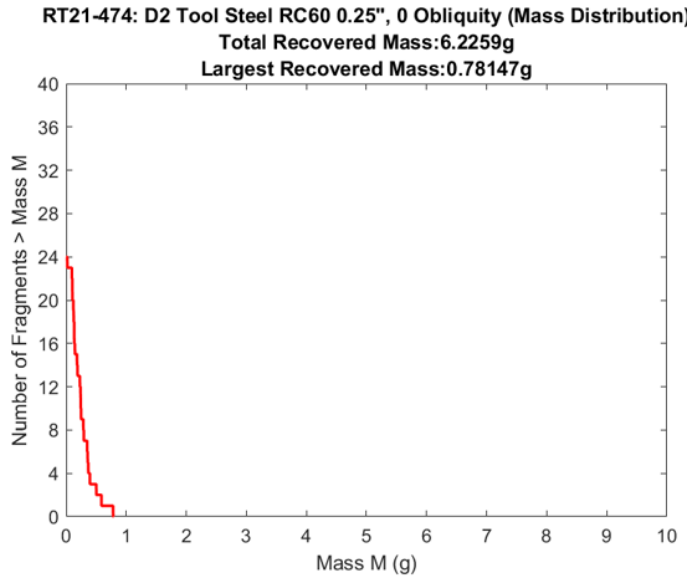
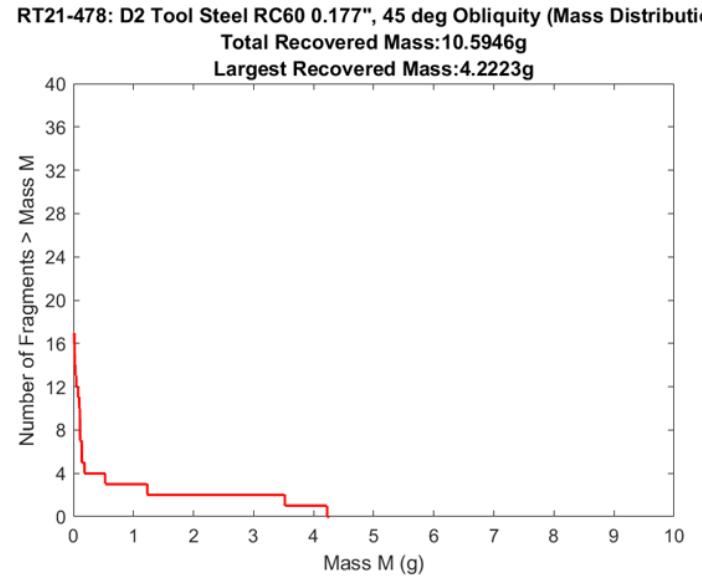
TEST RESULTS – THICK STEEL BARRIERS









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TEST RESULTS

Table 4: Test Results

Test No.	Mat.	Thick. (in)	Obl. (deg)	AD (lb/ft^2)	$V_{S,HSV}$ (ft/s)	$V_{S,TOA}$ (ft/s)	$V_{R,HSV}$ (ft/s)*	ΔV_{HSV} (ft/s)*	$\Delta V_{HSV}/AD$ (ft/s)/ (lb/ft^2)*	Total Debris Mass (g)	Largest Frag Mass (g)
469	4340 RC38	0.125	0	5.105	8198	8186	6683	1515	296.8	4.465	0.959
473	D2 RC60	0.125	0	5.105	8475	8383	6842	1633	319.9	5.441	1.002
471	4340 RC38	0.088	45	5.105	8383	8482	6566 6693	1817 1690	355.9 331.1	13.715	8.375
475	D2 RC60	0.088	45	5.105	8489	8456	7146 6728	1343 1761	263.1 345.0	13.031	7.353
470	4340 RC38	0.250	0	10.21	8597	8461	5874	2723	266.7	10.619	1.293
474	D2 RC60	0.250	0	10.21	8539	8400	5857	2682	280.3	6.226	0.782
472	4340 RC38	0.177	45	10.21	8480	8392	5314 5303	3166 3177	310.1 311.2	10.166	3.475
478	D2 RC60	0.177	45	10.21	8297	8383	5986 5623	2311 2674	226.4 261.9	10.595	4.222

*For oblique impacts, top number is front of debris cloud at early times, bottom number is largest debris fragment at late times

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TEST RESULTS (CONT'D)

- For all presented areal densities considered, hardness:
  - mildly improves residual velocity at 0 obliquity
  - moderately worsens residual velocity at 45° obliquity
- For the more soft, ductile 4340 RC38 steel
  - Obliquity significantly improved residual velocity
  - Obliquity significantly worsened residual mass
- For the more hard, brittle D2 RC60 steel
  - Obliquity moderately worsened residual velocity
  - Obliquity significantly worsened residual mass

Better residual velocity at obliquity requires good ductility
Fragment breakup highly spall dominated!

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PRELIMINARY MODELING

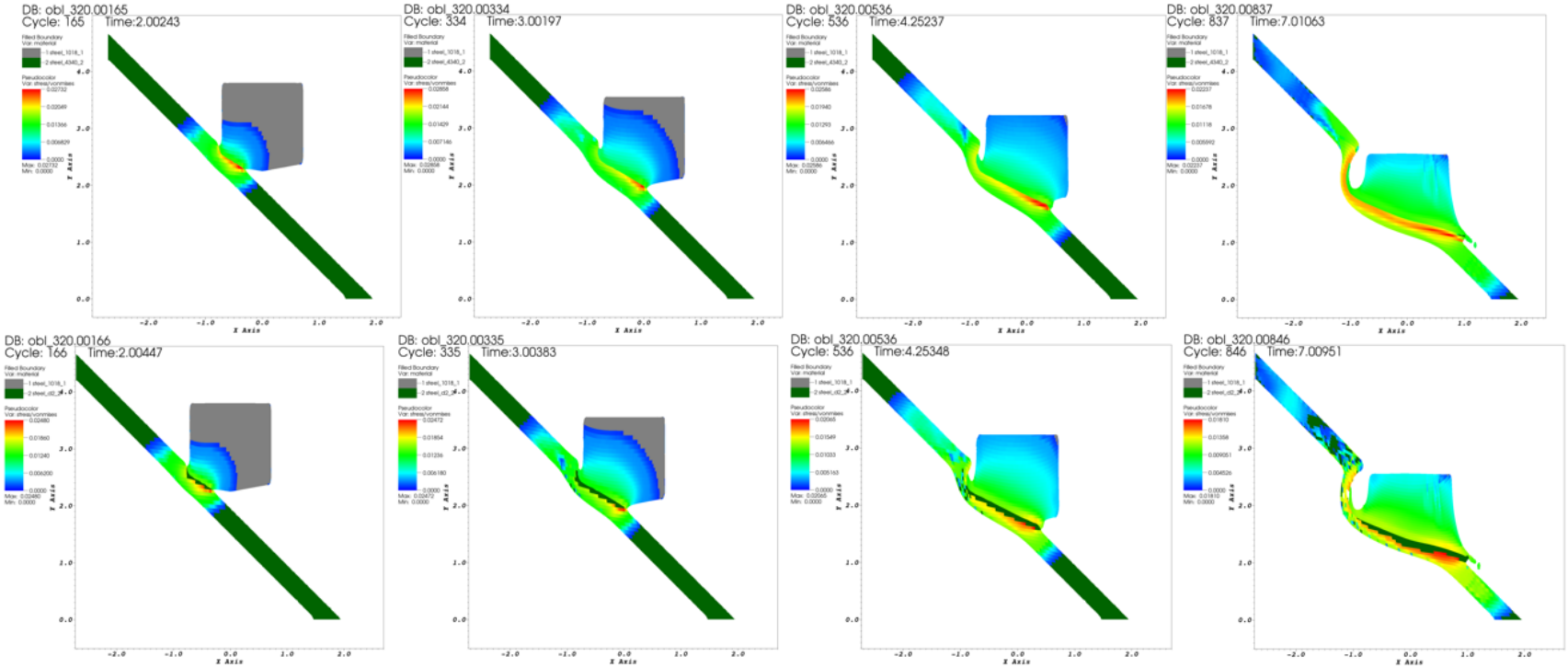

Fig. 5. ALE3D Models to interrogate target failure behavior: 30 kbar spall stress and no failure strain (top row), 10 kbar target spall stress and 0.5 equivalent plastic strain to failure (bottom row)

Obliquity effect does not appear to be caused by spallation ahead of fragment penetration

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QUESTIONS

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U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

Computational Energetic Material Cook-off Scenarios

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Senior Research Scientist (Insensitive Munitions)

Armaments Center

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Equations for Heat Transfer

The generalized equation for conductive heat transfer (without mass transfer) with internal heat generation (Q) is given by:

$$-\lambda\nabla^2 T + \rho c\frac{dT}{dt} = Q$$

where:

λ = Material Thermal Conductivity
∇^2 = Lapace's Operator
T = Temperature
ρ = Density
c = Heat Capacity
Q = Internal Heat Generation

The Arrhenius equation is commonly used for the thermal decomposition of energetic materials:

$$Q = \rho\Delta H Z e^{(-\frac{E_a}{RT})}$$

where:

E_a = Activation Energy
R = The Universal Gas Constant
H = Material Heat of Reaction
Z = A Material Time Constant

The generalized equation is then:

$$-\lambda\nabla^2 T + \rho c\frac{dT}{dt} = \rho\Delta H Z e^{(-\frac{E_a}{RT})}$$

With one dimensional Heat Transfer:

$$\frac{dT}{dt} = \frac{1}{\rho c}\left(\rho\Delta H Z e^{(-\frac{E_a}{RT})} + \lambda\frac{1}{r}\frac{\partial^2(ru)}{\partial r^2}\right)$$

At r=0

$$\frac{dT}{dt} = \frac{1}{\rho c}\left(\rho\Delta H Z e^{(-\frac{E_a}{RT})} + \lambda 3\frac{\partial^2 T}{\partial r^2}\right)$$

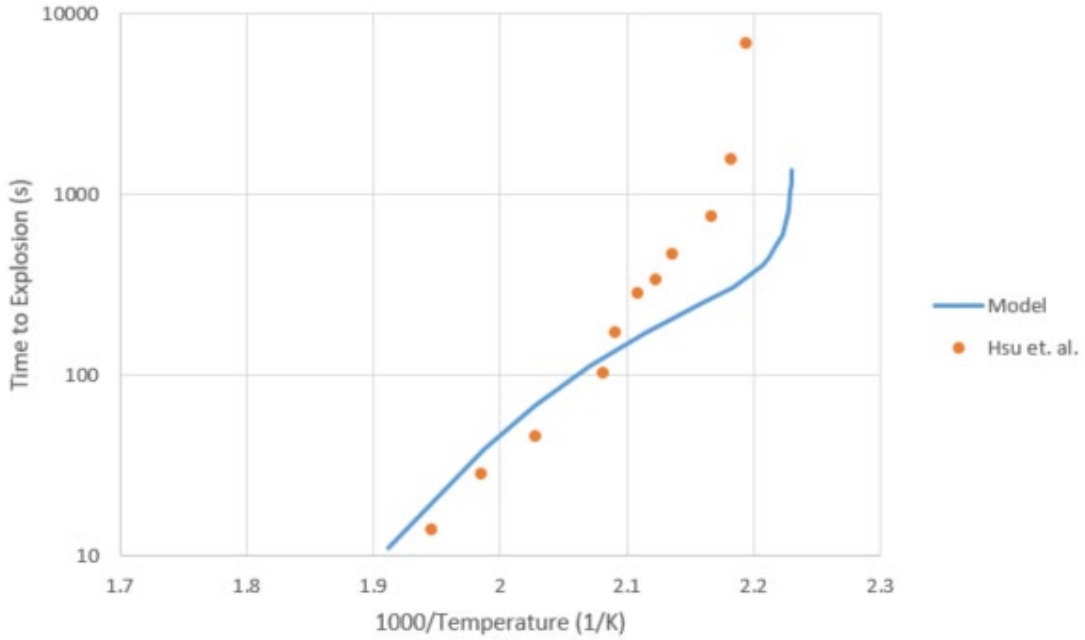
COMPARISON TO EXISTING DATA

The computer program stopped when a temperature in any of the intervals was high enough (550 to 600K (277-327 ° C)) that a run-away reaction could be assumed. As long as this cut-off temperature was suitably high, the results were not sensitive to this value as the temperature is rising very rapidly. The program was written in the python language, and could be easily modified for any particular problem. The variables used in the model are from Cooper.

Lawrence Livermore National Laboratory has conducted a One-Dimensional Time to Explosion test on RDX.

The test uses a spherical test sample at a diameter of 12:7x10_3 m (:5 inches) clamped between two aluminum anvils.

The approximation for the model was made such that the outer surface of the sample is constant at the test temperature. The model and the data were plotted in an Arrhenius plot.



Cooper, P. W. (2018). Explosives engineering. John Wiley & Sons.

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CRITICAL TEMPERATURES

Frank-Kamenetskii's solution determines the temperature at which a steady state solution cannot be determined, and a run-away reaction occurs. This method provides a critical temperature, however it does not predict the time to reaction. The time to reaction can be very long near the critical temperature. Additionally, the ignored decomposition of the material and its reduction in the available heat of reaction may have a significant influence on the cook-off.

$$\frac{E_a}{T_c} = R\ ln\left(\frac{r^2\ \rho\ H\ Z\ E_a}{3.32\ T_c^2\ \lambda\ R_g}\right)$$

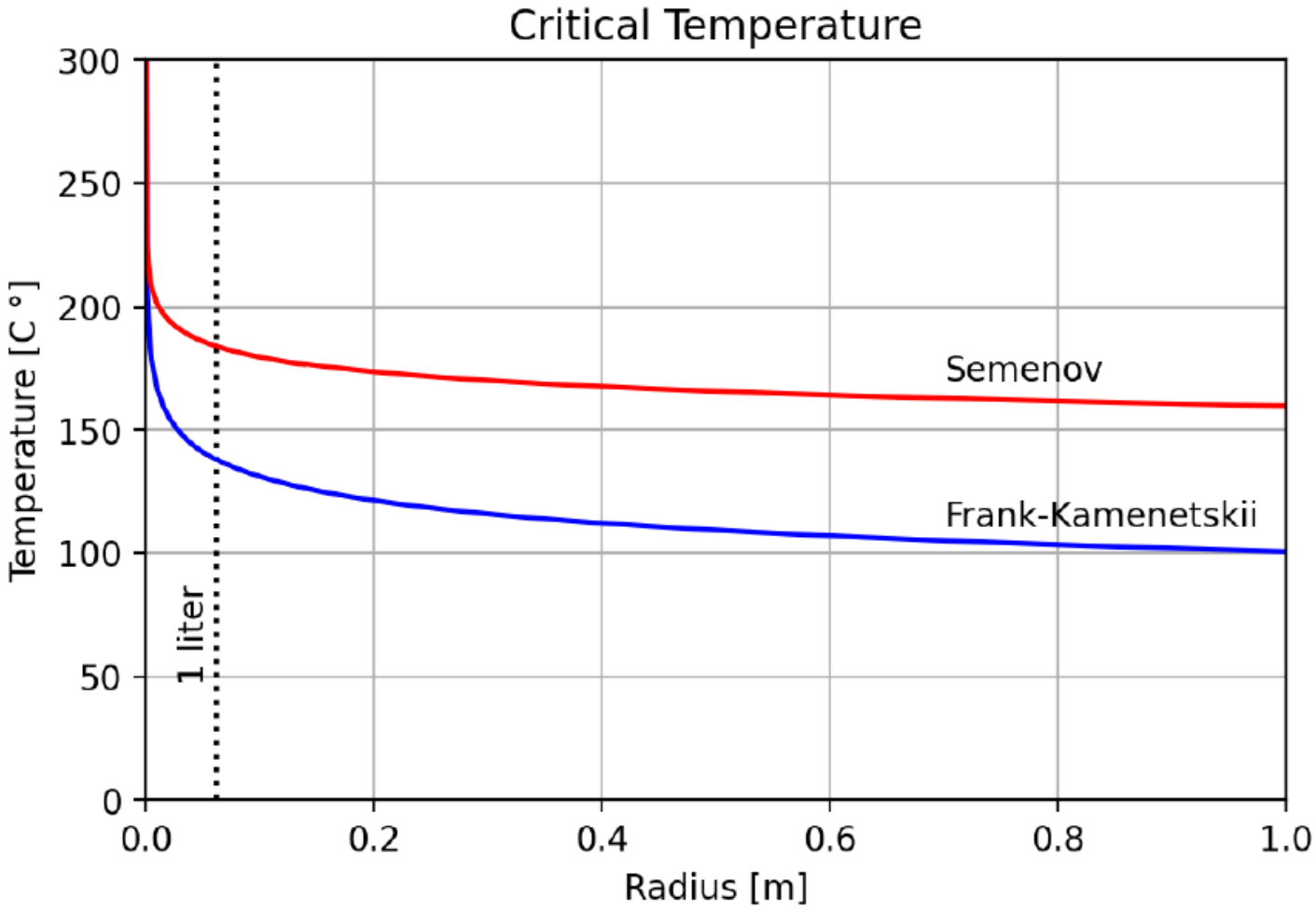
Semenov developed a critical temperature model for well stirred liquids.

$$T_c = \frac{E_a}{R}\frac{1}{ln\left(\frac{V\rho HZE_a}{S\alpha RT_c{}^2}\right)}$$

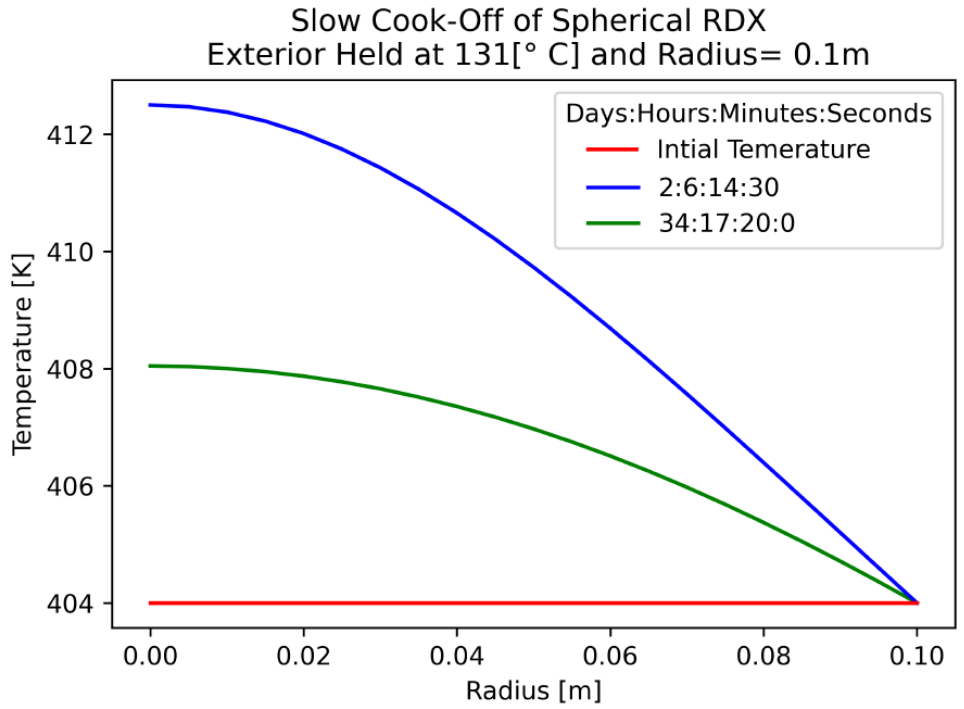
where:

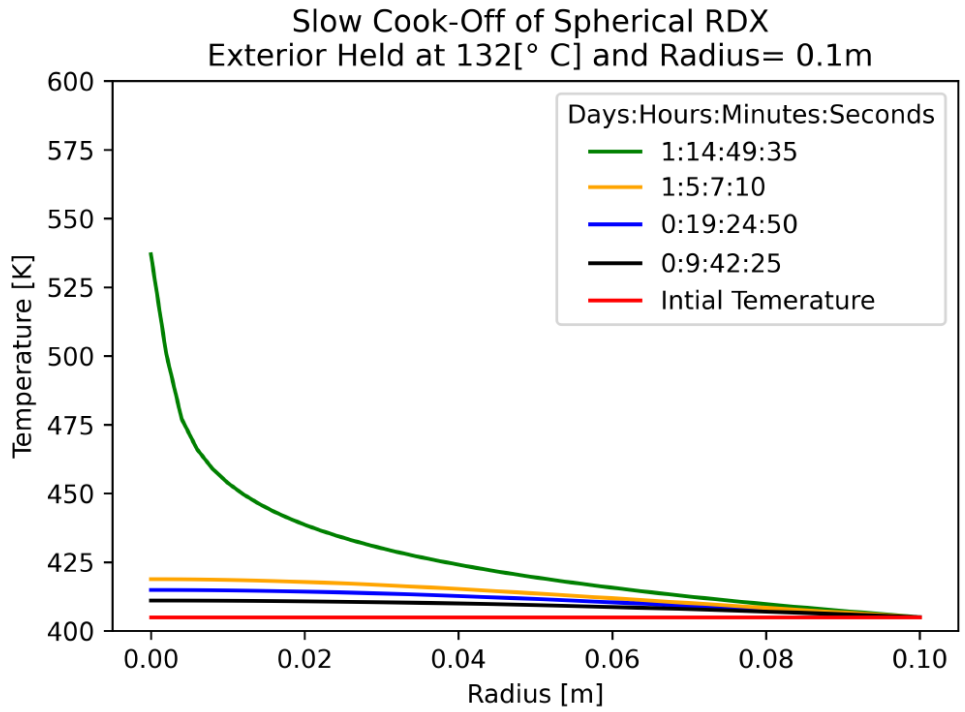
T_c = Critical Temperature
V = Volume
S = Surface Area
α = Convection coefficient

CRITICAL TEMPERATURE FOR RDX



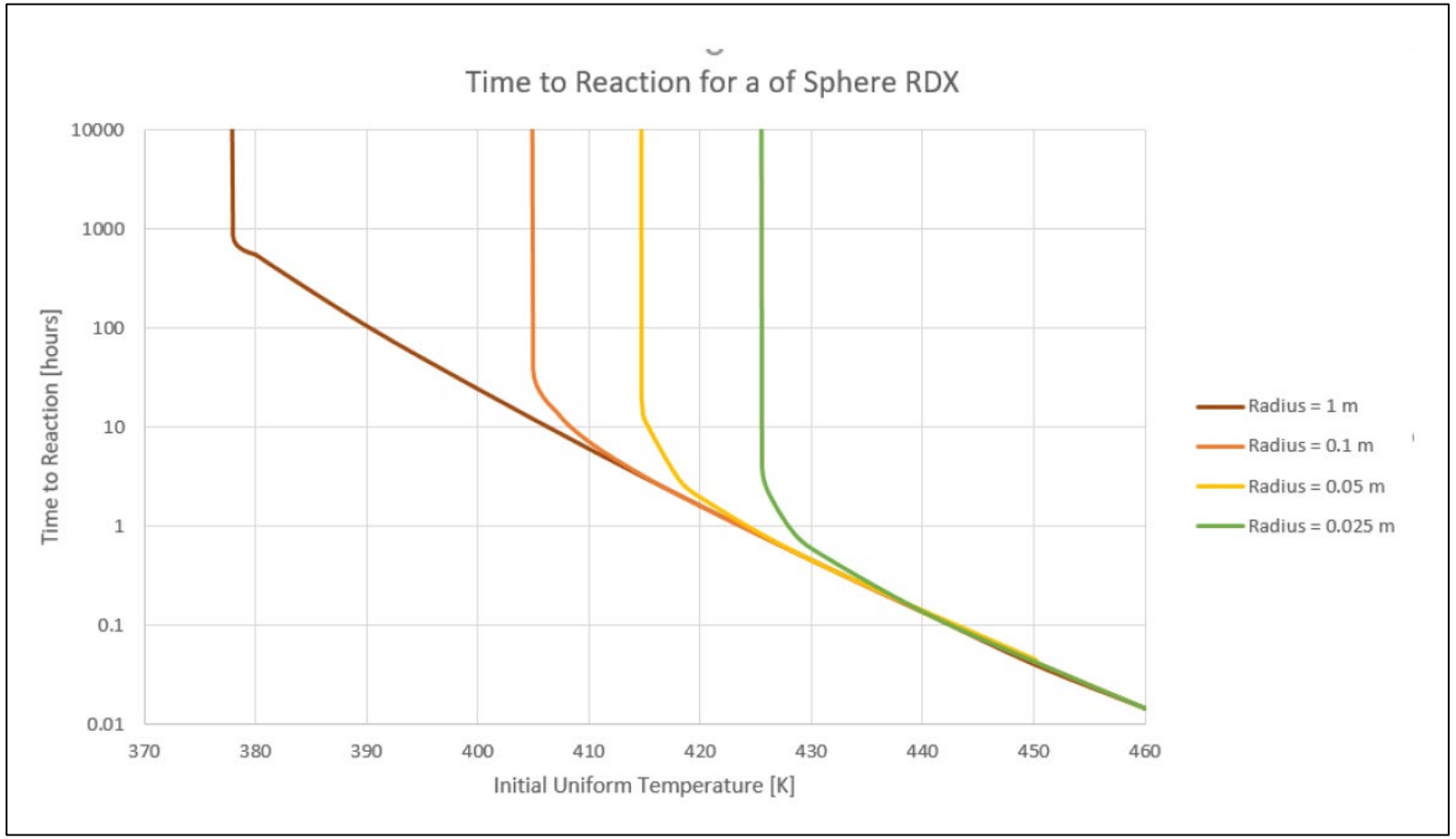
EFFECTS OF MATERIAL DEGRADATION



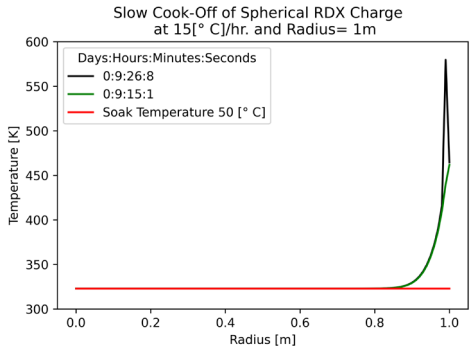


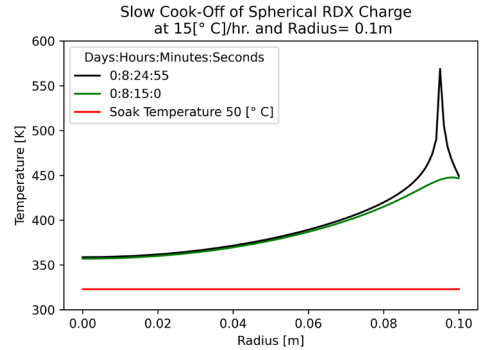
For a 0.1 m radius sphere, the Frank-Kamenetskii critical cook-off temperature is 403.96K (130.96˚C). A cook-off temperature of 404K (131˚C) resulted in the material reaching a maximum of 412.5K (139.5˚C) at 2 days and 6 hours, after which the degraded explosive produced less heat and the material started to cool.

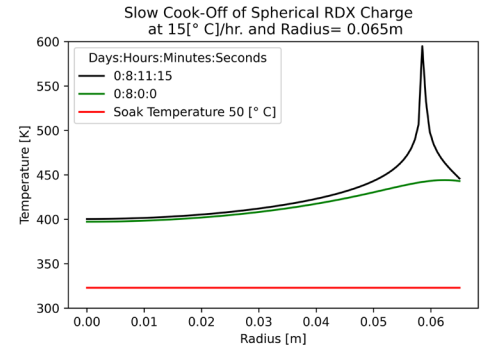
EFFECT OF SIZE

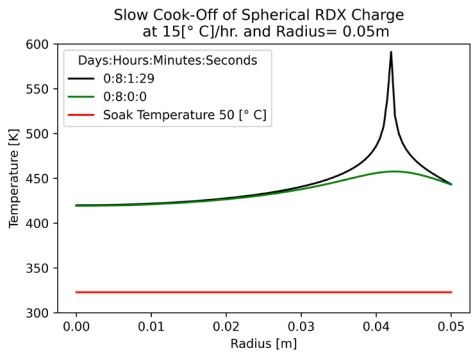


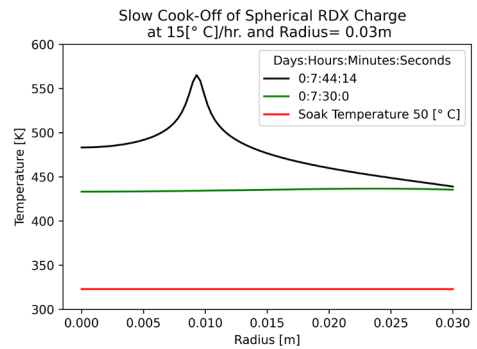
SLOW COOK-OFF OF VARIOUS DIAMETER SPHERES, 15˚C/HR. OLD RATE

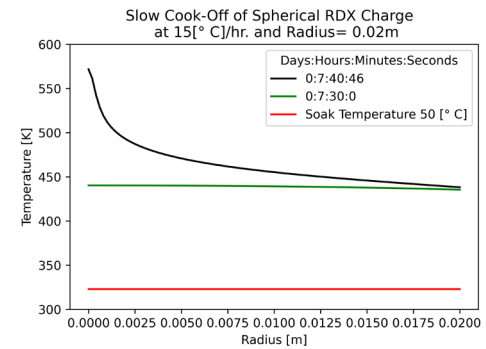


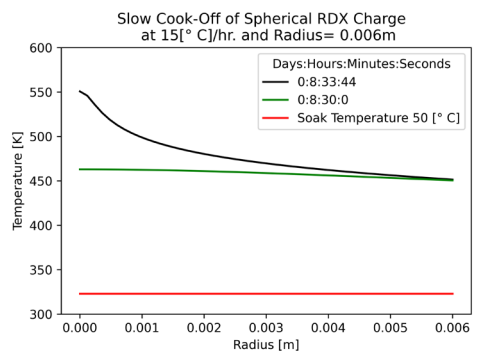






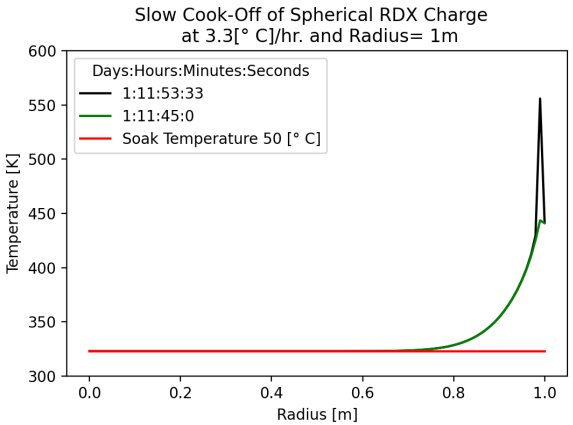


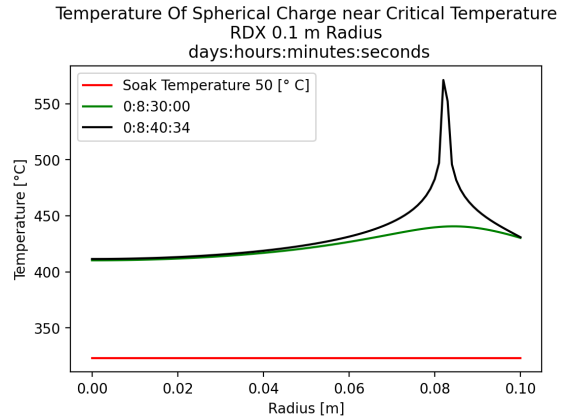


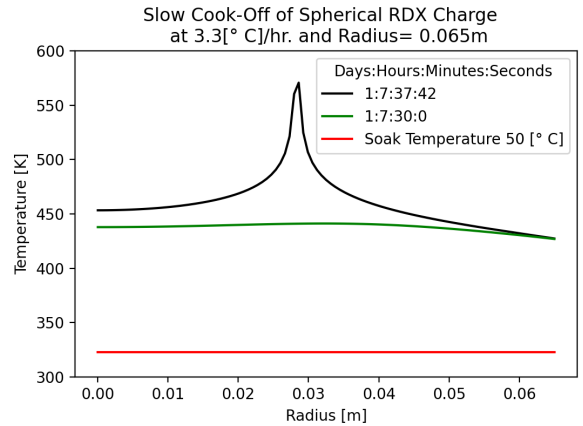


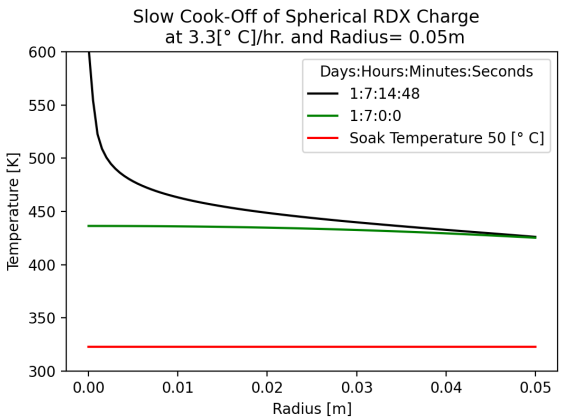
Old Rate 3.3˚C/hr.

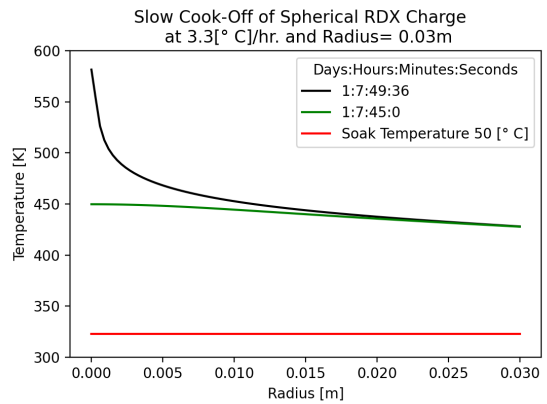
SLOW COOK-OFF OF VARIOUS DIAMETER SPHERES, 3.3˚C/HR. NEW RATE

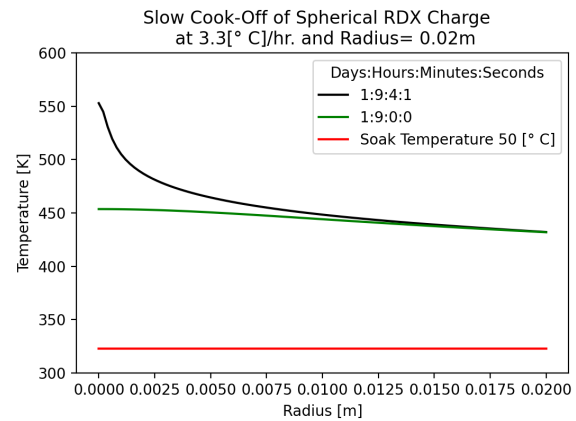




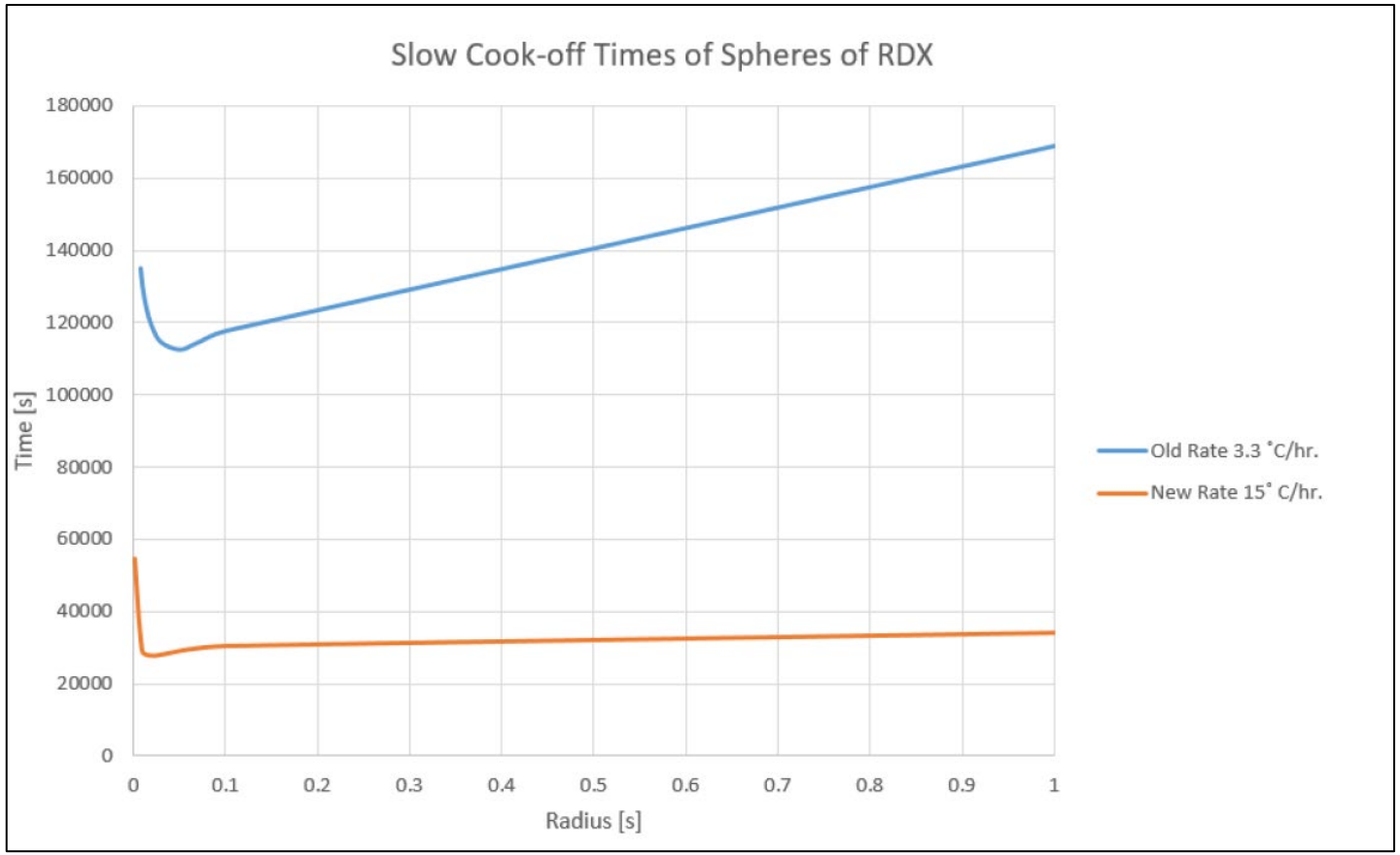








TIME TO REACTION WITH INCREASING SIZE, OLD AND NEW RATE



CONCLUSION

This study was conducted to find trends in the predicted values for cook-off using a simple Arrhenius equation for reaction. This should predict the following trends:

- Effects of degradation of the energetic materials in cook-off scenarios are more pronounced for slower rates and for smaller charges.
- Slower rates tend to move the ignition towards the center of the charge, but also allow for a greater degradation of the material and potentially less violent reactions.
- Faster cook-off rates not only decrease the time to ignition, they decrease the effects of size.
- It is possible to heat an item slowly enough such that no violent reaction occurs. This effect is more pronounced for smaller charges.
- Often impending violent reactions have no indication on the surface of the charge as there is no rapid increase in temperature on the surface.

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

(U) Energetic Defects Characterization (EDC)

(U) An AI approach to automated defect recognition

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Mathematician | Operations Research Analyst

ESIC—Systems Engineering Directorate—Systems Analysis Division

Distribution Statement A:
Approved for public release;
Distribution unlimited.

18 OCT 2022

Project Overview

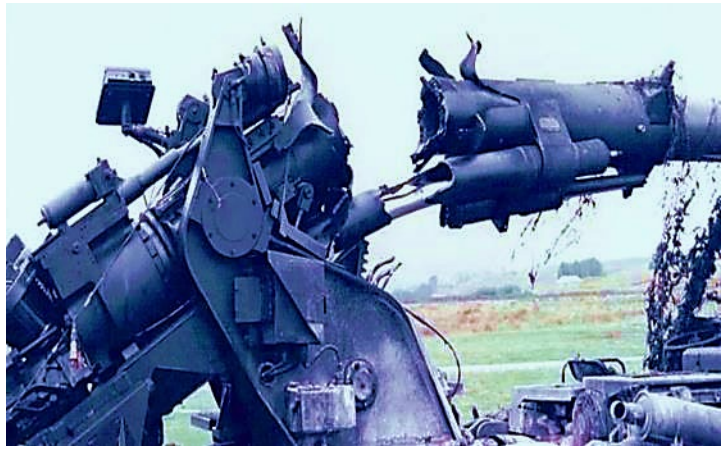
What is EDC?

Why does it matter?

ENERGETIC DEFECT CHARACTERIZATION

Problem:

- ***Defective*** artillery *have caused* catastrophic failures at gun launch, with ***consequences*** resulting in fatalities and damage to personnel and platforms.
- ***Current and future*** *energetic requirements* exceed prior gun/barrel designs and flight environments.



https://mothership.sg/2019/02/1997-waiouru-accident-history-nsf-die/

https://www.nbcnews.com/news/world/haunting-image-soldier-killed-blast-released-army-n754346

https://www.quora.com/How-does-an-exploded-shell-in-the-barrel-of-a-tank-look-like

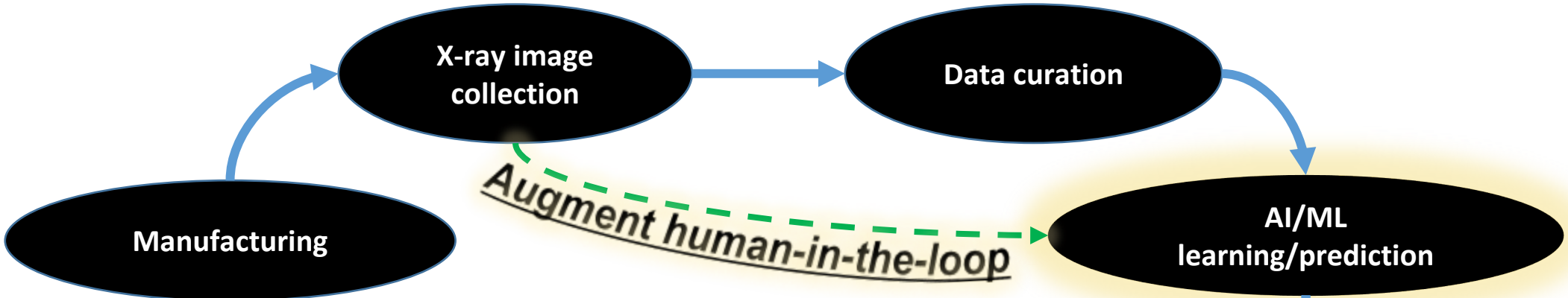
Solution:

- **Technical Approach**
  - Develop capabilities to enable experimental and computational evaluation & prediction of energetics with defects, AI/ML on images.
- **Deliverable**
  - Self-sufficient, stand-alone predictive capability

WHERE WE FIT INTO THE BIG PICTURE?

Imaging with defect detection in mind
- Instrumentation
- Calibration

Reporting with traceability and AI in mind
- Meta data
- Defect categorization



Better munitions
- Iteratively smarter inputs/outputs
- Safer and increased reliability

CNN output can inform manufacturing processes
- Predictions + Traceability = Optimized process control

AI/ML
- Powerful learning tools
- Academic/industry precedence for AI + X-ray

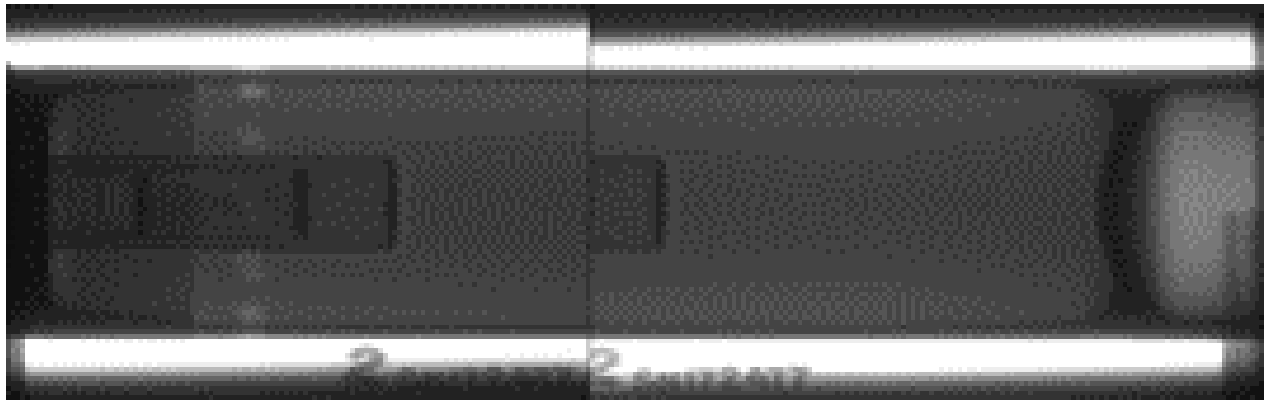
Support categorization of defect hazard levels

The Data

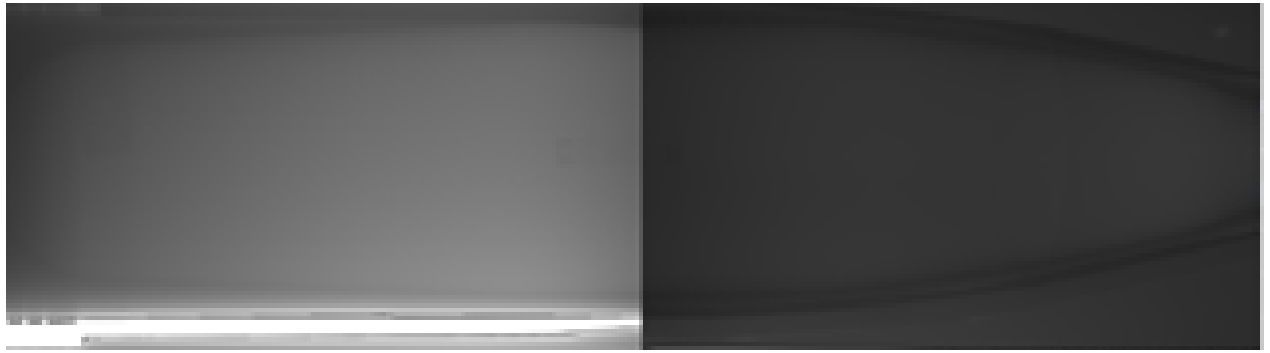
What format?

How much?

X-RAY DATA

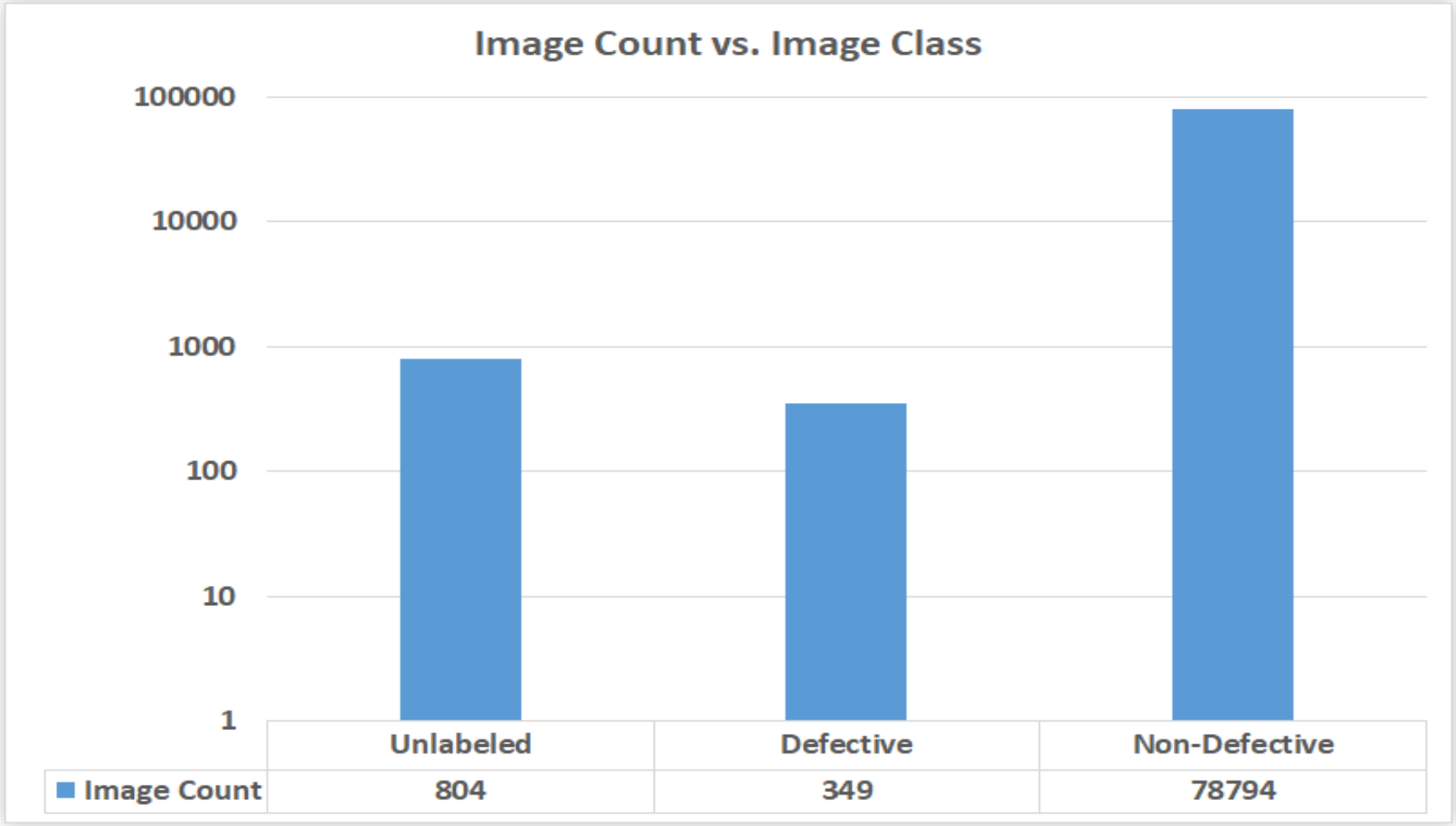


Type-1	2012—2015	Pressed	X-ray	4	600 GB
Munition	**Date**	**Explosive**	**Format**	**Aspects**	**Set Size**
Type-2	2020—2021	Melt Pour	X-ray	1	680 GB



TYPE-2 IMAGE SET CHARACTERISTICS

- Data suggests that only 1 in ~217 munitions is defective
- Will have to overcome data imbalance and any mislabeling

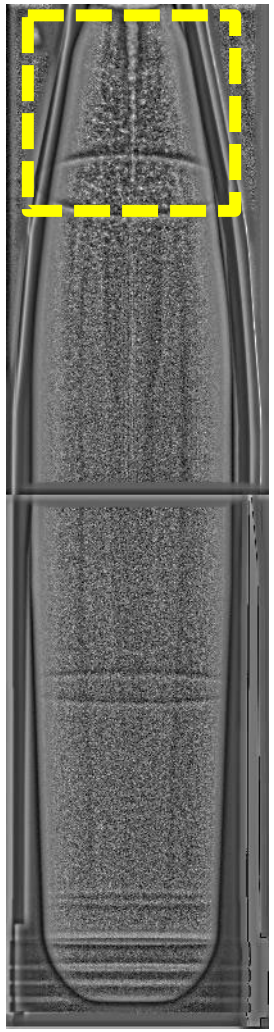


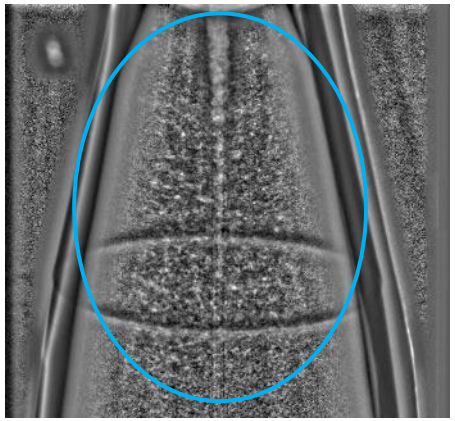
16 bit—grayscale—TIFF format

Considering Data Quality

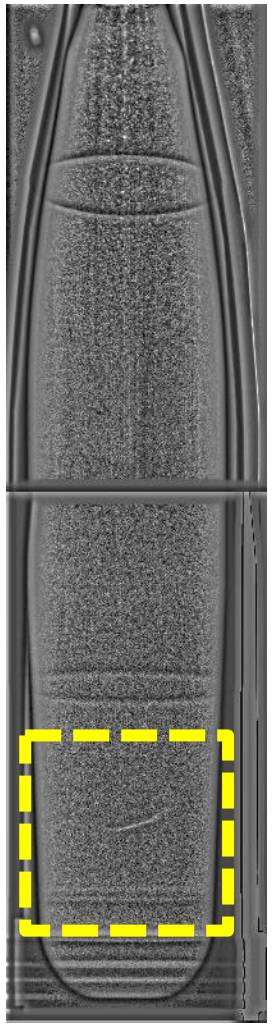
Pedigree of labels?

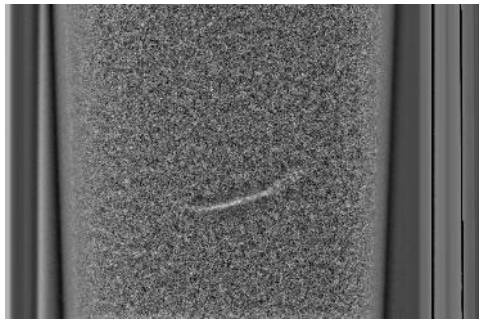
MANUAL IMAGE INSPECTION



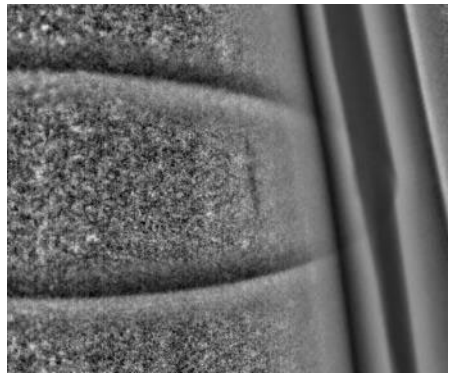


- **Labeled Defective**
- Shrink Porosity
- 37 Images



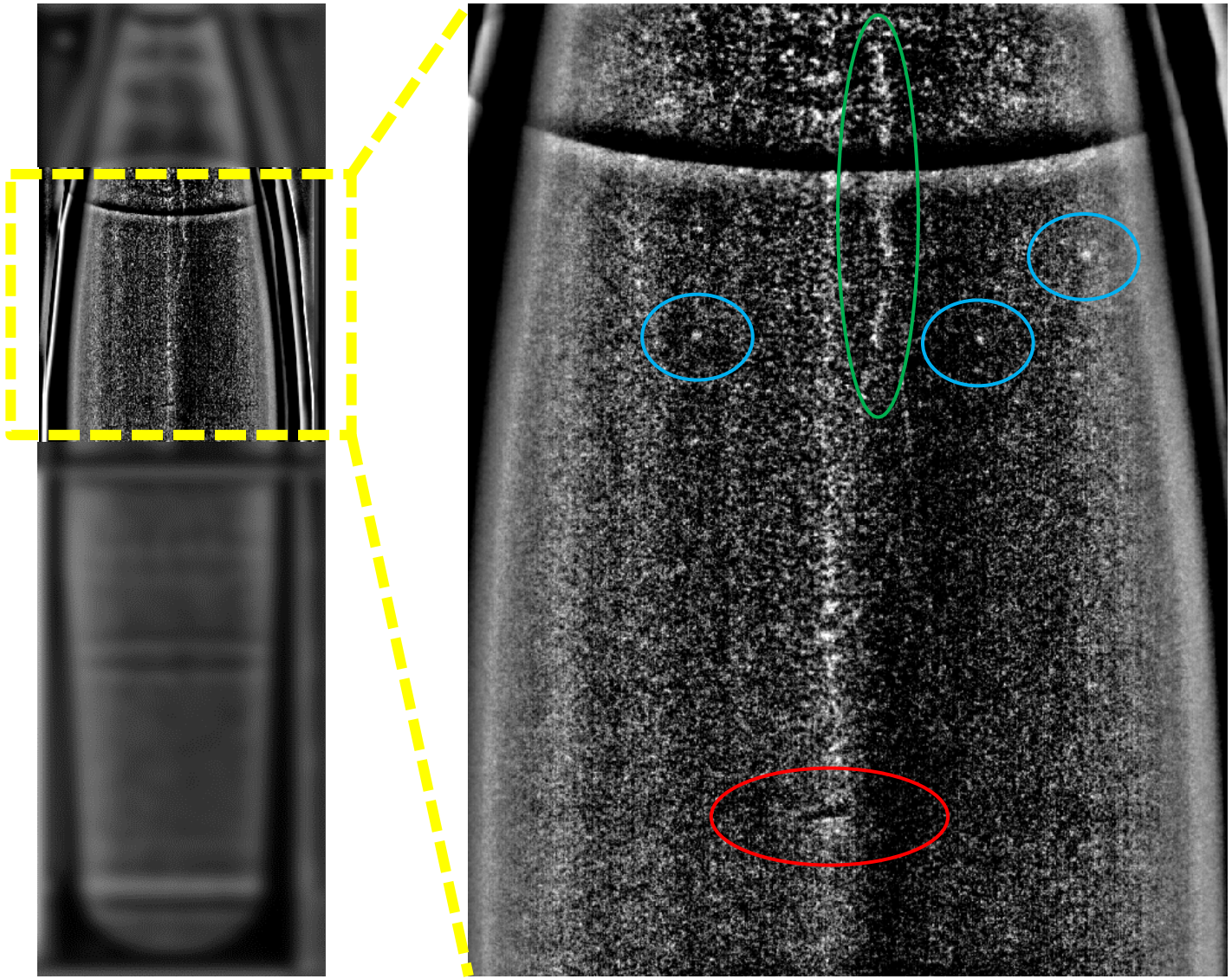


- **Labeled Defective**
- Cracks
- 58 Images



- **Labeled Defective**
- Foreign Material
- 8 Images

MANUAL IMAGE INSPECTION



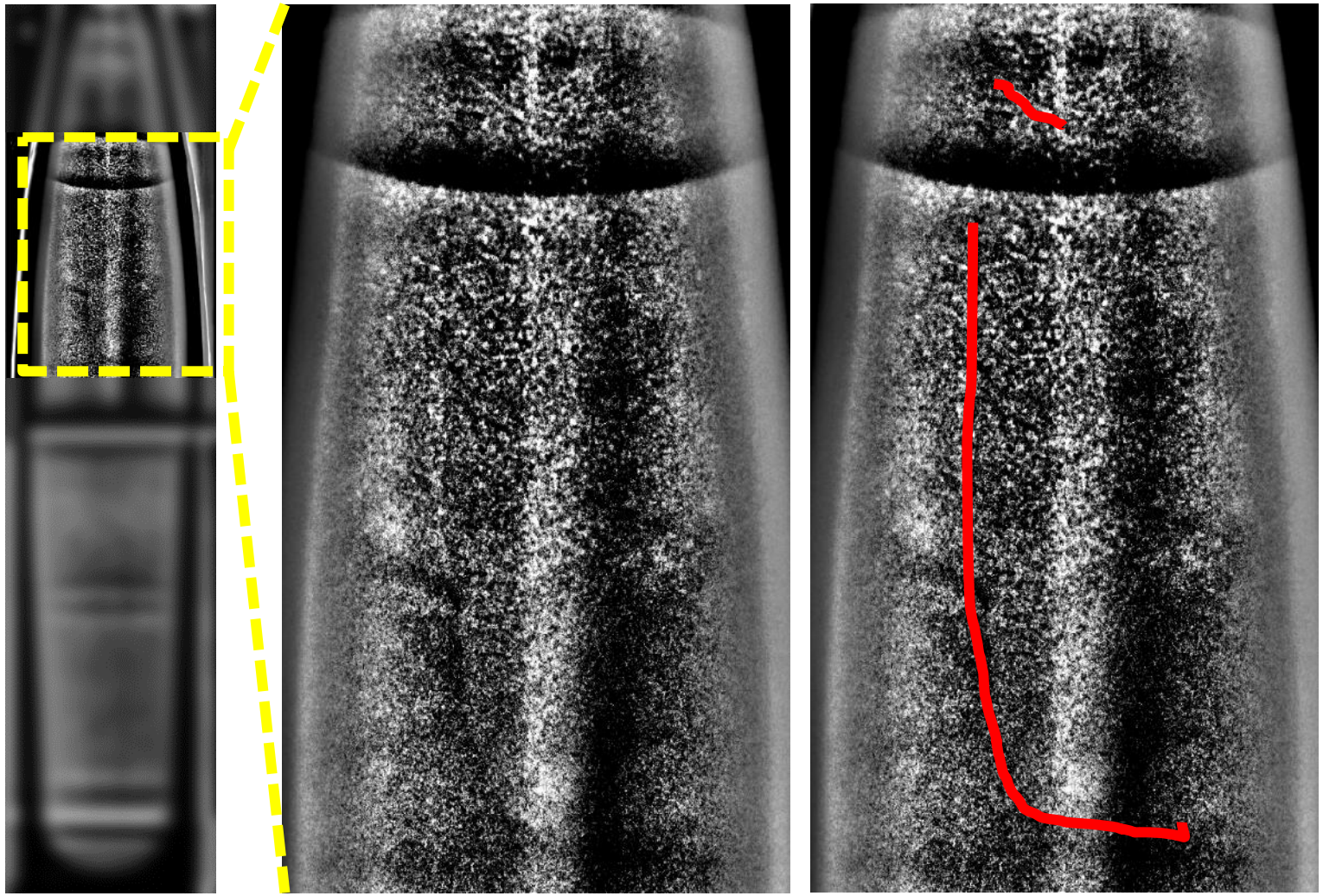
Piping

Gas/shrink porosity

Crack

- **Is the data accurately curated for AI/ML?**
  - Image below **tagged as Non-defective**
  - **SME confirmed** presence of **anomalies**
    - **Possibly not sufficient to fail the Type-2 munition MILSPEC**

MANUAL IMAGE INSPECTION



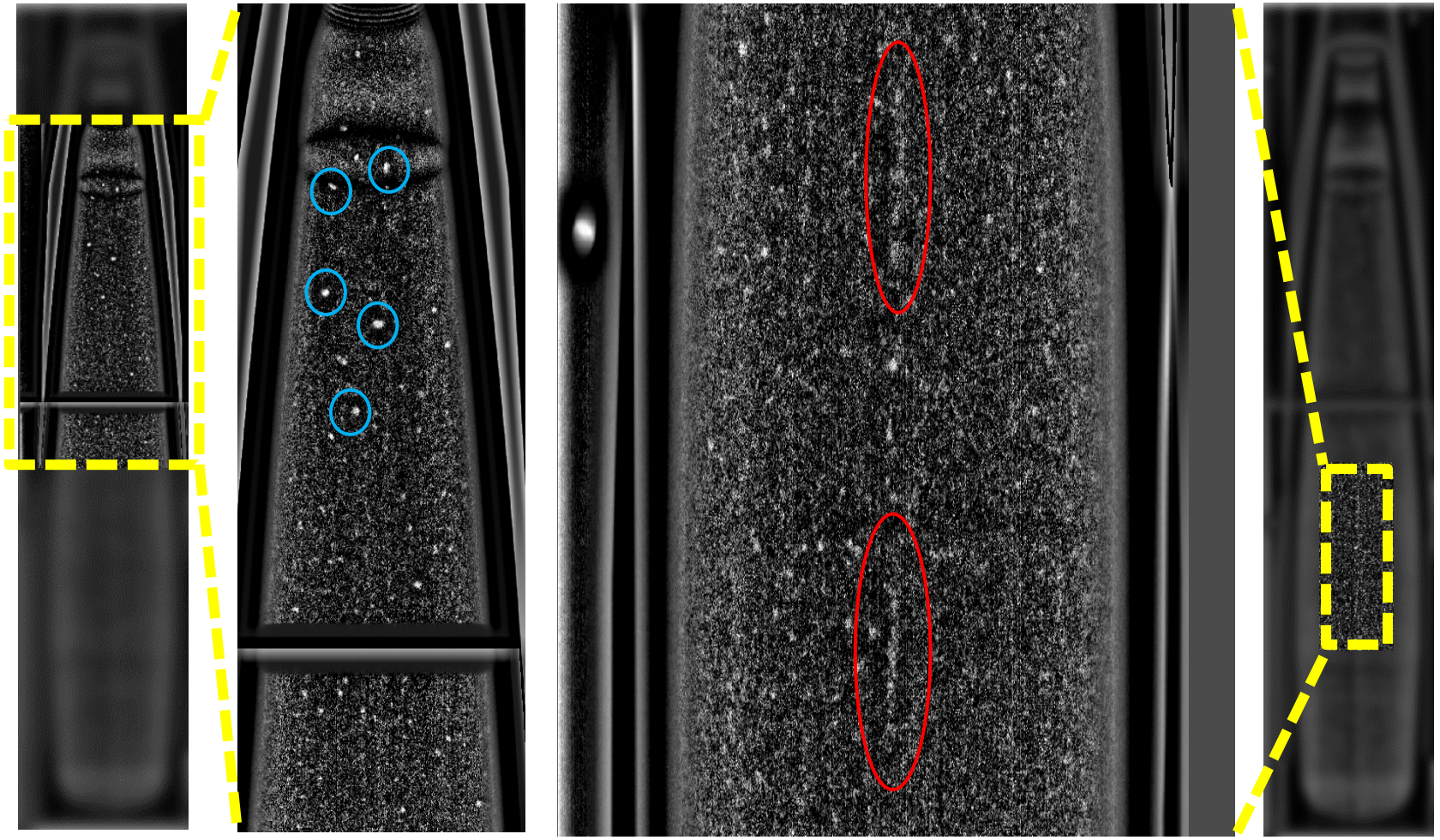
Piping

Gas/shrink porosity

Crack

- **Is the data accurately curated for AI/ML?**
  - Image below **tagged as "Non-defective"**
  - **SME confirmed** presence of **anomalies**
    - **Possibly not sufficient to fail the Type-2 munition MILSPEC**
    - Internal team assessed anomalies as a crack and the SME assessed as shrink porosity

MANUAL IMAGE INSPECTION



Piping

Gas/shrink porosity

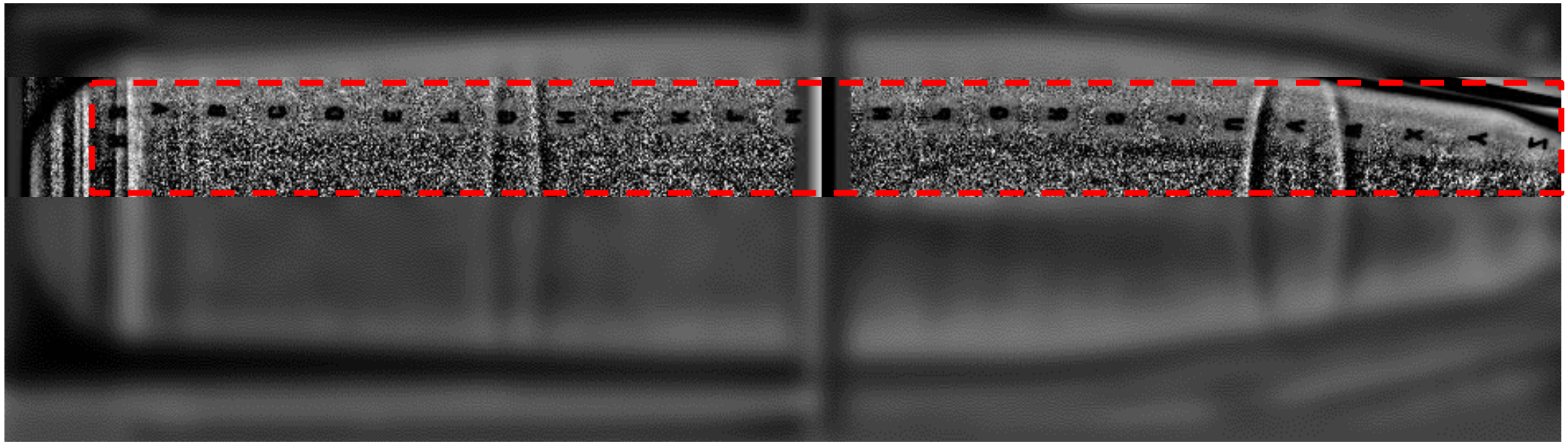
Crack

- **Is the data accurately curated for AI/ML?**
  - Image not present in curation data but in the data set
  - **SME confirmed** presence of **anomalies**
    - **Possibly not sufficient to fail the Type-2 munition MILSPEC**

MANUAL IMAGE INSPECTION

- **Are the images consistent enough across class type?**
  - Image below has the alphabet running along the munition

- **Too easy to find inconsistencies by accident**
  - Traditional CNN classification labels are set without uncertainty
    - A cat is a cat, a dog is a dog
    - In contrast, the Type-1 munition images & labels are riddled with oddities



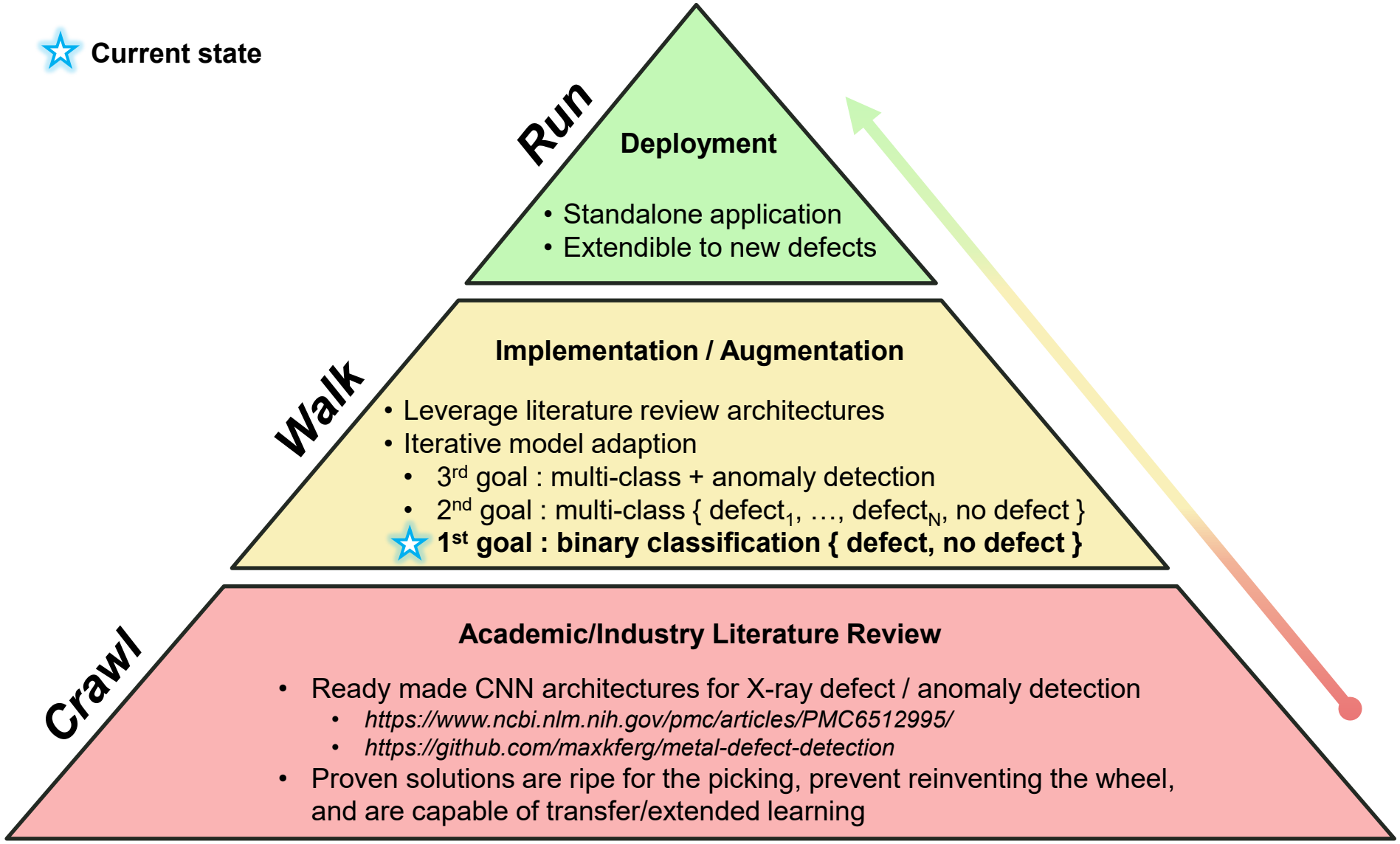
Can we use an anomaly detector to remove or reclassify outlier data?

High-level Methodology

Crawl, walk, run

PATH TO TRAINING ARMY DEFECT DETECTION MODEL

☆ Current state

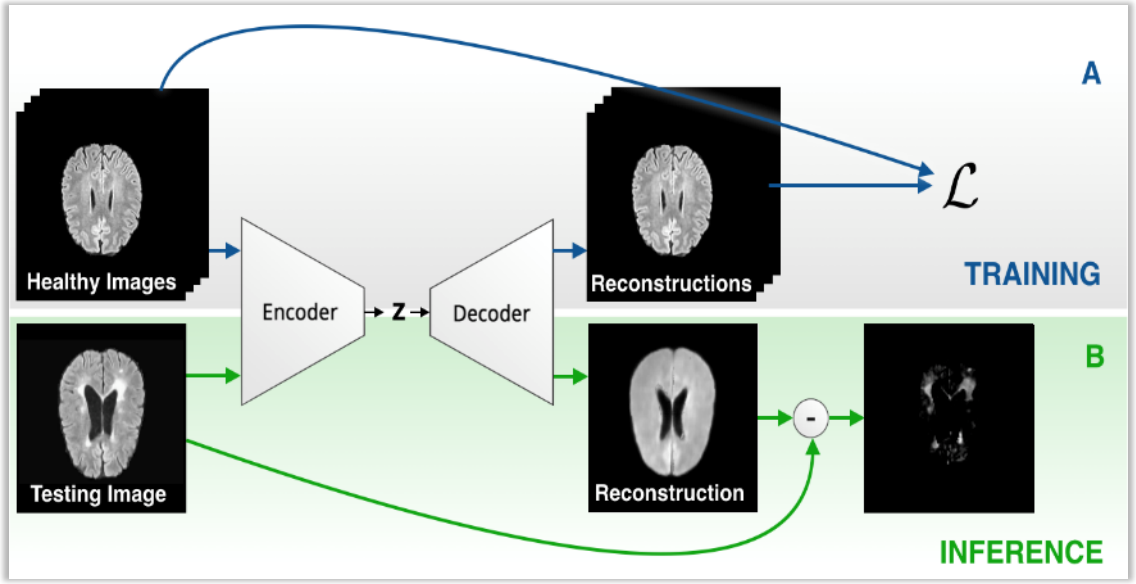


Binary Classification

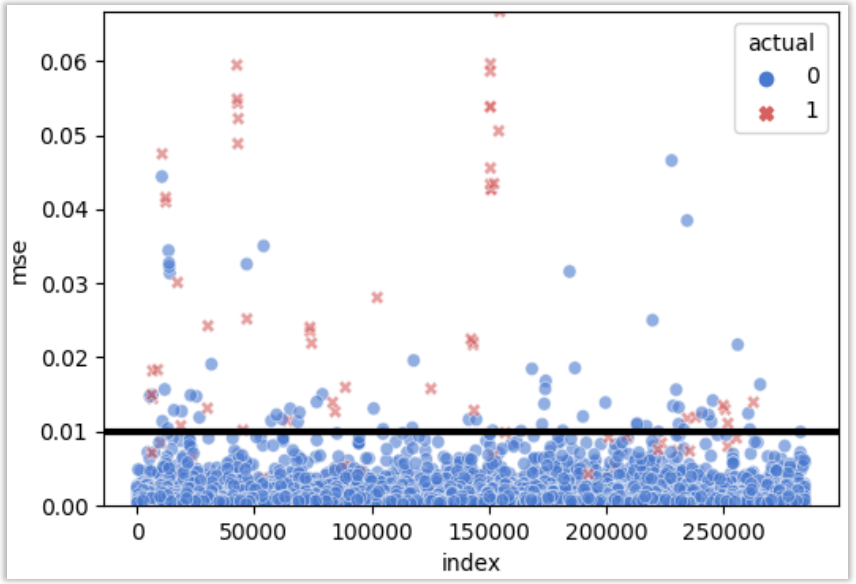
A layered defense approach

EDC AI PLANNED ARCHITECTURE

- **1st Layer : Autoencoder Anomaly Detector**
  - AI to characterize Non-defective munition images
    - Model learns a compression and decompression algorithm for Non-defective munition images
    - Trained model applied to Defective munition images will poorly compress and decompress resulting in a useful discriminator metric—reconstruction loss
    - Reconstruction loss analyzed via minimized cross-entropy to establish optimal threshold to flag outlier/anomalistic input images



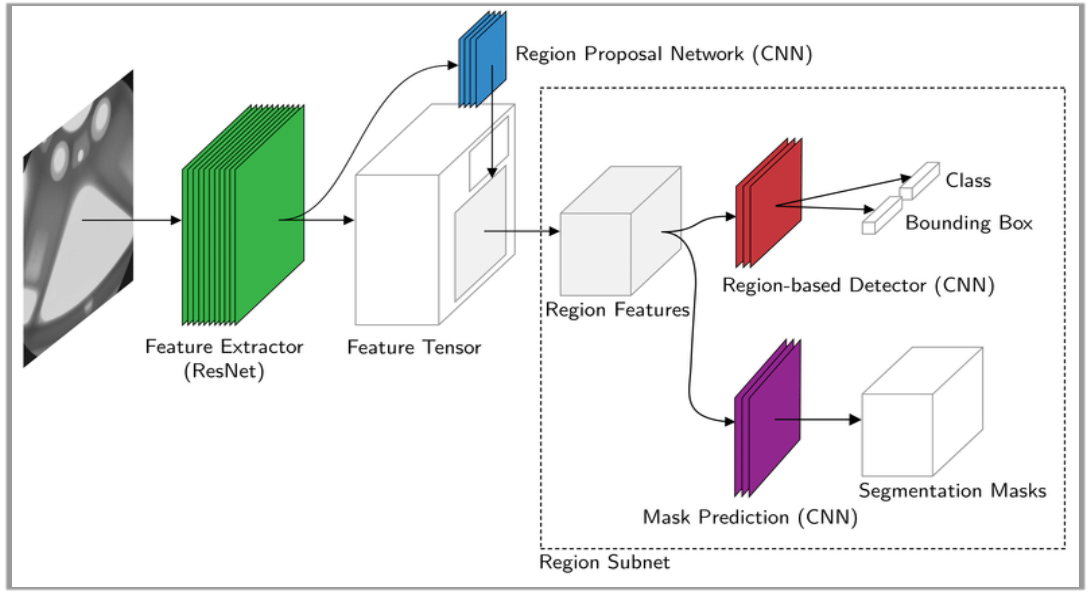
https://deepai.org/publication/autoencoders-for-unsupervised-anomaly-segmentation-in-brain-mr-images-a-comparative-study

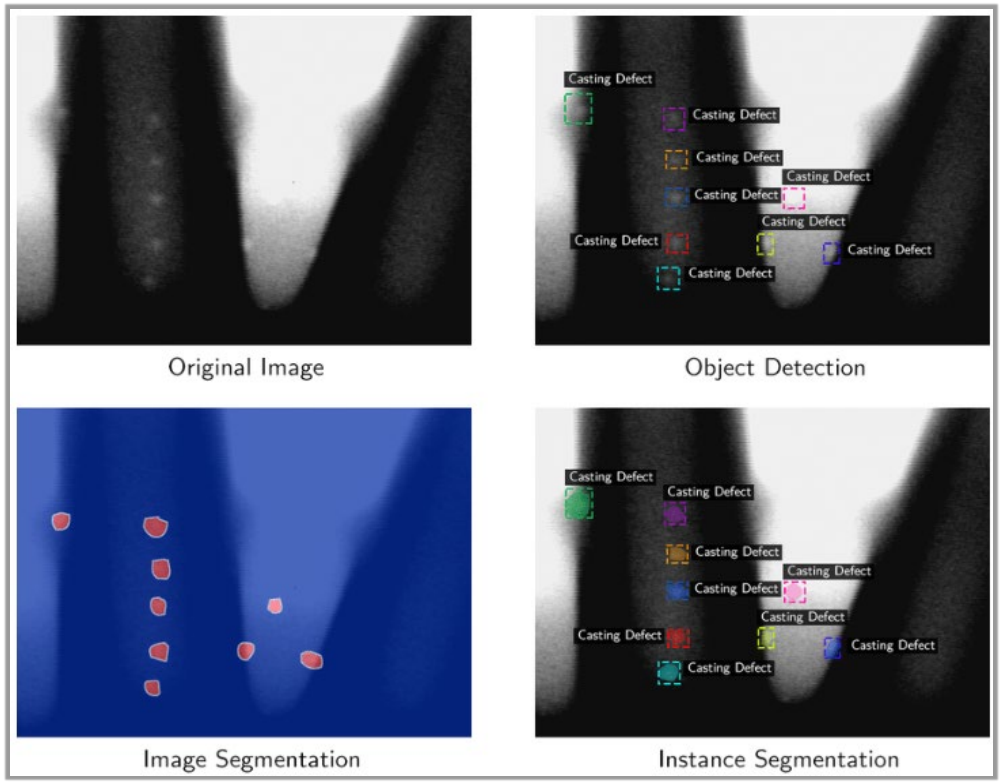


https://minimatech.org/wp-content/uploads/2021/02/threshold_line.png

EDC AI PLANNED ARCHITECTURE

- **2nd Layer : Feature Extractor + MILSPEC**
  - Line, edge, cluster detector
    - Length, width, density measurement
    - Assessments against MILSPEC thresholds
    - Flag and tag ROIs for expert analysis

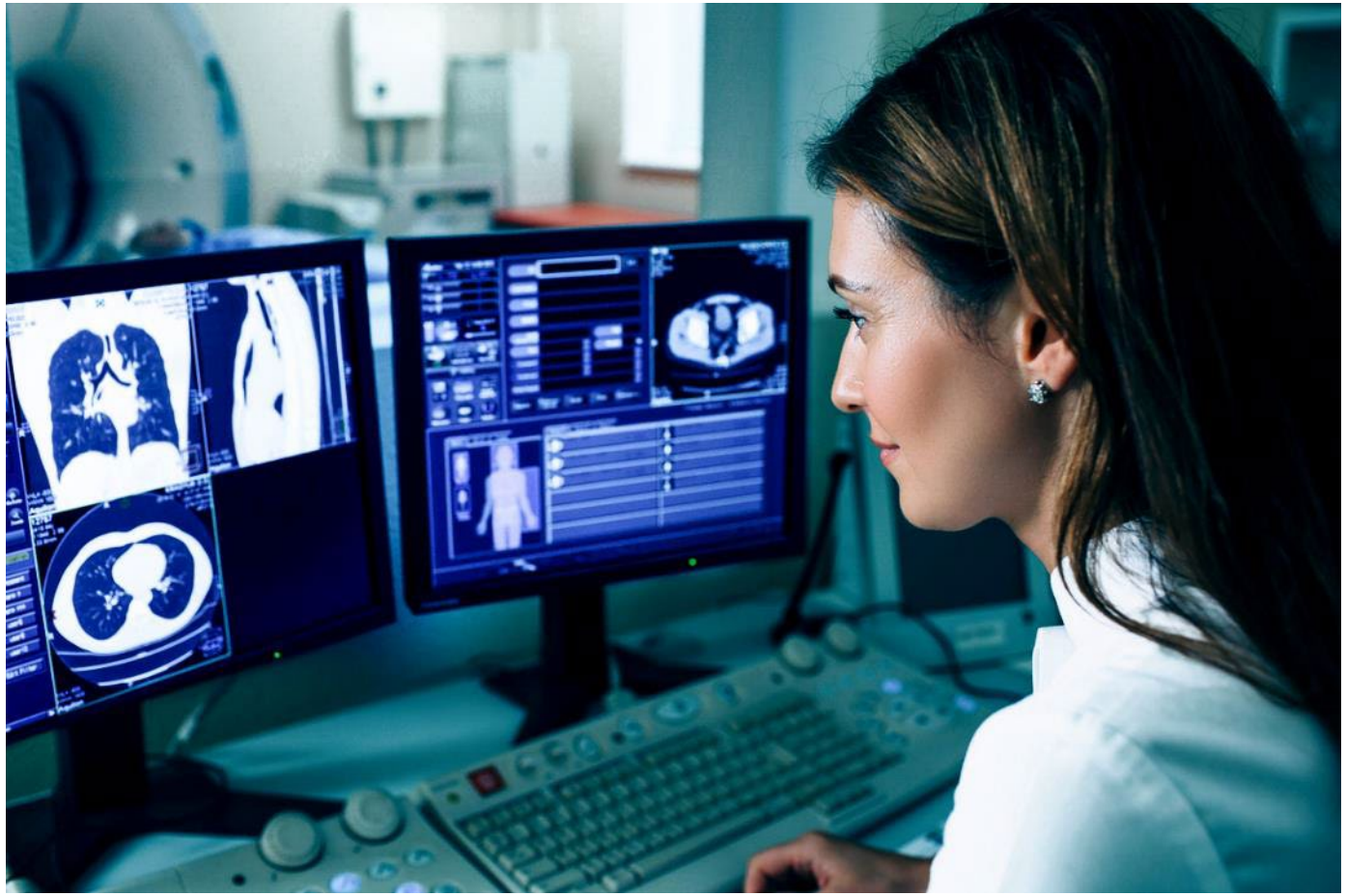




https://www.researchgate.net/figure/The-neural-network-architecture-of-the-proposed-defect-detection-system-The-system_fig5_327392506

EDC AI PLANNED ARCHITECTURE

- **3rd Layer : Human-in-the-loop**
  - Focused attention to flagged images failing 1st and 2nd layer AI filtering



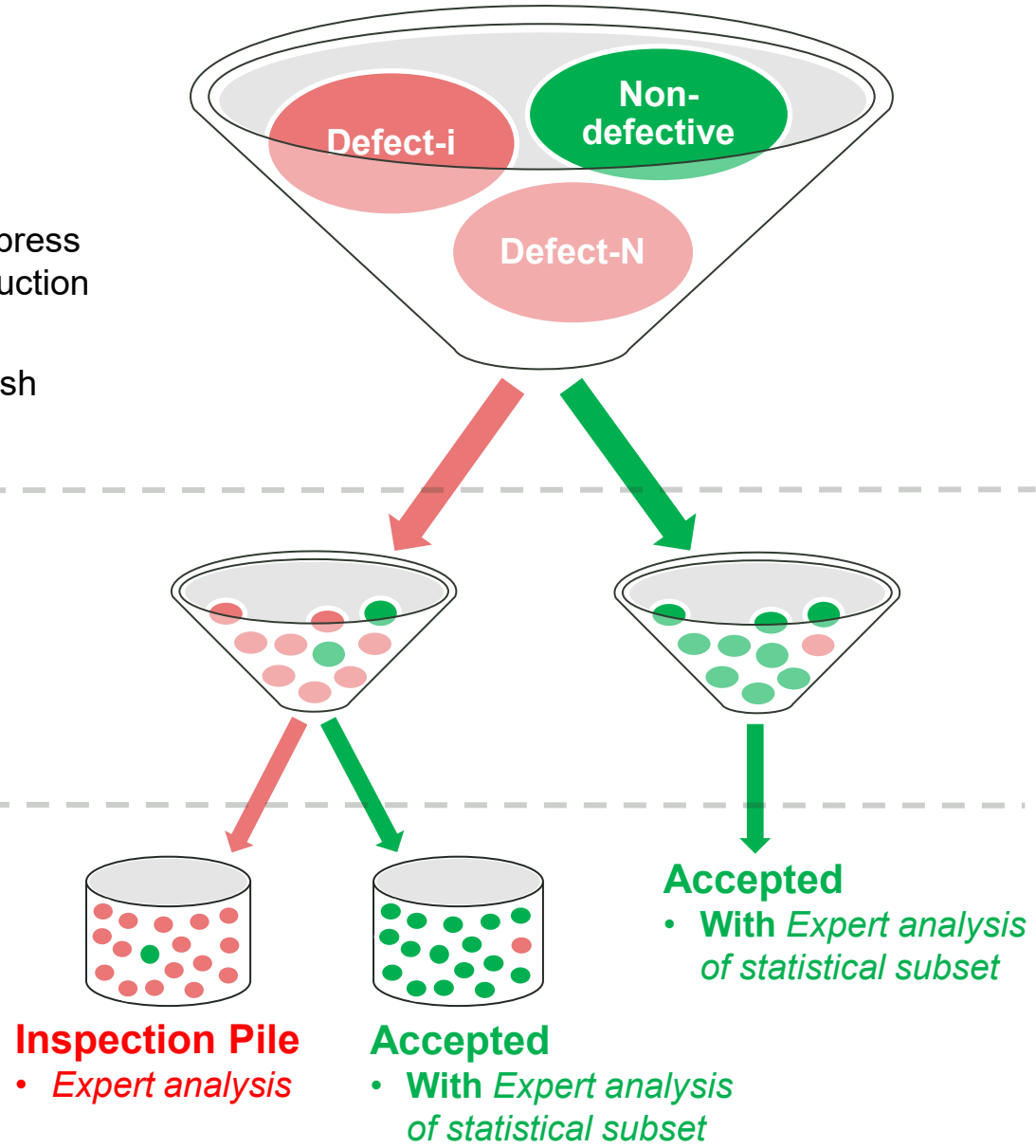
https://windsorimaging.com/wp-content/uploads/2020/04/Windsor-Imaging-The-History-of-the-Digital-X-Ray.jpg

PLANNED ARCHITECTURE OVERVIEW

- **1st Layer : Autoencoder Anomaly Detector**
  - AI to characterize Non-defective munition images
    - Model learns a compression and decompression algorithm for Non-defective munition images
    - Trained model applied to Defective munition images will poorly compress and decompress resulting in a useful discriminator metric—reconstruction loss
    - Reconstruction loss analyzed via minimized cross-entropy to establish optimal threshold to flag outlier/anomalistic input images

- **2nd Layer: Feature Extractor + MILSPEC**
  - Line, edge, cluster detector
    - Length, width, density measurement
    - Assessments against MILSPEC thresholds
    - Flag and tag ROIs for expert analysis

- **3rd Layer : Human-in-the-loop**
  - Focused attention to flagged images failing 1st and 2nd order AI filtering



Computing Resources

What is HPCMP?

DOD HPCMP

DOD High Performance Computing Modernization Program

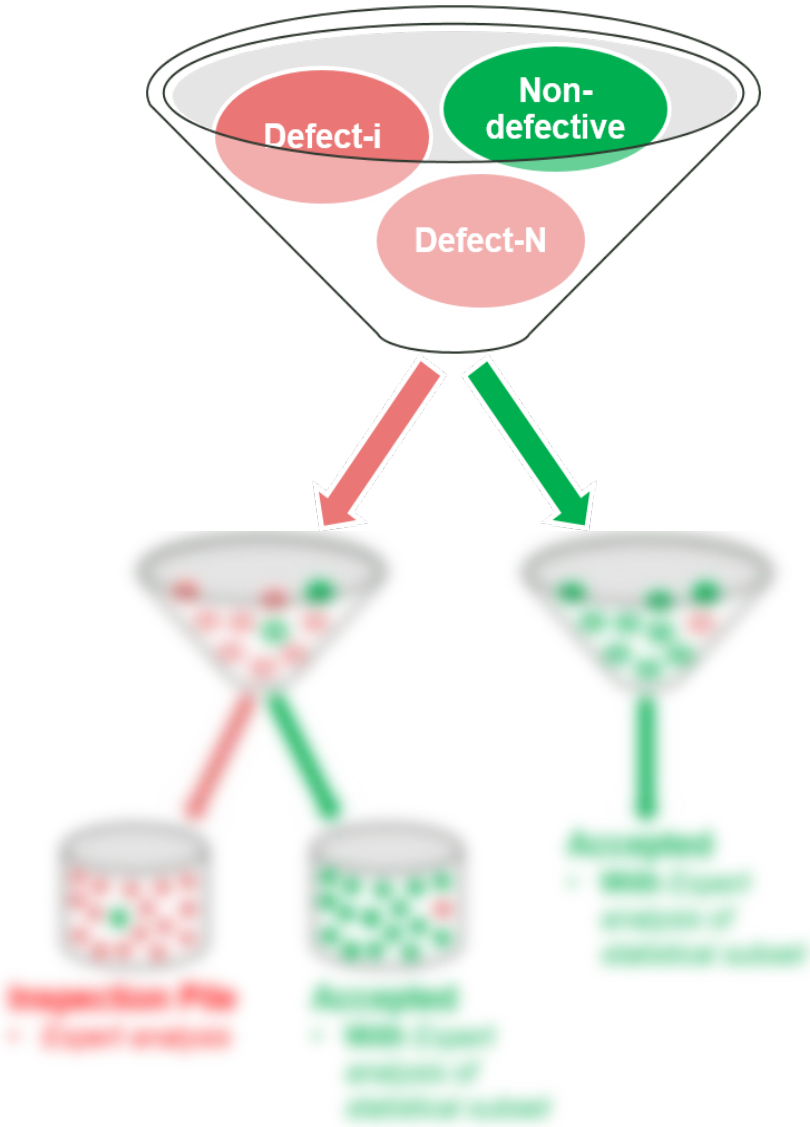
The U.S. Army *E*ngineer *R*esearch and *D*evelopment *C*enter

ERDC ENGINEER RESEARCH & DEVELOPMENT CENTER — DISCOVER | DEVELOP | DELIVER

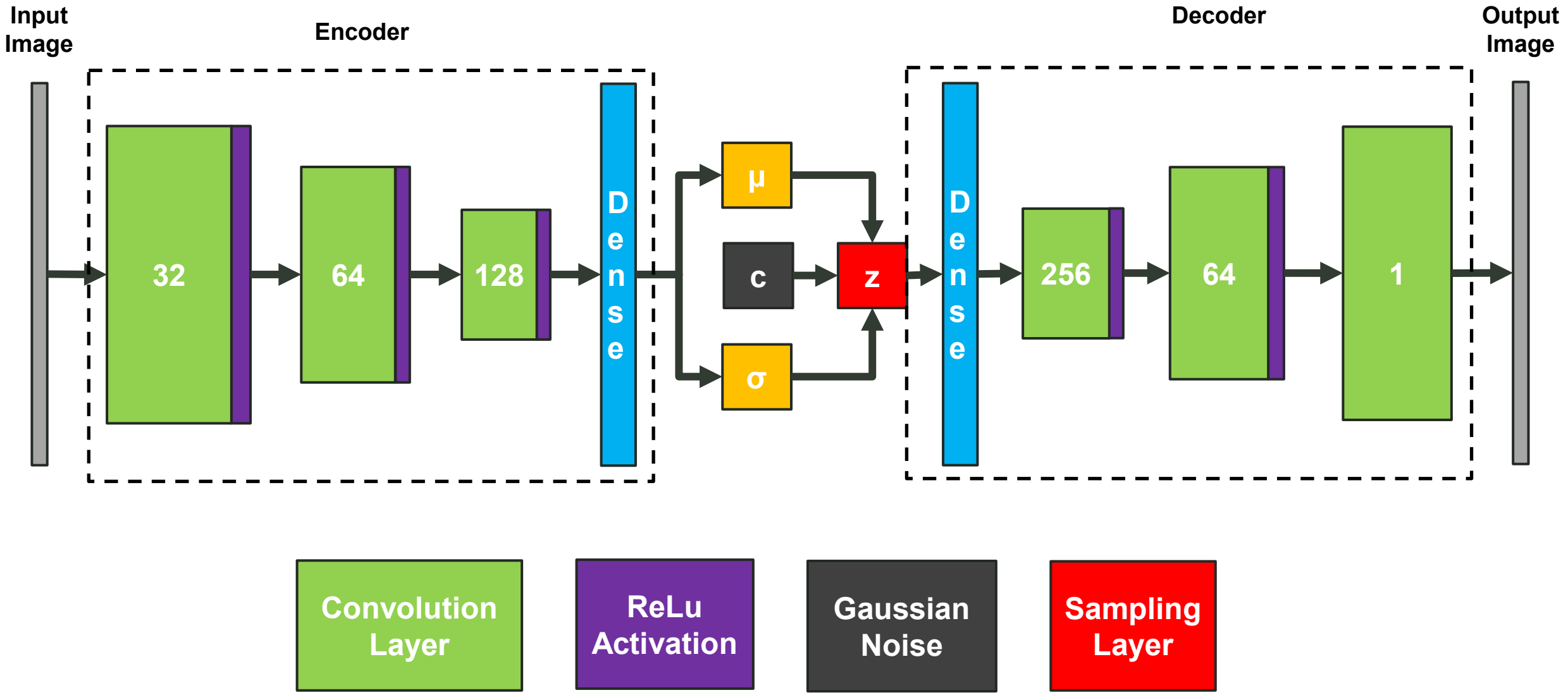
Onyx is a Cray XC40/50 system. It has 4,810 standard compute nodes, 4 large-memory compute nodes, 32 GPU compute nodes, 32 Knights Landing (Phi) compute nodes, and 64 Machine Learning Accelerator (MLA) multi-GPGPU nodes (a total of 4,942 compute nodes or 217,128 compute cores). It is rated at 6.06 peak PFLOPS.

1st Layer Architecture

The anomaly detector



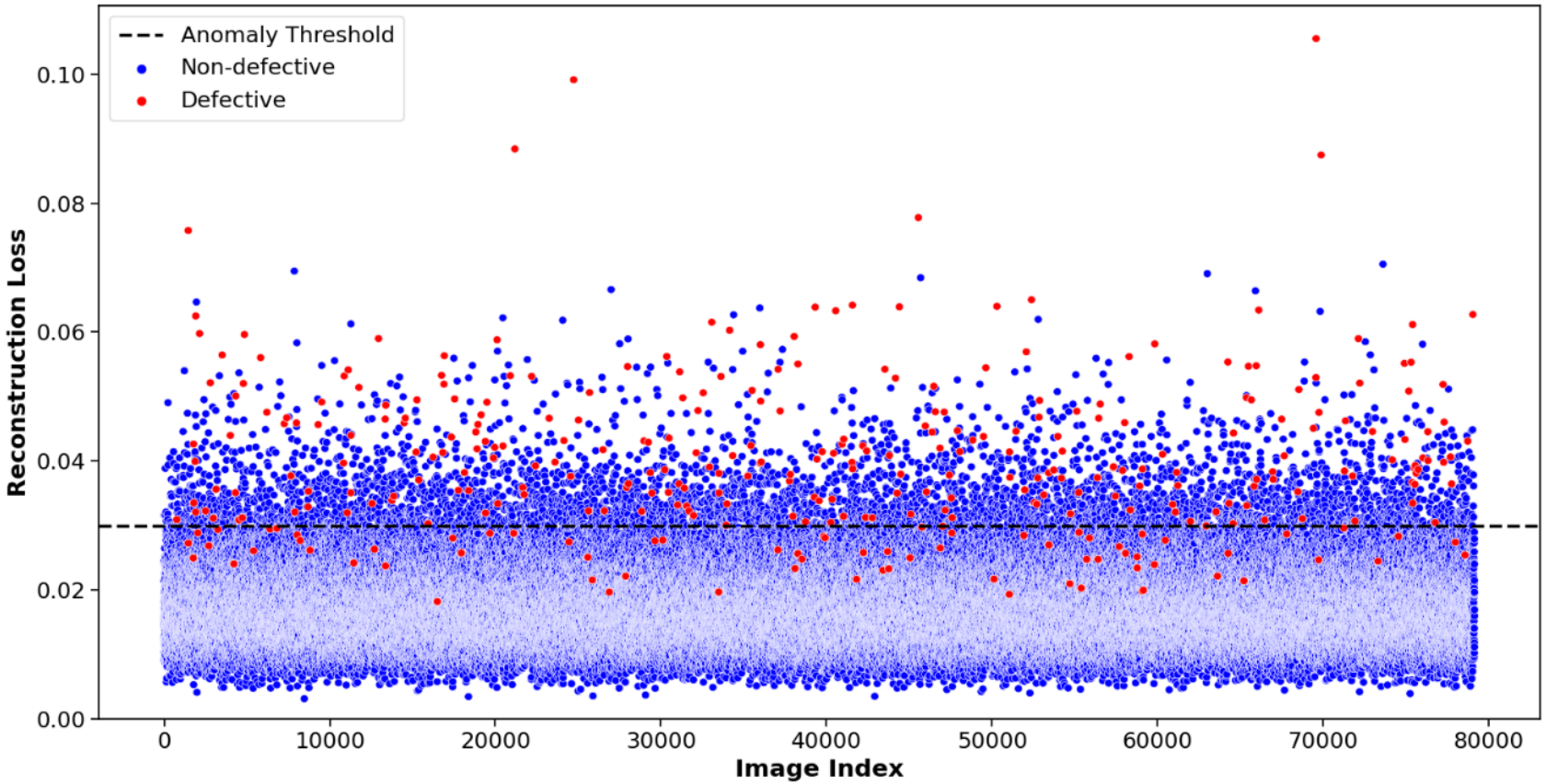
AUTOENCODER ARCHITECTURE



ANOMALY DETECTOR PREDICTIONS

Leverage 1st training to interrogate outliers from Non-defective image set

- Remove images with questionable class labels, e.g. images with alphabet soup
- Removals will tighten up learned distribution of normal image set
- Tighter normal image distribution makes setting anomaly threshold less subjective
- Effect will be decreased false positives



ANOMALY DETECTOR PATH FORWARD

1. **Mask image to isolate munition**
   - Noisy and distractive features occurring outside the munition ROI
2. **Reclassify or remove normal images having questionable labels**
   - Retrain the model
3. **Reevaluate Autoencoder threshold**
   - Minimized cross-entropy

		Predicted	
		Non-Defective	*Defective*
Actual	*Non-defective*	68847 (87.38%)	9947 (12.62%)
	Defective	74 (21.2%)	275 (78.8%)

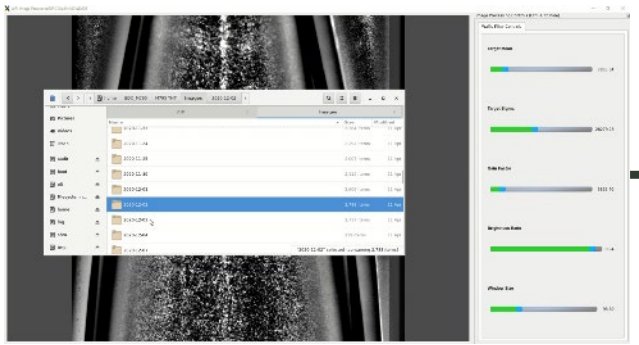
Unacceptable performance given the stakes

Deployable Capability

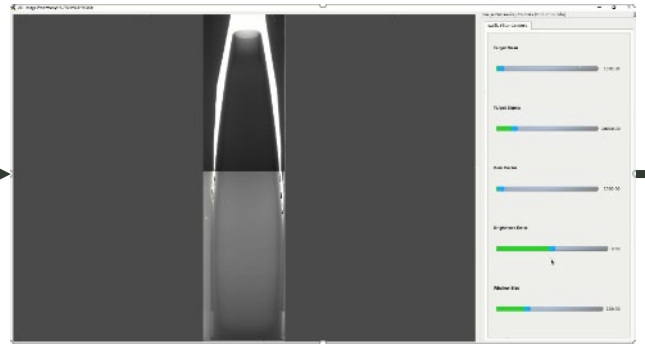
Tooling and capability integration in parallel

DEPLOYABLE TOOLS

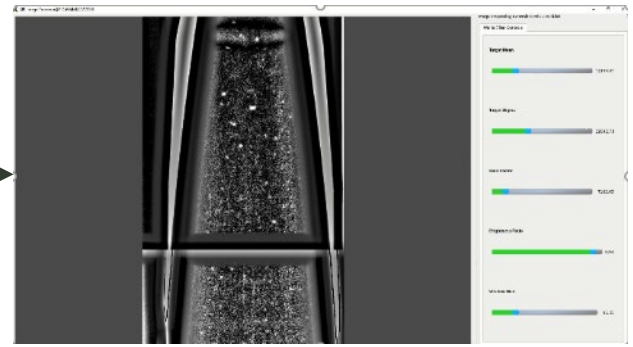
Wallis Filter



Browse & Drag-drop images

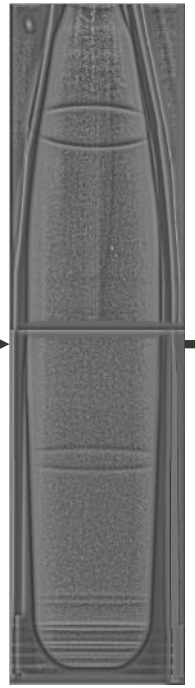


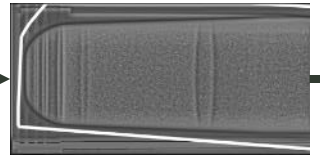
Apply filter settings & pan/zoom



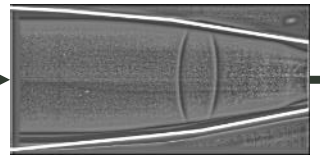
Edge Detection

Wallis Filter

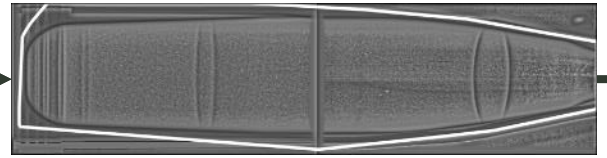




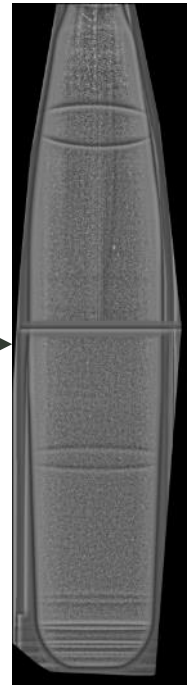
- Otsu Thresholding
- Contour Detection
- Dilation + Erosion
- Convex Hull



Combine Hulls



Background Subtraction



PATH FORWARD

Improving 1st Binary Classifier Layer

- Addressing data quality and outliers

Developing 2nd Binary Classifier Layer

- Feature Extractor + MILSPEC
- Collaborating with United States Military Academy

Striving to Reduce Catastrophic Events

https://www.nbcnews.com/news/world/haunting-image-soldier-killed-blast-released-army-n754346

Validation of Sample Extraction and Analysis Techniques for Simultaneous Determination of Legacy and IM Constituents

ER19-5078

Austin Scircle
USACE Engineer Research and Development Center

IMEM Symposium 2022

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Technical Objectives

- Demonstrate and validate extraction and analysis methods (developed under SERDP ER-2722) for simultaneous determination of 24 IM and legacy energetic compounds, in addition to surrogates, in environmental waters, soils/sediments, and tissues
- Submit final methods and validation study results to USEPA as an addendum to current Method 8330B
  - To provide an option (not an across-the-board replacement) only when legacy and IM –or– IM only determinations are required
  - To encourage standardization across DoD, contract, and research labs
- Minimize cost by reducing # of extractions, # of sample preps, and # of analyses when legacy and/or IM determinations are required
- Enable identification of environmental issues associated with IM lifecycle and investigate early with a standardized and accepted technique

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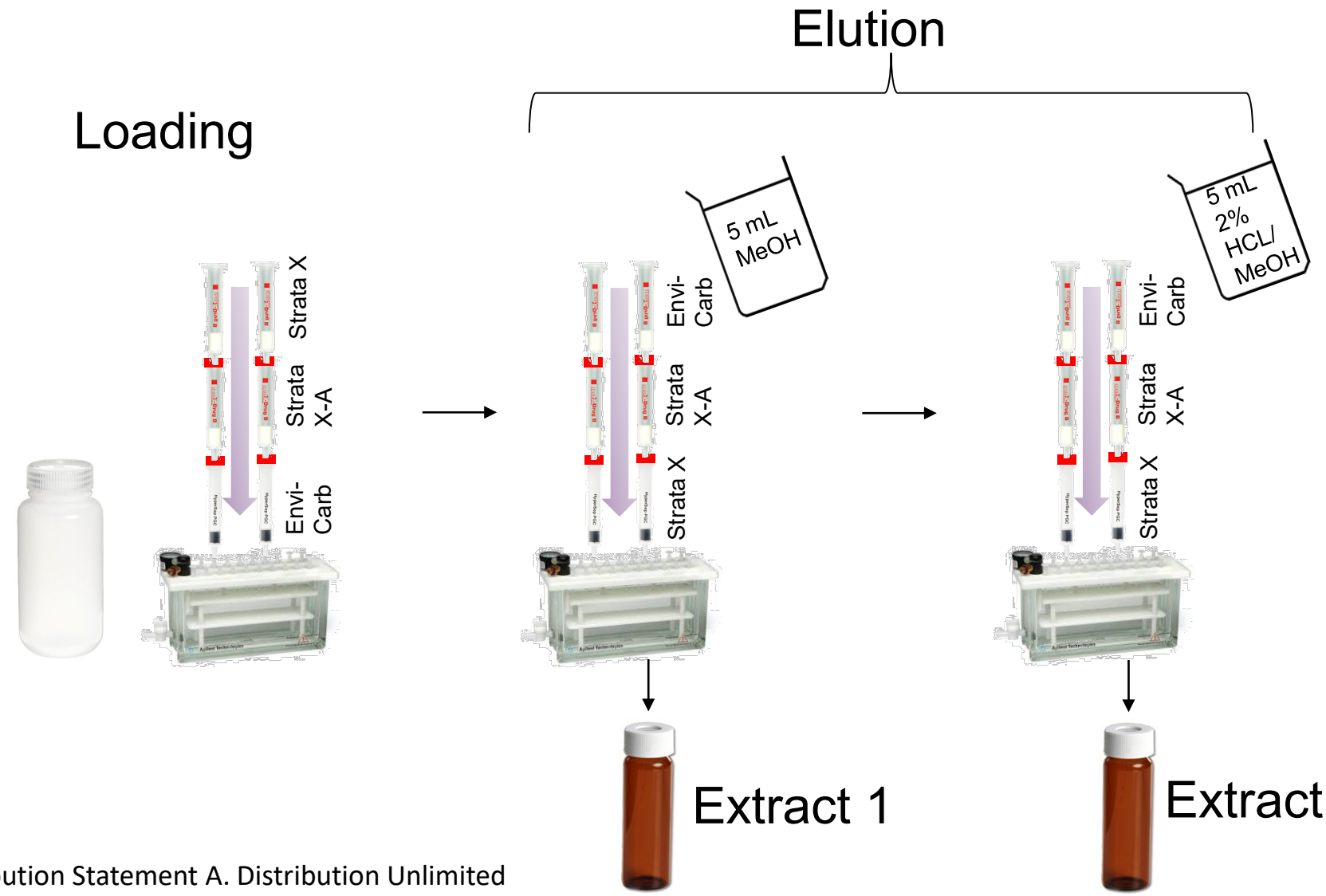
Aqueous Extraction Methods

Low-Level Aqueous SPE Method



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Solid Extraction Procedures

- 2 Step solvent extraction with sonication for soils
  - 6 hours with methanol
  - 14 hours with acidified methanol:water
  - Combine and dilute with deionized water to final 50:50 ratio
- Tissue solvent extraction
  - Single methanol extraction
  - Clean up process to remove interfering components

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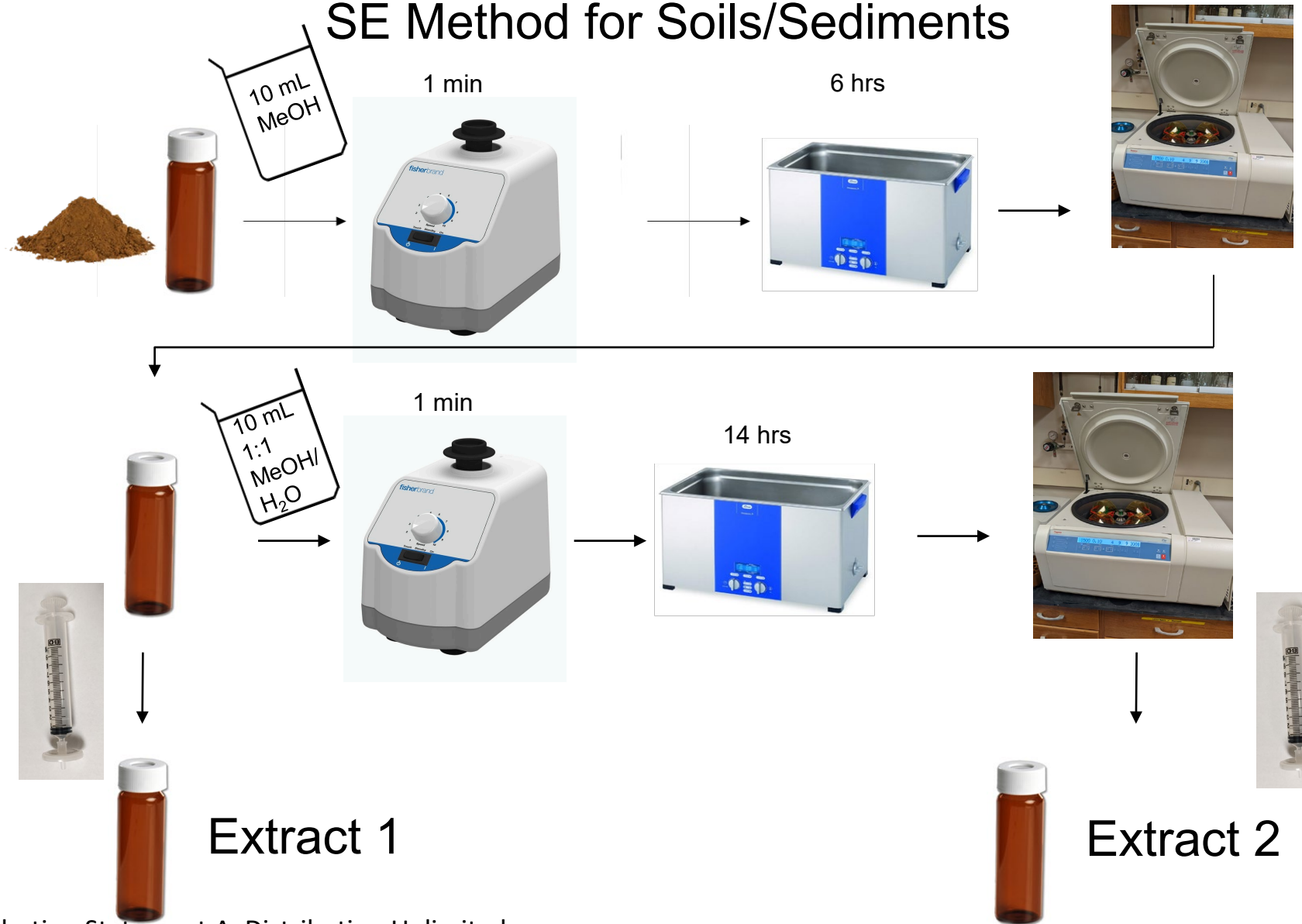
Extraction Methods

SE Method for Soils/Sediments



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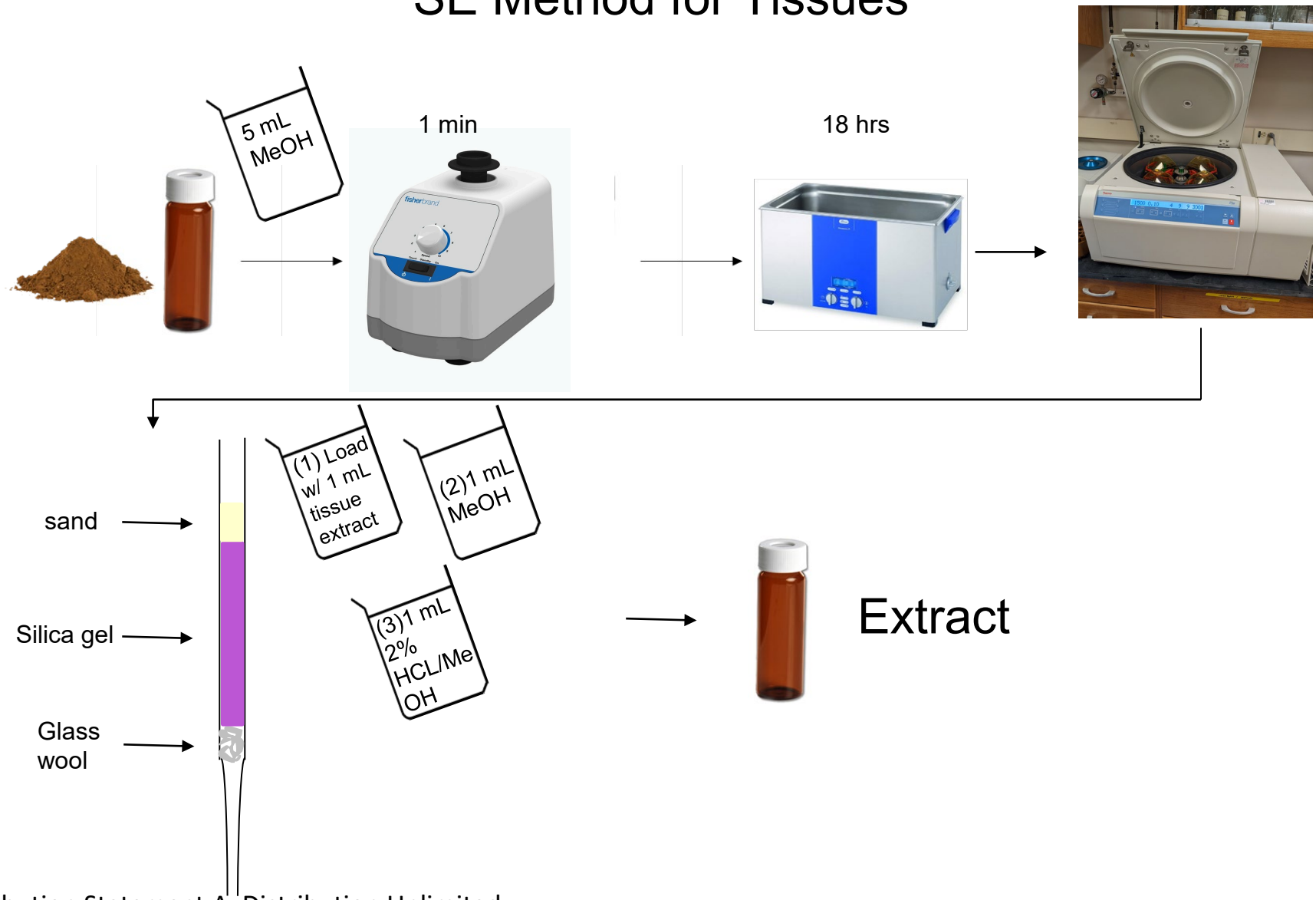
Extraction Methods

SE Method for Tissues



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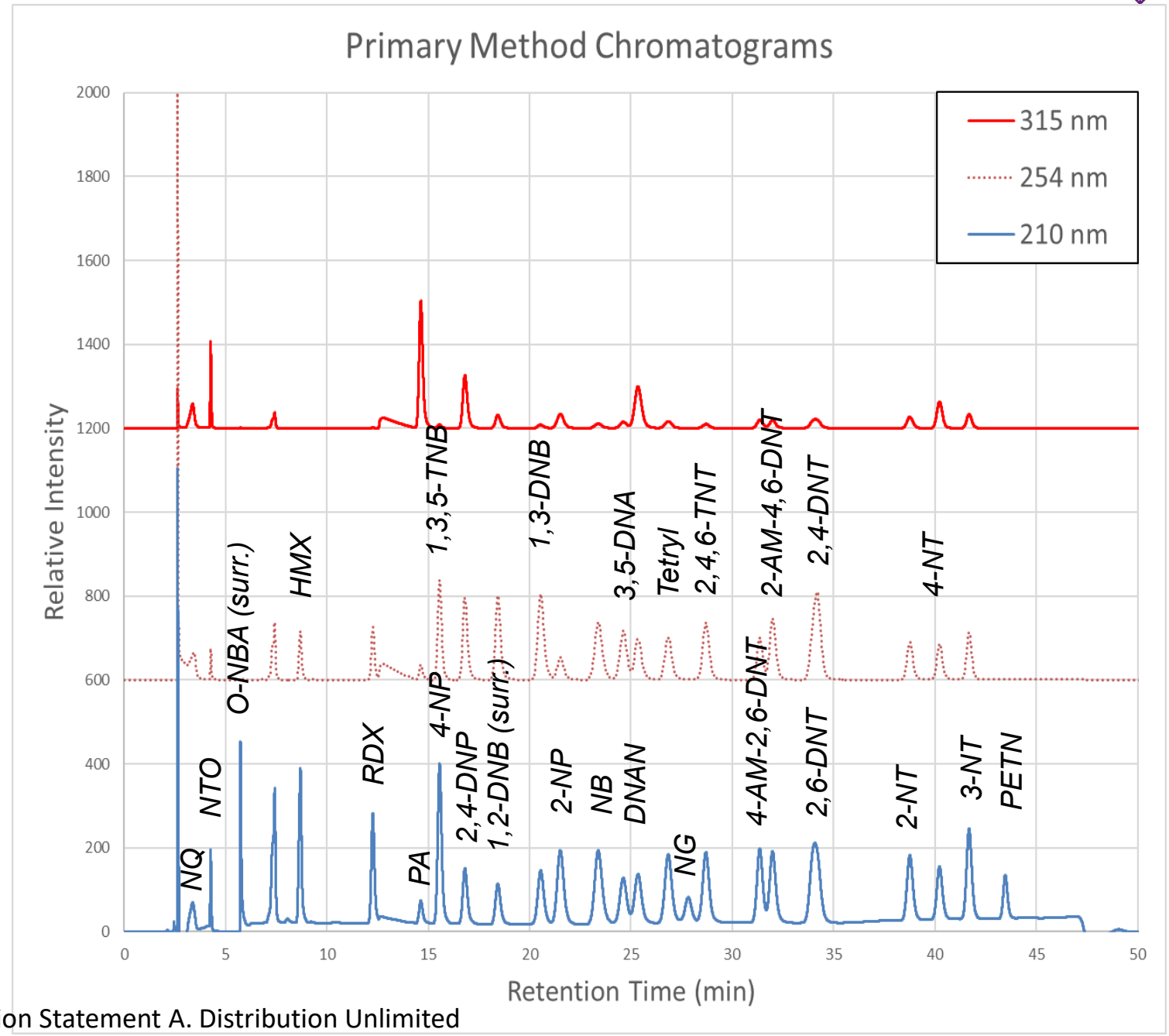

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Test Design

- **Laboratory-Spiked Synthetic Round Robin Study**
  - 4 DoD (Fed), 1 Non-DoD (Fed), 1 DoD (Contractor), 1 Commercial, 1 Academic labs
  - 5 different waters, 3 different soils, 2 different tissues
  - LCS recovery ranges determined from Reagent Water Matrix
    - Compared relative to existing 8330B ranges
  - Natural water (surface and ground) matrices compared to these recovery ranges
    - Compared relative to existing 8330B ranges
- **Semi-Synthetic Samples Round Robin Study**
  - 2 DoD (Fed), 1 Non-DoD (Fed), 1 Commercial,
  - 2 different waters from IAAP (manhole sump, process water)
  - Compared recoveries to above calculated LCS ranges and existing 8330B ranges

- *Combined synthetic and field sample approach follows initial development of EPA Method 8330A (Bauer, et al., 1989)*

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Laboratory Descriptions

- ERDC-EL-EPC
  - Primary site – Vicksburg, MS
  - Instrumentation: Agilent 1200/1220 HPLC's w/ DAD and 1260 HPLC w/ DAD + 6120B Single Quad MS
  - Personnel: 5 (4 in Lab)
- ERDC-CRREL
  - Collaborator site – Hanover, NH
  - Instrumentation: Agilent 1200 HPLC w/ DAD detector
  - Personnel: 2 (1 in Lab)
- USGS- Water Mission Area, Project Laboratories Branch
  - Collaborator site – Reston, VA
  - Instrumentation: Agilent 1200 HPLC w/ 1200 MWD
  - Personnel: 3 (1 in Lab); Location change from CO to VA
- American Ordnance, LLC
  - Synthetic and Semi-Synthetic Round Robin Participant site (DoD Contractor at Iowa Army Ammunition Plant) – Middletown, IA
  - LC/MS method contributor
  - Instrumentation: ThermoFisherSci Vanquish Flex UHPLC w/ DAD + Endura Triple Quad MS
  - Personnel: 2 then 1
- APPL, Inc.
  - Synthetic and Semi-Synthetic Round Robin Participant site (Commercial Laboratory) – Clovis, CA
  - Instrumentation: Agilent 1290 Infinity HPLC w/ DAD (Binary pump)
  - Personnel: 4
- Jackson State University
  - Synthetic and Semi-Synthetic Round Robin Participant site (Academic Institution) – Jackson, MS
  - Instrumentation: Shimadzu Prominence LC-20AD HPLC w/ SPD-20A UV-Vis Detector (Binary pump)
  - Personnel: 2 (1 in Lab)
- ERDC-EL-EPE
  - Synthetic Round Robin Participant site – Vicksburg, MS
  - Instrumentation: ThermoSci Ultimate HPLC 3000 w/ DAD
  - Personnel: 3 (2 in Lab, then 1)
- ERDC-EL-EPP
  - Synthetic Round Robin Participant site – Vicksburg, MS
  - Instrumentation: Agilent 1100 HPLC w/ DAD
  - Personnel: 2; Joined in Mar 2020
- USACE Environmental and Munitions Center of Expertise (CX)
  - Statistical evaluations and reporting
  - Personnel: 1

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Test Design – Method Performance Assessment

- Data Analysis, Laboratory Feedback, and Assessing Method Performance
  - ♦Each laboratory had observations and/or challenges associated with different aspects of the extraction and/or analysis method, and implemented the method on their instrumentation following guidelines distributed in ESTCP ER19-5078 method SOPs
    - Universal feedback related to method complexity
  - ♦Laboratories reported:
    - Sample data using provided Excel template with determined amounts of analytes,
    - Prep QC sample data, including surrogate recoveries (%)
    - Calibration curve and analytical QC data issues (ICVs, CCVs)
  - ♦After data collection, the data was reviewed and outliers were detected using Cochran and Grubbs tests
    - Data points were omitted on basis of the statistical outlier tests or physical justification, but were NOT removed due solely to poor performance of a laboratory
    - Average compound concentrations, percent recoveries (%), and standard deviations (SD) are reported

- Statistical analysis was used to determine the lower and upper control limits for the legacy and IM energetic compounds for the method (and then compared to DoD QSM Ver5.4 for 8330B for relative method performance information)

Performance Assessment – Direct Injection

Direct Injection Tolerance Intervals and USEPA 8330B Lower and Upper Control Limits		
Analyte	**91% Tolerance Interval Recovery Range (N = 7)**	**Lower and Upper Control Limit (8330B)**
1,2-DNB (surr.)	74 – 112	83 – 119
1,3-DNB	88 – 119	78 – 120
1,3,5-TNB	95 – 125	73 – 125
1,4-DNB (surr.)	95 – 140 (26% TI)	
2-Am-4,6-DNT	88 – 115	79 – 120
2-NP	88 – 121	
2-NT	86 – 118	70 – 127
2,4-DNP	96 – 131	
2,4-DNT	86 – 116	78 – 120
Picric Acid (PA)	93 – 147 (90% TI)	
2,4,6-TNT	95 – 151	71 – 123
2,6-DNT	86 – 132	77 – 127
3-NT	88 – 168	73 – 125
3,5-DNA	87 – 154	71 – 117
4-Am-2,6-DNT	87 – 113	76 – 125
4-NP	93 – 145	
4-NT	87 – 125	71 – 127
DNAN	93 – 134	
HMX	96 – 122	65 – 135
NB	88 – 113	65 – 134
NG	72 – 189	74 – 127
NQ	55 – 145	
NTO	72 – 124	
o-NBA (surr.)	68 – 140 (87% TI)	
PETN	86 – 133	73 – 127
RDX	93 – 125	68 – 130
Tetryl	84 – 144	64 – 128

Highlighted entries are additional analytes not included in USEPA Method 8330B

Control Limits for LCS Calculated from Reagent Water Matrix

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Performance Assessment - SPE

SPE Tolerance Intervals and USEPA 8330B Lower and Upper Control Limits			
Analyte	**95% Tolerance Interval Recovery Range (N = 6)**	**95% Tolerance Interval Recovery Range (Highest performing lab) (N=1)**	**Lower and Upper Control Limit (8330B)**
1,2-DNB (surr.)	69 – 119	88 – 106	83 – 119
1,3-DNB	39 – 130	81 – 113	78 – 120
1,3,5-TNB	69 – 166	91 – 109 (9% TI)	73 – 125
1,4-DNB (surr.)	47 – 132		
2-Am-4,6-DNT	37 – 137	84 – 109	79 – 120
2-NP	58 – 182	76 – 106	
2-NT	46 – 200	66 – 103	70 – 127
2,4-DNP	81 – 163	83 – 105	
2,4-DNT	50 – 123	73 – 119	78 – 120
Picric Acid (PA)	57 – 127	75 – 104	
2,4,6-TNT	51 – 142	85 – 112	71 – 123
2,6-DNT	37 – 126	84 – 121	77 – 127
3-NT	47 – 280	80 – 127	73 – 125
3,5-DNA	49 – 200	85 – 105	71 – 117
4-Am-2,6-DNT	50 – 161	86 – 107	76 – 125
4-NP	64 – 139	85 – 100	
4-NT	44 – 169	67 – 111	71 – 127
DNAN	47 – 131	76 – 114	
HMX	65 – 163	117 – 162	65 – 135
NB	60 – 131	74 – 105	65 – 134
NG	58 – 177	81 – 115	74 – 127
NQ	0 – 257	81 – 115	
NTO	11 – 160	57 – 114	
o-NBA (surr.)	41 – 110	68 – 127	
PETN	25 – 164	83 – 103	73 – 127
RDX	13 – 157	97 – 110	68 – 130
Tetryl	47 – 152	87 – 101	64 – 128

Highlighted entries are additional analytes not included in USEPA Method 8330B

Control Limits for LCS Calculated from Reagent Water Matrix

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Performance Assessment - Soils

Soil Tolerance Intervals and USEPA 8330B Lower and Upper Control Limits (Soil #1)		
Analyte	**82% Tolerance Interval Recovery Range (N = 3)**	**Lower and Upper Control Limit (8330B)**
1,2-DNB (surr.)	77 – 94	78 – 119
1,3-DNB	65 – 119	73 – 119
1,3,5-TNB	74 – 130	80 – 116
1,4-DNB (surr.)	57 – 127	
2-Am-4,6-DNT	81 – 118	71 – 123
2-NP	56 – 101	
2-NT	94 – 186	70 – 124
2,4-DNP	90 – 131	
2,4-DNT	103 – 150	75 – 121
Picric Acid (PA)	69 – 108	
2,4,6-TNT	97 – 137	71 – 120
2,6-DNT	97 – 137	79 – 117
3-NT	89 – 142	67 – 129
3,5-DNA	82 – 108	86 – 118
4-Am-2,6-DNT	72 – 123	64 – 127
4-NP	63 – 108	
4-NT	82 – 136	71 – 124
DNAN	77 – 119	
HMX	66 – 140	74 – 124
NB	93 – 126	67 – 129
NG	0 – 119	73 – 124
NQ	58 – 138	
NTO	83 – 119	
o-NBA (surr.)	56 – 89	
PETN	85 – 131	72 – 128
RDX	63 – 131	67 – 129
Tetryl	66 – 121	68 – 135

Highlighted entries are additional analytes not included in USEPA Method 8330B

Control Limits for LCS Calculated from ASTM Fat Clay Matrix

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Performance Assessment - Tissues

Tissue Tolerance Intervals and USEPA 8330B Lower and Upper Control Limits			
Analyte	**95% Tolerance Interval Recovery Range (N = 4)**	**57% Tolerance Interval Recovery Range (Highest performing lab) (N=1)**	**Lower and Upper Control Limit (8330B)***
1,2-DNB (surr.)	43 – 100 (59% TI)	Not used	78 – 119
1,3-DNB	44 – 118	46 – 109	73 – 119
1,3,5-TNB	26 – 3480	40 – 99	80 – 116
1,4-DNB (surr.)	54 – 120	54 – 87	
2-Am-4,6-DNT	33 – 164	40 – 143	71 – 123
2-NP	41 – 219	26 – 147 (95% TI)	
2-NT	45 – 198	45 – 116	70 – 124
2,4-DNP	38 – 338	41 – 113	
2,4-DNT	21 – 118	32 – 142 (95% TI)	75 – 121
Picric Acid (PA)	14 – 704	51 – 107	
2,4,6-TNT	36 – 134	50 – 115	71 – 120
2,6-DNT	38 – 274	13 – 127 (95% TI)	79 – 117
3-NT	48 – 189	48 – 116	67 – 129
3,5-DNA	46 – 204	44 – 117	86 – 118
4-Am-2,6-DNT	29 – 138	38 – 93	64 – 127
4-NP	5 – 289	14 – 136 (95% TI)	
4-NT	83 – 119	46 – 120	71 – 124
DNAN	46 – 175	41 – 271	
HMX	28 – 194	20 – 148 (95% TI)	74 – 124
NB	33 – 155	43 – 106	67 – 129
NG	0 – 588	2 – 161 (95% TI)	73 – 124
NQ	0 – 2800	23 – 128	
NTO	34 – 6380	46 – 112	
o-NBA (surr.)	13 – 271	13 – 122	
PETN	21 – 215	8 – 132 (95% TI)	72 – 128
RDX	19 – 291	19 – 197	67 – 129
Tetryl	0 – 64	7 – 36	68 – 135

Highlighted entries are additional analytes not included in USEPA Method 8330B

**8330B Soil recovery limits are not particularly comparable to tissue matrices*

Control Limits for LCS Calculated from all Tissue Matrices

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Challenges

- Due to COVID-19 pandemic, 6 out of the 8 participant laboratories (including the primary site at ERDC-EL-EPC) were closed from mid-March until mid-June, resulting in a multi-month delay
- Delay was compounded by further impacts at some laboratories, caused primarily by issues of personnel shortages (5 labs), personnel turnover (3 labs) and wildfires (1 lab), which significantly impacted ability to quickly process data
- Bulk soil spiking error(s)

A. Kimble (ERDC-EL) assisting with soil spiking

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Key Points

1. All laboratories were able to successfully implement methods
2. Statistical results show comparable yet slightly wider recovery ranges in comparison to USEPA 8330B
   - Attributable to (1) expanded analyte list, (2) method complexity, and possibly (3) laboratory pandemic limitations (e.g. superior performance of experienced laboratories, delays with data analysis and reporting, etc.)
   - Similar ranges reported for Methods 8081, 8141, 8270
3. Extraction methods are difficult and require attentive analysts, prior experience (HPLC, SPE, 8330B, etc.) is useful and GENERALLY improves method performance, emphasizing that this is not expected to be a replacement for 8330B.

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Publications

- Crouch, R.A., et al. (***2020***) Methods for Simultaneous Determination of Legacy and Insensitive Munition (IM) Constituents in Aqueous, Soil/Sediment, and Tissue Matrices. *Talanta*, ***217***, 121008. https://doi.org/10.1016/ j.talanta.2020.121008.

- Crouch, R.A., et al. Development and Optimization of Extraction and Analytical Methods for Simultaneous Determination of IM and Legacy Explosive Compounds. USACE Engineer Research and Development Center, Environmental Laboratory [Vicksburg, MS], ERDC/EL TR-21-11.

- ESTCP Final Report (in review)

- ESTCP Journal Article (in review)

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BACKUP SLIDES

ER19-5078: Validation of Sample Extraction and Analysis Techniques for Simultaneous Determination of Legacy and Insensitive Munition (IM) Constituents

Performers:

- Anthony Bednar, Austin Scircle, Rebecca Crouch, Jared Smith, Bobbi Stromer, Ashley Kimble, Thomas Georgian, Jay Clausen, Samuel Beal, and Adam Mumford

Technology Focus

- Inter-laboratory validation of extraction and analysis of 24 legacy and IM energetic compounds in water, soil/sediment, and tissue matrices

Demonstration Site

- Validation study participants include 4 DoD, 1 non-DoD Federal, 2 Commercial, and 1 Academic Laboratory across the United States

Demonstration Objectives

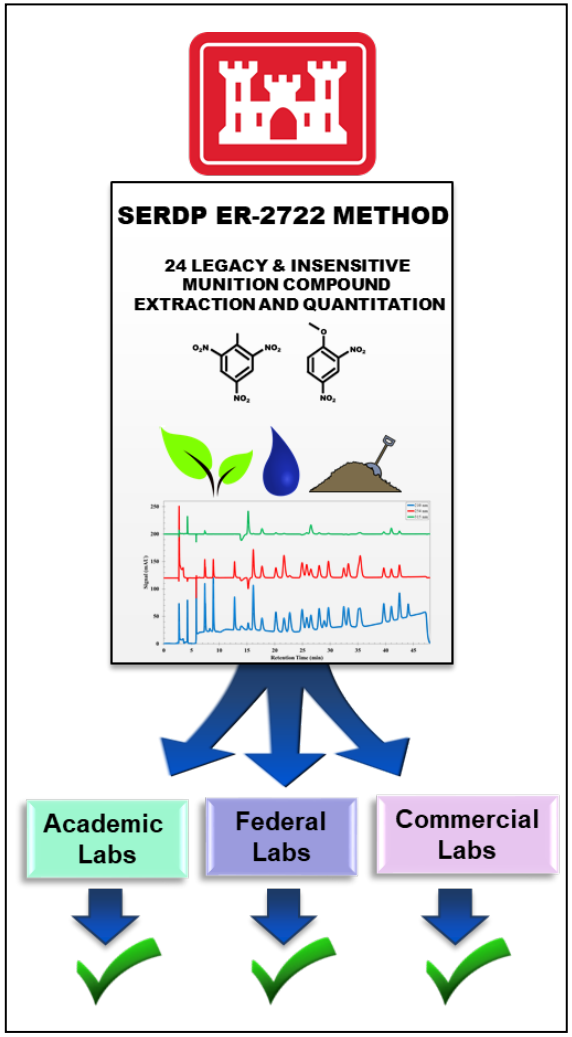
- Successful extraction and analysis of controlled synthetic and semi-synthetic environmental samples by each participating laboratory

Project Progress and Results

- All lab and statistical analyses are complete
- Methods show promise and are roughly comparable in performance to the methods found in USEPA 8330B

Implementation

- The method has been submitted to USEPA as an addendum to current energetic materials analysis Method 8330B



Performance Assessment – Direct Injection

Direct Injection Recoveries Surface Waters (~ 3 mg/L spike)												
										Multi-Lab		
Analyte	**Lab A**	**Lab B**	**Lab C**	**Lab E (1)**	**Lab E (2)**	**Lab F**	**Lab G**	**Lab H**	**Lab I**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	99.9	86.1	89.0	115.8	Not used	88.3	102.6	85.9	Not used	95.4	± 13.4	138
1,3-DNB	105.0	102.4	111.6	99.9	98.3	90.6	95.6	89.7	100.2	99.4	± 9.8	178
1,3,5-TNB	104.9	103.4	114.4	100.7	97.8	90.3	98.4	101.8	108.9	102.3	± 10.7	178
1,4-DNB (surr.)	Not used	Not used	Not used	Not used	119.8	Not used	Not used	Not used	98.1	108.9	± 18.4	60
2-Am-4,6-DNT	103.8	102.2	112.3	99.3	97.4	90.1	93.2	96.2	100.1	99.4	± 9.8	178
2-NP	99.7	99.3	117.6	97.8	104.4	97.0	85.7	106.5	95.2	100.3	± 10.5	178
2-NT	102.6	96.6	90.4	95.6	93.8	88.2	91.8	88.9	100.7	94.3	± 9.3	178
2,4-DNP	98.8	107.4	124.2	103.8	101.7	94.4	95.0	102.9	96.3	102.7	± 11.2	178
2,4-DNT	101.9	102.7	109.8	98.6	98.9	90.9	101.9	89.0	99.4	99.2	± 10.1	178
Picric Acid (PA)	120.8	106.0	112.6	98.8	91.7	93.7	95.6	93.4	107.8	101.7	± 14.5	178
2,4,6-TNT	105.4	103.1	111.3	100.1	98.4	89.7	95.6	97.9	100.9	100.3	± 9.8	178
2,6-DNT	107.6	102.4	118.1	102.7	94.9	90.6	105.9	89.1	109.5	102.3	± 26.8	178
3-NT	103.2	98.4	94.7	95.9	94.4	88.6	91.6	97.3	100.0	96.0	± 12.3	178
3,5-DNA	103.9	103.5	90.1	104.2	92.4	92.4	95.1	96.8	98.4	97.4	± 12.5	178
4-Am-2,6-DNT	101.4	103.1	112.3	98.0	97.8	90.9	93.8	94.3	99.1	99.0	± 10.0	178
4-NP	92.4	108.5	143.3	103.7	103.1	95.9	95.0	106.1	100.0	105.3	± 16.1	178
4-NT	103.8	97.3	99.1	93.7	93.4	89.7	89.9	96.8	109.8	97.0	± 13.5	178
DNAN	100.5	105.8	123.0	101.9	97.9	88.6	94.6	101.5	94.7	101.0	± 11.2	178
HMX	106.5	102.8	117.8	100.3	97.9	89.7	92.8	98.3	99.2	100.6	± 11.0	178
NB	102.7	102.6	111.3	98.4	97.2	92.6	93.5	92.6	97.9	98.8	± 7.6	178
NG	103.6	112.7	98.9	99.1	96.9	111.0	89.3	99.9	139.1	105.6	± 43.0	178
NQ	96.5	109.8	120.5	78.2	83.6	75.4	118.2	85.1	116.1	98.2	± 22.6	178
NTO	91.1	99.4	118.7	102.6	94.4	92.8	87.2	94.4	111.0	99.1	± 11.4	178
o-NBA (surr.)	113.1	85.3	108.7	110.9	120.6	87.6		94.5	97.4	102.3	± 16.0	158
PETN	99.2	123.3	111.5		101.8	91.5	96.2	94.9	106.8	103.1	± 15.5	178
RDX	108.7	104.2	113.1	103.5	97.9	92.2	94.7	93.1	99.2	100.7	± 10.2	178
Tetryl	104.2	102.6	110.8	96.6	88.7	88.4	90.0	99.3	100.9	98.0	± 10.6	178

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment – Direct Injection

Direct Injection Recoveries Groundwaters (~3 mg/L spike)												
										Multi-Lab		
Analyte	**Lab A**	**Lab B**	**Lab C**	**Lab E (1)**	**Lab E (2)**	**Lab F**	**Lab G**	**Lab H**	**Lab I**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	99.1	89.5	86.1	101.8	Not used	84.1	103.5	84.6	Not used	92.7	± 10.6	140
1,3-DNB	109.1	93.5	111.0	103.6	97.9	87.8	101.4	90.1	100.8	99.5	± 9.6	180
1,3,5-TNB	108.3	94.4	113.6	104.3	97.5	86.9	102.3	102.1	101.0	101.1	± 9.5	180
1,4-DNB (surr.)	Not used	Not used	Not used	Not used	130.1	Not used	Not used	Not used	96.7	113.4	± 20.9	40
2-Am-4,6-DNT	107.4	93.3	112.2	102.9	97.5	87.1	99.6	93.6	100.0	99.3	± 9.4	180
2-NP	103.4	92.0	116.7	102.7	103.9	100.7	92.9	109.3	91.3	101.4	± 9.7	180
2-NT	105.6	91.7	88.5	99.9	91.1	81.9	98.2	92.7	100.1	94.4	± 8.4	180
2,4-DNP	102.7	98.1	120.8	107.8	101.6	93.6	100.1	100.5	97.3	102.5	± 10.3	180
2,4-DNT	107.0	93.9	110.4	103.5	99.1	87.5	95.0	91.5	100.4	98.7	± 10.7	180
Picric Acid (PA)	110.4	96.7	93.3	102.7	95.6	92.9	102.6	95.1	103.1	99.6	± 9.6	167
2,4,6-TNT	108.6	94.1	110.6	103.5	98.1	86.1	100.1	111.9	101.3	101.6	± 11.8	180
2,6-DNT	110.7	93.5	119.9	105.6	93.9	88.4	96.5	91.1	109.2	101.1	± 13.5	180
3-NT	106.3	92.6	93.1	99.8	92.3	83.3	98.7	95.5	89.6	94.6	± 8.6	180
3,5-DNA	107.7	94.3	105.3	103.8	90.2	85.8	102.8	113.2	100.5	98.4	± 13.7	180
4-Am-2,6-DNT	106.4	93.8	113.7	103.5	98.2	87.5	98.6	90.2	98.2	98.9	± 9.9	180
4-NP	100.4	99.5	136.4	107.2	103.3	95.0	100.7	108.3	100.4	105.7	± 14.2	180
4-NT	106.8	91.0	97.9	97.6	91.6	83.9	96.6	95.7	115.1	97.4	± 10.6	180
DNAN	105.2	96.5	121.2	105.7	98.4	83.1	100.0	115.9	92.7	102.1	± 13.5	180
HMX	111.2	94.9	116.7	103.9	97.6	87.1	104.5	108.7	102.0	102.8	± 10.8	180
NB	106.2	101.1	110.7	102.7	97.3	86.7	103.8	101.9	99.8	101.1	± 7.4	180
NG	107.7	103.8	96.4	104.4	96.7	99.9	94.2	138.1	173.9	112.8	± 53.2	180
NQ	101.2	98.5	122.2	79.3	82.3	70.9	111.2	67.7	112.5	94.0	± 20.5	180
NTO	96.4	92.7	117.7	104.4	92.9	90.1	91.8	97.0	102.9	98.4	± 11.2	180
o-NBA (surr.)	108.9	88.9	112.3	97.0	131.1	84.1		95.0	98.6	102.0	± 16.7	160
PETN	103.0	118.6	111.4		95.8	92.5	100.9	96.0	103.1	102.7	± 17.1	180
RDX	112.1	95.0	112.4	107.3	97.8	87.1	99.7	93.8	100.5	100.6	± 10.0	180
Tetryl	107.2	93.6	110.3	99.3	89.4	85.4	96.4	119.8	101.6	100.3	± 12.9	180

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - SPE

SPE Recoveries Surface Waters (~0.02 mg/L spike)									
							Multi-Lab		
Analyte	**Lab A**	**Lab C**	**Lab E**	**Lab F**	**Lab G**	**Lab H**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	84.9	91.8	Not used	88.8	73.2	54.7	77.2	± 26.7	90
1,3-DNB	89.3	103.0	94.3	89.3	90.2	49.2	85.9	± 22.9	120
1,3,5-TNB	62.2	47.0	92.5	76.0	65.9	30.3	62.2	± 25.6	117
1,4-DNB (surr.)	Not used	Not used	106.5	Not used	Not Used	Not used	106.5	± 14.4	20
2-Am-4,6-DNT	91.5	105.2	90.0	87.4	97.0	44.4	85.9	± 27.7	120
2-NP	80.4	138.1	88.5	98.4	88.3	48.5	90.4	± 32.3	120
2-NT	83.5	139.1	88.6	81.8	85.8	56.1	89.1	± 32.6	120
2,4-DNP	92.4	123.5	93.2	101.6	99.6	64.3	95.8	± 25.1	120
2,4-DNT	89.2	102.3	94.6	87.9	86.5	63.4	87.3	± 19.4	120
Picric Acid (PA)	87.6		96.5	84.0	77.7	67.1	82.6	± 17.5	99
2,4,6-TNT	77.4	75.0	92.2	86.1	69.9	46.6	74.5	± 21.7	120
2,6-DNT	99.0	109.7		90.5	92.5	58.6	90.1	± 25.9	100
3-NT	95.2	148.8	93.3	81.0	94.7	71.8	97.5	± 31.7	119
3,5-DNA	95.5	142.5	90.1	95.1	97.6	43.8	94.1	± 36.6	120
4-Am-2,6-DNT	87.7	100.2	83.6	79.7	86.9	38.4	79.4	± 23.5	120
4-NP	90.6	114.4	94.2	92.9	98.6	52.5	90.5	± 23.9	120
4-NT	87.2	125.9	89.0	84.1	87.0	67.5	90.1	± 25.5	120
DNAN	91.8	113.6	93.4	92.4	91.7	61.7	90.8	± 24.4	120
HMX	126.8	112.1	91.6	88.7	98.5	56.9	95.7	± 23.6	120
NB	86.2	117.1	91.7	85.7	91.6	82.0	90.8	± 21.4	119
NG	95.0	110.4	74.8	106.2	89.2	58.9	89.1	± 28.8	120
NQ	2.1	20.4	45.3	24.3		0.0	17.9	± 42.5	95
NTO	114.7	115.1	117.7	86.1	128.8	80.0	107.1	± 27.1	120
o-NBA (surr.)	91.9	103.2	95.0	79.1	84.9	68.6	85.7	± 17.7	100
PETN	97.6	126.8	88.0	97.0	192.7	45.8	107.3	± 161.2	119
RDX	105.1	112.8	91.5	90.0	97.1	52.0	91.4	± 32.6	119
Tetryl	45.7	31.5	71.1	62.1	34.2	34.2	46.5	± 21.1	120

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - SPE

SPE Recoveries Groundwaters (~0.02 mg/L spike)									
							Multi-Lab		
Analyte	**Lab A**	**Lab C**	**Lab E**	**Lab F**	**Lab G**	**Lab H**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	95.9	96.3	Not used	104.8	106.7	68.9	94.5	± 18.2	99
1,3-DNB	94.8	110.1	96.3	97.3	94.6	65.1	92.9	± 16.3	119
1,3,5-TNB	90.8	112.8	99.8	102.1	101.0	41.2	91.1	± 28.1	119
1,4-DNB (surr.)	Not used	Not used	103.3	Not used	Not used	Not used	103.3	± 8.0	20
2-Am-4,6-DNT	94.8	96.0	93.8	100.4	95.0	54.8	89.1	± 20.4	119
2-NP	89.8	124.3	94.7	120.1	93.8	54.9	96.0	± 27.1	119
2-NT	84.0	107.1	90.6	98.8	88.6	64.1	88.7	± 16.0	119
2,4-DNP	95.0	118.7	95.4	114.2	103.4	58.9	97.4	± 26.8	119
2,4-DNT	92.7	107.5	100.9	93.4	89.8	81.6	94.2	± 10.6	119
Picric Acid (PA)	89.9		100.5	104.1	98.9	95.2	97.7	± 14.0	100
2,4,6-TNT	102.3	117.2	97.0	97.7	95.7	54.9	93.9	± 22.4	119
2,6-DNT	99.7	110.9		97.4	90.0	72.6	93.9	± 15.0	99
3-NT	87.2	122.0	96.7	105.8	93.3	81.7	97.6	± 15.5	119
3,5-DNA	95.3	110.7	95.9	108.8	96.3	42.2	91.4	± 26.0	119
4-Am-2,6-DNT	96.0	85.8	92.6	105.5	93.7	42.7	86.1	± 25.6	119
4-NP	96.2	114.6	95.4	137.5	101.6	44.0	98.1	± 34.2	119
4-NT	86.9	103.4	90.0	95.9	88.9	73.5	89.7	± 12.0	119
DNAN	94.5	108.7	94.8	104.8	95.9	52.5	91.7	± 22.0	119
HMX	131.8	106.2	96.2	117.4	94.4	44.8	98.4	± 32.8	119
NB	89.4	105.2	96.3	104.2	94.7	76.4	94.3	± 15.9	119
NG	89.5	129.5	59.3	123.5	103.0	40.8	90.6	± 39.3	119
NQ	7.3	14.6	39.7	16.6		0.0	15.6	± 13.9	99
NTO	86.6	92.4	77.9	82.6	75.8	73.3	81.3	± 9.4	119
o-NBA (surr.)	84.3	110.6	99.2	82.8	100.0	85.0	93.5	± 13.8	119
PETN	100.8	110.2	100.2	127.2	106.9	33.1	96.3	± 35.7	119
RDX	102.2	113.6	95.0	128.1	100.5	34.3	95.5	± 35.8	119
Tetryl	58.3	58.3	75.6	101.8	69.6	30.6	65.8	± 27.3	119

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - SPE

Low-level SPE Recoveries Groundwaters (~2 µg/L spike)					
			Multi-Lab		
Analyte	**Lab A**	**Lab E**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	96.7	Not used	96.7	5.0	8
1,3-DNB	99.0	126.6	112.8	20.0	16
1,3,5-TNB	98.0	162.6	130.3	38.3	16
1,4-DNB (surr.)	Not used	117.5	117.5	16.4	8
2-Am-4,6-DNT	103.4	137.0	120.2	21.1	16
2-NP	77.1	108.6	92.9	19.1	16
2-NT	85.9	107.7	96.8	16.7	16
2,4-DNP	104.8	114.5	109.7	7.6	16
2,4-DNT	95.8	164.9	130.4	43.9	16
Picric Acid (PA)	99.9	131.1	115.5	21.2	16
2,4,6-TNT	138.0	203.4	170.7	42.9	16
2,6-DNT	122.0	88.6	105.3	22.5	16
3-NT	124.4	1005.8	565.1	570.3	16
3,5-DNA	95.5	106.6	101.0	9.1	16
4-Am-2,6-DNT	110.7	148.9	129.8	22.9	16
4-NP	102.2	111.1	106.6	8.1	16
4-NT	106.6	112.8	109.7	14.3	16
DNAN	75.5	121.4	98.4	29.1	16
HMX	142.5	138.5	140.5	18.4	16
NB	99.7	114.1	106.9	13.5	16
NG	90.5	101.3	95.9	47.7	8
NQ		45.8	45.8	19.6	16
NTO	79.1	95.6	87.3	23.8	16
o-NBA (surr.)	73.0	95.9	84.4	22.4	16
PETN	184.9	145.5	165.2	55.4	16
RDX	103.1	119.1	111.1	12.9	16
Tetryl	45.1	72.2	58.6	20.0	16

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment – SPE SemiSynthetic

SPE Recoveries Field collected waters (varying spike concentration from 0.019 to 0.12 mg/L)								
					Multi-Lab			8330B
Analyte	Lab A	Lab C	Lab E	Lab G	AVG	SD	N	Lab G
1,2-DNB (surr.)	108.7	110.0	Not used	97.7	104.6	11.4	48	99.2
1,3-DNB	101.1	82.5	85.8	136.1	101.2	99.1	77	88.4
1,3,5-TNB	94.5	81.1	81.1	139.4	98.8	88.9	77	86.6
1,4-DNB (surr.)	Not used	Not used	102.7	Not used	102.7	17.9	20	
2-Am-4,6-DNT	100.2	92.1	82.9	139.8	103.5	97.0	77	88.0
2-NP	85.8	108.1	84.6	126.8	101.1	90.4	77	
2-NT	92.9	111.2	81.4	130.8	103.8	97.2	77	77.9
2,4-DNP	19.7	17.9	70.7	20.4	40.7	26.8	48	
2,4-DNT	134.5	77.6	82.0	126.7	104.9	93.7	79	95.0
Picric Acid (PA)	113.9	68.9	88.1	136.8	101.7	88.3	77	
2,4,6-TNT	95.8	75.7	50.2	93.2	78.3	36.8	77	84.2
2,6-DNT	97.7	79.6	0.0	137.7	77.7	114.7	77	88.7
3-NT	95.5	109.7	84.5	134.4	105.8	102.2	77	78.8
3,5-DNA	101.3	121.5	84.5	132.5	109.6	96.5	77	81.7
4-Am-2,6-DNT	97.8	97.2	78.9	140.5	103.3	91.5	77	89.8
4-NP	101.9	101.2	86.9	141.3	107.6	98.6	77	
4-NT	96.1	97.0	80.4	128.7	100.3	87.5	77	80.7
DNAN	26.2	21.3	60.7	35.9	41.7	23.0	48	
HMX	114.8	84.8	85.6	143.4	106.8	89.6	77	83.5
NB	100.0	94.5	84.7	876.0	208.1	279.9	68	85.9
NG	115.7	120.2	55.5	132.6	105.3	95.3	77	89.2
NQ	5.7	8.8	9.5	6.4	7.6	4.1	77	
NTO	68.4	106.0	7.6	85.8	66.2	38.5	77	
o-NBA (surr.)	110.6	132.2	184.5	98.9	132.7	39.1	67	
PETN	99.4	107.2	86.2	141.2	108.2	97.6	77	82.6
RDX	108.0	110.0	71.3	118.8	101.6	40.8	77	89.7
Tetryl	94.3	67.9	68.4	135.1	91.1	88.9	77	91.7

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment – Low Level SPE

Low-level SPE Recoveries Surface Waters (~2 µg/L spike)					
			Multi-Lab		
Analyte	**Lab A**	**Lab E**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	79.2	Not used	79.2	13.0	7
1,3-DNB	85.7	111.7	98.7	16.6	15
1,3,5-TNB	23.9	69.2	46.5	25.4	15
1,4-DNB (surr.)	Not used	102.1	102.1	7.4	8
2-Am-4,6-DNT	97.1	105.5	101.3	10.2	15
2-NP	46.1	99.2	72.7	29.6	15
2-NT	83.4	95.6	89.5	10.5	15
2,4-DNP	97.6	116.3	106.9	11.0	15
2,4-DNT	83.6	142.5	113.1	32.3	15
Picric Acid (PA)	92.1	74.2	83.2	17.2	15
2,4,6-TNT	27.3	105.1	66.2	45.8	15
2,6-DNT	124.3	84.2	104.2	22.6	15
3-NT	120.4	165.5	143.0	74.1	15
3,5-DNA	101.3	106.2	103.8	9.5	15
4-Am-2,6-DNT	113.8	103.9	108.9	12.1	15
4-NP	96.9	128.4	112.6	18.7	15
4-NT	84.4	91.9	88.2	13.1	15
DNAN	84.5	131.6	108.1	26.5	15
HMX	92.6	117.7	105.1	16.1	15
NB	100.4	102.4	101.4	7.4	15
NG	91.7	84.3	88.0	31.7	15
NQ		52.4	52.4	26.4	8
NTO	505.6	110.7	308.1	218.1	15
o-NBA (surr.)	79.9	88.7	84.3	12.8	15
PETN	95.1	170.5	132.8	76.6	15
RDX	93.7	122.3	108.0	16.5	15
Tetryl	12.9	27.0	20.0	13.2	15

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - Soils

Soil Recoveries (Soil #2) (~4 mg/Kg spike)						
				Multi-Lab		
Analyte	**Lab A**	**Lab E (1)**	**Lab E (2)**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	95.7	Not used	Not used	95.7	± 3.2	10
1,3-DNB	105.3	96.2	114.1	105.2	± 9.8	30
1,3,5-TNB	101.8	97.6	110.4	103.3	± 7.8	30
1,4-DNB (surr.)	Not used	105.3	95.4	100.3	± 12.7	30
2-Am-4,6-DNT	106.4	104.5	118.1	109.6	± 10.1	30
2-NP	70.5	58.9	78.6	68.0	± 13.4	30
2-NT	81.4	128.7	116.7	108.9	± 22.9	30
2,4-DNP	103.3	102.8	106.2	104.1	± 6.0	30
2,4-DNT	103.3	139.8	106.2	116.4	± 17.7	30
Picric Acid (PA)	104.7	106.2	85.5	98.8	± 11.2	30
2,4,6-TNT	111.4	122.8	117.1	117.1	± 9.8	30
2,6-DNT	113.0	106.3	128.4	115.9	± 10.7	30
3-NT	82.5	112.2	79.3	91.3	± 16.0	30
3,5-DNA	108.4	99.3	103.0	103.6	± 8.7	30
4-Am-2,6-DNT	105.7	89.7	117.2	104.2	± 14.2	30
4-NP	104.5	85.5	98.3	96.1	± 10.3	30
4-NT	86.6	104.2	85.1	92.0	± 10.9	30
DNAN	80.9	103.1	110.5	98.2	± 14.4	30
HMX	102.4	103.1	91.9	99.1	± 6.9	30
NB	76.5	118.6	54.2	83.1	± 28.5	30
NG	96.9	110.3	102.7	103.3	± 13.4	30
NQ	107.5	115.4	88.7	103.9	± 15.8	30
NTO	26.9	59.7	89.9	58.8	± 26.5	30
o-NBA (surr.)	92.3	87.5	93.1	91.0	± 5.8	30
PETN	102.1	104.8	106.5	104.5	± 6.7	30
RDX	98.7	96.1	94.7	96.5	± 6.4	30
Tetryl	85.2	96.1	112.1	97.8	± 13.3	30

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - Soils

Soil Recoveries (Soil #3) (~4 mg/kg spike)						
				Multi-Lab		
Analyte	**Lab A**	**Lab E (1)**	**Lab E (2)**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	91.8	Not used	Not used	91.8	± 1.7	10
1,3-DNB	105.7	106.5	103.8	105.3	± 5.6	30
1,3,5-TNB	105.1	109.9	98.1	104.4	± 7.8	30
1,4-DNB (surr.)	Not used	111.3	90.2	100.8	± 13.7	20
2-Am-4,6-DNT	105.0	108.8	102.7	105.5	± 6.6	30
2-NP	83.0	86.8	79.8	83.2	± 9.2	30
2-NT	102.2	172.3	126.5	133.7	± 30.9	30
2,4-DNP	104.0	101.9	93.9	99.9	± 6.2	30
2,4-DNT	103.4	174.6	100.0	126.0	± 36.1	30
Picric Acid (PA)	104.6	108.8	82.0	98.5	± 14.6	30
2,4,6-TNT	109.1	134.2	115.2	119.5	± 12.3	30
2,6-DNT	115.6	118.3	126.4	120.1	± 9.9	30
3-NT	103.0	136.7	84.6	108.1	± 22.4	30
3,5-DNA	100.9	105.2	84.6	96.9	± 11.1	30
4-Am-2,6-DNT	98.0	89.2	96.4	94.5	± 7.3	30
4-NP	104.1	95.1	85.3	94.8	± 10.0	30
4-NT	103.4	129.1	86.6	106.3	± 18.6	30
DNAN	81.2	106.2	107.5	98.3	± 13.0	30
HMX	110.8	118.4	102.6	110.6	± 9.0	30
NB	101.7	121.3	67.6	96.9	± 23.0	30
NG	109.4	105.1	100.1	104.9	± 23.1	30
NQ	104.2	140.5	89.2	111.3	± 22.6	30
NTO	30.7	60.3	87.7	59.6	± 24.1	30
o-NBA (surr.)	89.1	77.6	79.3	82.0	± 7.9	30
PETN	102.7	113.3	95.0	103.7	± 14.8	30
RDX	108.9	113.6	99.8	107.4	± 8.7	30
Tetryl	75.6	113.4	94.0	94.3	± 16.5	30

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Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - Soils

Low Level Soil Recoveries (Soil #1) (~2 mg/kg spike)						
				Multi-Lab		
Analyte	**Lab A**	**Lab E (1)**	**Lab E (2)**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	94.2	Not used	Not used	94.2	± 2.2	10
1,3-DNB	102.7	92.4	122.2	105.7	± 13.4	30
1,3,5-TNB	102.4	91.9	120.9	105.1	± 13.4	30
1,4-DNB (surr.)	Not used	106.1	89.4	97.8	± 10.6	20
2-Am-4,6-DNT	103.2	71.9	125.8	100.3	± 23.2	30
2-NP	70.9	41.4	97.0	127.5	± 69.1	30
2-NT	101.3	182.9	177.3	153.8	± 41.7	30
2,4-DNP	98.8	104.9	117.9	107.2	± 10.2	30
2,4-DNT	101.7	186.3	117.8	135.3	± 53.1	30
Picric Acid (PA)	102.0	101.6	87.6	97.1	± 10.8	30
2,4,6-TNT	103.2	131.4	136.4	123.7	± 15.1	30
2,6-DNT	115.5	162.6	160.8	146.3	± 23.2	30
3-NT	101.0	159.9	115.9	125.6	± 25.8	30
3,5-DNA	103.2	112.6	97.0	104.3	± 7.3	30
4-Am-2,6-DNT	104.3	64.9	116.1	95.1	± 23.8	30
4-NP	106.8	69.0	104.2	93.4	± 17.7	30
4-NT	101.8	144.3	98.0	114.7	± 25.1	30
DNAN	81.5	150.4	123.2	118.4	± 29.4	30
HMX	69.4	128.0	98.2	88.4	17.0	30
NB	101.0	144.1	85.2	110.1	25.5	30
NG	95.1	106.0	103.7	101.6	± 45.4	30
NQ	83.0	303.5	102.3	162.9	± 102.2	30
NTO	34.7	74.6	139.0	82.8	± 44.7	30
o-NBA (surr.)	94.0	91.0	85.4	90.1	± 6.1	30
PETN	102.4	112.1	127.2	113.9	± 18.4	30
RDX	71.9	97.5	87.4	85.6	± 11.8	30
Tetryl	76.1	144.4	130.1	101.3	± 23.0	30

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Increased exceedances at lower concentration level

Performance Assessment - Tissues

Tissue Recoveries (~20 mg/kg spike)							
					Multi-Lab		
Analyte	**Lab C**	**Lab E**	**Lab H**	**Lab I**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	70.4	Not used	86.0	Not used	78.2	18.6	78
1,3-DNB	77.7	75.4		87.1	80.1	22.4	115
1,3,5-TNB	58.0	66.2	1373.0	87.2	396.1	901.2	154
1,4-DNB (surr.)	Not used	61.4	81.7	80.9	74.6	11.8	115
2-Am-4,6-DNT	83.0	81.6	101.7	79.9	86.5	32.8	154
2-NP	111.3	72.7	84.7	113.8	95.7	38.9	154
2-NT	115.0	75.3	93.1	122.2	101.4	38.4	154
2,4-DNP	91.9	74.3	79.4	176.6	105.6	68.3	154
2,4-DNT	69.1	70.1	79.2	49.0	66.8	25.5	154
Picric Acid (PA)	133.0	74.3	83.8	168.6	115.0	102.0	165
2,4,6-TNT	70.3	77.2	93.2	82.9	80.9	23.3	154
2,6-DNT	107.1	70.0	87.7	184.8	112.4	60.5	154
3-NT	112.9	77.4	97.6	115.8	100.9	35.4	154
3,5-DNA	119.7	74.7	78.7	113.0	96.5	39.2	154
4-Am-2,6-DNT	67.2	64.0	88.9	74.3	73.6	25.4	154
4-NP	118.8	75.2	88.2	173.8	114.0	60.2	153
4-NT	105.2	77.6	89.6	113.1	96.4	34.7	154
DNAN	77.2	78.8	77.8	101.5	83.8	40.5	154
HMX	106.1	67.1	94.9	98.2	91.6	35.9	154
NB	72.3	71.2	89.7	91.8	81.3	27.3	154
NG	49.1	41.7	95.9	173.6	90.1	87.3	152
NQ	77.8	47.3	26.2	1576.5	432.0	788.7	144
NTO	116.1	75.8	2320.6	3361.2	1468.4	1995.8	154
o-NBA (surr.)	177.6	81.1	124.6	72.0	113.8	60.1	154
PETN	80.4	69.8	98.8	116.3	91.3	42.3	154
RDX	103.7	87.0	141.6	107.0	109.8	59.5	154
Tetryl	14.4	8.2	32.2	19.2	18.5	15.4	132

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - Tissues

Average Tissue Recoveries (Earthworm) (~20 mg/kg spike)							
					Multi-Lab		
Analyte	**Lab C**	**Lab E**	**Lab H**	**Lab I**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	43.5	Not used	59.6	Not used	72.3	19.1	40
1,3-DNB	43.9	50.5		63.9	72.6	20.7	60
1,3,5-TNB	52.0	44.5	3470.7	62.1	694.4	1174.9	80
1,4-DNB (surr.)	Not used	55.4	82.3	74.8	73.1	10.3	60
2-Am-4,6-DNT	34.1	47.0	65.4	51.4	71.1	23.7	80
2-NP	55.4	42.0	55.5	89.2	80.7	25.6	80
2-NT	68.0	46.8	72.3	93.8	89.2	24.4	80
2,4-DNP	39.7	45.1	47.2	289.8	111.0	89.8	80
2,4-DNT	23.3	44.0	43.3	37.0	58.8	24.7	80
Picric Acid (PA)	392.8	56.3	134.1	189.2	142.2	119.5	80
2,4,6-TNT	37.1	54.7	64.5	57.3	75.6	22.2	80
2,6-DNT	45.0	48.7	48.1	108.6	95.2	46.7	80
3-NT	66.1	48.1	67.6	95.9	86.3	22.1	80
3,5-DNA	66.2	46.9	55.0	88.6	82.3	24.6	80
4-Am-2,6-DNT	29.6	45.7	66.9	49.1	70.0	22.5	80
4-NP	206.9	56.8	89.5	321.7	117.9	70.1	80
4-NT	57.9	49.4	53.7	90.8	81.7	23.0	80
DNAN	35.7	42.8	57.6	65.6	71.9	35.9	80
HMX	57.1	49.2	60.8	62.4	77.3	31.9	80
NB	33.7	46.2	54.6	73.0	71.1	21.4	80
NG	57.3	36.2	49.4	67.0	105.7	75.5	80
NQ		27.8	0.0	2533.2	706.5	998.8	70
NTO	47.7	50.5	4849.5	6087.9	2276.1	2410.9	80
o-NBA (surr.)	189.4	13.3	184.3	97.9	119.1	77.9	80
PETN	32.8	28.3	56.2	53.2	71.9	24.6	80
RDX	44.7	18.8	76.8	84.8	73.2	23.6	80
Tetryl		0.0	35.6	12.2	11.8	13.0	60

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Performance Assessment - Tissues

Average Tissue Recoveries (Ryegrass) (~20 mg/kg spike)							
					Multi-Lab		
Analyte	**Lab C**	**Lab E**	**Lab H**	**Lab I**	**AVG**	**SD**	**N**
1,2-DNB (surr.)	82.5	Not used	112.4	Not used	84.2	16.3	38
1,3-DNB	68.0	105.4		116.2	88.0	21.5	55
1,3,5-TNB	23.7	85.5	90.1	101.6	73.9	23.1	74
1,4-DNB (surr.)	Not used	56.7	83.1	79.4	76.0	13.2	55
2-Am-4,6-DNT	136.2	130.9	159.3	113.1	103.6	32.8	74
2-NP	178.2	109.3	123.1	176.8	112.1	44.1	74
2-NT	186.4	106.9	136.6	171.8	117.4	44.1	74
2,4-DNP	152.7	108.6	113.4	125.4	98.2	30.7	74
2,4-DNT	84.8	100.2	115.4	69.6	77.5	22.1	74
Picric Acid (PA)	39.5	89.3	51.9	255.2	85.3	71.9	74
2,4,6-TNT	58.6	106.5	134.1	110.4	87.1	23.0	74
2,6-DNT	176.6	94.4	139.0	271.9	130.6	68.2	74
3-NT	185.9	108.5	139.5	162.9	116.9	40.1	74
3,5-DNA	199.8	110.5	111.6	161.2	111.5	46.1	74
4-Am-2,6-DNT	105.7	88.2	129.9	107.4	81.0	26.4	74
4-NP	180.3	107.1	85.2	132.4	109.0	47.0	74
4-NT	169.8	115.7	134.9	157.1	112.0	38.3	74
DNAN	115.7	103.5	109.4	134.7	96.4	41.5	74
HMX	134.8	107.6	151.9	141.3	106.6	33.9	74
NB	107.3	99.9	102.1	138.8	92.2	28.9	74
NG	43.7	15.2	166.6	199.9	107.0	96.3	74
NQ	72.6	44.7	59.2	1515.5	282.6	465.1	74
NTO	215.2	104.7	219.4	2107.1	559.1	675.6	74
o-NBA (surr.)	103.6	113.2	75.1	77.1	108.2	30.6	74
PETN	128.6	95.9	154.1	184.6	112.5	47.0	74
RDX	168.4	164.5	291.5	186.2	149.0	62.0	74
Tetryl	20.2	23.1	20.8	29.7	25.4	14.6	72

Highlighted entries are outside calculated tolerance intervals, but within 8330B Control Limits
Highlighted entries are outside both calculated tolerance intervals and 8330B Control Limits

Test Design – Round Robins

- Laboratory-Spiked Synthetic Samples (MAR// JUN-SEP 2020)
  - Highly unlikely any field-collected sample would contain all analytes of interest
  - Need theoretical concentration in samples to determine laboratory recovery efficiencies
  - Synthetic samples were generated by spiking reagent water, “clean” field collected water and soils/sediments, and laboratory generated “clean” tissues with reference standards of all analytes at two concentration levels (n=10 for each level in each matrix; *Total of 220 samples per lab, or 268 including QA/QC – MB, LCS, LOD, LOQ*)
  - All “clean” matrices pre-processed according to current EPA Method 8330B, SW-846 Ch. 4, and DoD QSM Ver5.4
  - Samples batch spiked (*double blind*, randomized), dried (*for soils), homogenized, aliquotted in *randomized order* (*for soils, per ISM in EPA Method 8330B), and distributed to each lab
  - Abided by all existing sample hold times (7/14 d extraction, 40 d analysis) and conditions (e.g., dark, cold storage) established by EPA Method 8330

Test Design – Round Robins

- Semi-Synthetic Follow-On Round Robin Study (OCT 2020 – FEB 2021)
  - ♦To provide data on potential real-world applicability
  - ♦Spike IM or legacy-containing field samples in the lab
  - ♦Mimic field activities as closely as possible that would release IM constituents
  - ♦All field samples pre-screened by ERDC-EL-EPC using ESTCP ER19-5078 methods, then amended with either IM (NQ, NTO, DNAN, etc.) or legacy (RDX, TNT, etc.) compounds to contain both
  - ♦Samples distributed to each laboratory (6), abiding by all sample hold times (7/14 d extraction, 40 d analysis) and conditions (e.g., dark, cold storage) established by EPA Methods 8330
    - Samples performed in replicate (n=10) to provide sufficient data for statistical evaluation
    - QC consist of MB, LCS, LOD, LOQ, MS(and GB, for soil) per 20 project samples (*evaluated per DoD QSM Ver5.3)

- ♦*Water (field-collected) samples*
  - Collected from 6 IM-containing locations at Iowa Army Ammunition Plant (IAAAP)
    - Pre- and post-treated processes waters, air filtration, manhole with groundwater infiltration, monitoring wells
  - Pre-screening of 6 process waters showed NQ/NTO/DNAN/TNT @ 1-250 ppm; PA/2-NP/HMX @ ~1 ppm; 2,4-DNP/RDX @ 1-20 ppm; NG/3,5-DNA/4-Am/2-Am/DNT's/TNB @ 1-5 ppm

Other Methods (8081) Performance Limits

DoD/DOE QSM 5.4
Appendix C
2021

Table C-16. Method 8081 Aqueous Matrix

CAS ID	Analyte	N Records	Mean	Standard Deviation	Lower Control Limit	Upper Control Limit
72-54-8	4,4'-DDD	3112	99.6	14.4	56	143
72-55-9	4,4'-DDE	3062	96	12.9	57	135
50-29-3	4,4'-DDT	2681	97	15.3	51	143
309-00-2	Aldrin	3021	89.5	14.7	45	134
319-84-6	alpha-BHC	3070	95.8	13.9	54	138
5103-71-9	alpha-Chlordane	2736	94.3	11.6	60	129
319-85-7	beta-BHC	3068	96.3	13.3	56	136
57-74-9	Chlordane	150	101.2	13	62	140
319-86-8	delta-BHC	3035	97.2	15	52	142
60-57-1	Dieldrin	3078	98	12.6	60	136
959-98-8	Endosulfan I	968	93.8	10.7	62	126
33213-65-9	Endosulfan II	3047	93.4	13.7	52	135
1031-07-8	Endosulfan sulfate	3013	97.2	11.9	62	133
72-20-8	Endrin	3635	98.7	13	60	138
7421-93-4	Endrin aldehyde	3018	91.1	13.5	51	132
53494-70-5	Endrin Ketone	2908	95.9	12.6	58	134
58-89-9	gamma-BHC [Lindane]	3693	96.4	12.5	59	134
5566-34-7	gamma-Chlordane	3008	95.8	13.2	56	136
76-44-8	Heptachlor	3597	91.9	12.8	54	130
1024-57-3	Heptachlor Epoxide	3574	96.9	12.1	61	133
118-74-1	Hexachlorobenzene	134	82.1	18.1	27.8	136.5
72-43-5	Methoxychlor	3569	99	15.2	54	145
2385-85-5	Mirex	340	88.8	12.6	51	127
877-09-8	Tetrachloro-m-xylene	1510	84.1	13.3	44	124
8001-35-2	Toxaphene	421	83.9	16.8	33	134

DoD/DOE QSM 5.4
Appendix C
2021

Table C-15. Method 8081 Solid Matrix

CAS ID	Analyte	N Records	Mean	Standard Deviation	Lower Control Limit	Upper Control Limit
789-02-6	2,4'-DDT	110	100.1	11.9	64	136
53-19-0	2,4-DDD	111	102.8	9.2	75	130
3424-82-6	2,4-DDE	111	102.2	9.5	74	131
72-54-8	4,4'-DDD	2995	97.7	13.9	56	139
72-55-9	4,4'-DDE	2938	95.3	13	56	134
50-29-3	4,4'-DDT	2470	95.8	15.1	50	141
309-00-2	Aldrin	2985	90.5	15.2	45	136
319-84-6	alpha-BHC	3021	90.9	15.3	45	137
5103-71-9	alpha-Chlordane	2681	93.7	13.2	54	133
319-85-7	beta-BHC	2989	93.1	14.3	50	136
57-74-9	Chlordane	229	95.7	17.7	43	149
319-86-8	delta-BHC	2943	93.3	15.3	47	139
60-57-1	Dieldrin	2987	95.7	13.4	56	136
959-98-8	Endosulfan I	984	92.2	13.2	53	132
33213-65-9	Endosulfan II	2913	93.1	13.5	53	134
1031-07-8	Endosulfan sulfate	2954	95.9	13.5	55	136
72-20-8	Endrin	3076	98.1	13.9	57	140
7421-93-4	Endrin Aldehyde	3004	86	17	35	137
53494-70-5	Endrin Ketone	2953	95.5	13.5	55	136
58-89-9	gamma-BHC [Lindane]	3153	92.1	14.4	49	135
5566-34-7	gamma-Chlordane	2749	94.3	13.7	53	135
76-44-8	Heptachlor	3144	91.6	14.9	47	136
1024-57-3	Heptachlor Epoxide	3093	93.9	13.9	52	136
118-74-1	Hexachlorobenzene	319	91.6	11.4	57	126
72-43-5	Methoxychlor	3021	97.6	15.2	52	143
2385-85-5	Mirex	303	96.4	10.6	65	128
877-09-8	Tetrachloro-m-xylene	1482	85.3	14.6	42	129
8001-35-2	Toxaphene	532	86.7	17.9	33	141

Other Methods (8270) Performance Limits

Table C-26. Method 8270 Aqueous Matrix

CAS ID	Analyte	N Records	Mean	Standard Deviation	Lower Control Limit	Upper Control Limit
92-52-4	1,1-Biphenyl	2247	82.1	11.1	49	115
95-94-3	1,2,4,5-Tetrachlorobenzene	2326	77.9	14.5	35	121
120-82-1	1,2,4-Trichlorobenzene	4716	72.6	14.5	29	116
95-50-1	1,2-Dichlorobenzene	4442	71.4	13.3	32	111
528-29-0	1,2-Dinitrobenzene [1,2-DNB]	112	83.9	8.3	59	109
122-66-7	1,2-Diphenylhydrazine [Azobenzene]	2244	85.4	12.2	49	122
99-35-4	1,3,5-Trinitrobenzene [1,3,5-TNB]	241	89.1	16	41	137
541-73-1	1,3-Dichlorobenzene	4375	68.6	13.6	28	110
99-65-0	1,3-Dinitrobenzene [1,3-DNB]	601	88.2	13.1	49	128
106-46-7	1,4-Dichlorobenzene	5433	70.4	13.9	29	112
90-13-1	1-Chloronaphthalene	211	84.5	8.8	58	111
90-12-0	1-Methylnaphthalene	3742	80	13.1	41	119
134-32-7	1-Naphthylamine	258	73.7	16.6	24	124
58-90-2	2,3,4,6-Tetrachlorophenol	2293	89	13	50	128
935-95-5	2,3,5,6-Tetrachlorophenol	266	85.6	11.7	50	121
608-27-5	2,3-Dichloroaniline	150	99.2	9.8	70	129
95-95-4	2,4,5-Trichlorophenol	5707	88.1	11.8	53	123
118-79-6	2,4,6-Tribromophenol	2059	91.5	16	43	140
88-06-2	2,4,6-Trichlorophenol	6136	87.2	12.4	50	125
120-83-2	2,4-Dichlorophenol	5330	84	12.2	47	121
105-67-9	2,4-Dimethylphenol	5298	77.5	15.6	31	124
51-28-5	2,4-Dinitrophenol	5127	82.9	20	23	143
121-14-2	2,4-Dinitrotoluene	6032	92.3	11.8	57	128

Table C-26. Method 8270 Aqueous Matrix

CAS ID	Analyte	N Records	Mean	Standard Deviation	Lower Control Limit	Upper Control Limit
87-65-0	2,6-Dichlorophenol	1583	84	11.4	50	118
606-20-2	2,6-Dinitrotoluene	5107	90.7	11.2	57	124
53-96-3	2-Acetylaminofluorene	228	98.9	12.9	60	138
91-58-7	2-Chloronaphthalene	5084	78	12.8	40	116
95-57-8	2-Chlorophenol	5571	77.5	13.2	38	117
93951-73-6	2-Chlorophenol-d4	119	79.9	8.7	54	106
321-60-8	2-Fluorobiphenyl	2263	81.2	12.4	44	119
367-12-4	2-Fluorophenol	2022	68.8	16.6	19	119
91-57-6	2-Methylnaphthalene	6330	80.7	13.6	40	121
95-48-7	2-Methylphenol (o-Cresol)	5800	73	14.5	30	117
88-74-4	2-Nitroaniline	4855	90.8	12.1	55	127
119-75-5	2-Nitrodiphenylamine	272	97.3	11.3	64	131
88-75-5	2-Nitrophenol	5097	84.6	12.7	47	123
109-06-8	2-Picoline [2-Methylpyridine]	195	71.6	12.6	34	109
91-94-1	3,3'-Dichlorobenzidine	4815	77.9	16.9	27	129
56-49-5	3-Methylcholanthrene	237	94	12.8	56	133
99-09-2	3-Nitroaniline	4808	84.4	14.5	41	128
65794-96-9	3/4-Methylphenol [m/p-Cresol]	3472	69.7	13.6	29	110
534-52-1	4,6-Dinitro-2-methylphenol	5097	90.1	15.5	44	137
101-55-3	4-Bromophenyl phenyl ether	5074	89.1	11.5	55	124
59-50-7	4-Chloro-3-methylphenol	5338	85.5	11.3	52	119
106-47-8	4-Chloroaniline [p-Chloroanlinie]	4687	75.3	14	33	117
7005-72-3	4-Chlorophenyl phenyl ether	5071	86.7	11.3	53	121
106-44-5	4-Methylphenol [p-Cresol]	2798	72.5	15.8	25	120
99-55-8	5-Nitro-o-toluidine [2-amino-4-nitrotoluene]	260	82.1	14.6	38	126
57-97-6	7,12-Dimethylbenz(a)-anthracene	373	97.1	11.9	61	133
83-32-9	Acenaphthene	6952	84.5	12.3	47	122
208-96-8	Acenaphthylene	6662	85.3	14.7	41	130
98-86-2	Acetophenone	2877	82.1	12	46	118
120-12-7	Anthracene	6792	89.6	11	57	123
140-57-8	Aramite	100	82.8	16.3	34	132

Other Methods (8270) Performance Limits

Table C-26. Method 8270 Aqueous Matrix

CAS ID	Analyte	N Records	Mean	Standard Deviation	Lower Control Limit	Upper Control Limit
1912-24-9	Atrazine	2328	92.8	16.4	44	142
103-33-3	Azobenzene	578	88.5	9.3	61	116
56-55-3	Benz(a)anthracene	6867	91.6	11.1	58	125
50-32-8	Benzo(a)pyrene	7045	90.8	12.4	54	128
205-99-2	Benzo(b)fluoranthene	6767	92	12.9	53	131
191-24-2	Benzo(g,h,i)perylene	6624	92	13.9	50	134
207-08-9	Benzo(k)fluoranthene	6803	93.2	12.1	57	129
100-51-6	Benzyl alcohol	3349	71.2	13.5	31	112
111-91-1	bis(2-Chloroethoxy)methane	5094	83.9	11.9	48	120
111-44-4	Bis(2-chloroethyl) ether	5139	80.8	12.6	43	118
39638-32-9	bis(2-Chloroisopropyl) ether	1140	83.4	15.4	37	130
117-81-7	Bis(2-ethylhexyl) phthalate	5288	95.2	13.3	55	135
85-68-7	Butyl benzyl phthalate	5173	93.3	13.5	53	134
86-74-8	Carbazole	4187	91.1	10.4	60	122
510-15-6	Chlorobenzilate	226	104.3	15.4	58	150
218-01-9	Chrysene	6779	91.3	10.7	59	123
124-18-5	Decane	126	66.9	12.8	29	105
84-74-2	Di-n-butyl phthalate	5329	93	11.4	59	127
117-84-0	Di-n-octyl phthalate	5222	95.5	15	51	140
2303-16-4	Diallate [cis or trans]	249	95.3	9.6	67	124
226-36-8	Dibenz(a,h)acridine	136	104.4	9.7	75	134
53-70-3	Dibenzo(a,h)anthracene	6840	92.7	13.8	51	134
132-64-9	Dibenzofuran	4963	85.3	10.8	53	118
84-66-2	Diethyl phthalate	5207	90.1	11.5	56	125
131-11-3	Dimethyl phthalate	4977	86	13.7	45	127
60-11-7	Dimethylaminoazobenzene	238	97.1	11.6	62	132
88-85-7	Dinoseb	144	93.4	10.8	61	126
101-84-8	Diphenyl ether	142	91.7	7.8	68	115
122-39-4	Diphenylamine	754	83	9.2	55	111
298-04-4	Disulfoton	122	92.5	12.5	55	130
62-50-0	Ethyl methanesulfonate	215	90.1	9.4	62	118
206-44-0	Fluoranthene	6826	92.6	11.9	57	128

Table C-26. Method 8270 Aqueous Matrix

CAS ID	Analyte	N Records	Mean	Standard Deviation	Lower Control Limit	Upper Control Limit
86-73-7	Fluorene	6786	88.1	12	52	124
118-74-1	Hexachlorobenzene	6263	88.7	12.1	53	125
87-68-3	Hexachlorobutadiene	5878	73.1	16.9	22	124
67-72-1	Hexachloroethane	5904	68	15.7	21	115
95-13-6	Indene	253	93.8	13.7	53	135
193-39-5	Indeno(1,2,3-cd)pyrene	6880	92.6	13.6	52	134
465-73-6	isodrin	212	97.6	10	68	128
78-59-1	Isophorone	5190	83.3	13.7	42	124
120-58-1	Isosafrole	230	91.1	11.8	56	126
66-27-3	Methyl methanesulfonate	237	70.1	12.3	33	107
298-00-0	Methyl parathion	121	101.6	19	45	159
100-75-4	n-Nitorosopiperidine	299	88.6	10.8	56	121
924-16-3	n-Nitrosodi-n-butylamine	322	90.4	10.3	60	121
621-64-7	n-Nitrosodi-n-propylamine	5145	84	11.7	49	119
55-18-5	n-nitrosodiethylamine	488	81.8	12.9	43	121
86-30-6	n-Nitrosodiphenylamine	3743	86.8	11.9	51	123
10595-95-6	n-Nitrosomethylethylamine	311	78.7	12.7	41	117
59-89-2	n-Nitrosomorpholine	214	86.2	10.3	55	117
930-55-2	n-Nitrosopyrrolidine	716	80.8	10.8	48	113
91-20-3	Naphthalene	6953	80	13.5	40	121
98-95-3	Nitrobenzene	5955	83	12.8	45	121
4165-60-0	Nitrobenzene-d5	2223	82.1	12.6	44	120
126-68-1	O,O,O-Triethyl phosphorothioate	212	92.6	8.8	66	119
95-53-4	o-Toluidine	296	69.9	13.2	30	110
593-45-3	Octadecane	151	89	13.1	50	128
56-38-2	Parathion	152	102.6	12.3	66	140
608-93-5	Pentachlorobenzene	401	91.1	10.7	59	123
76-01-7	Pentachloroethane	139	60.9	10.4	30	92
87-86-5	Pentachlorophenol	6083	86.4	17.1	35	138
82-68-8	Pentchloronitrobenzene	618	94.5	13.4	54	135
62-44-2	Phenacetin	241	97.9	8.9	71	124

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

Cook-Off Mitigation for Medium Caliber Ammunition

Nausheen Al-Shehab, Kevin Miers, Jacek Foltynski

CCDC Armaments Center, FCDD-ACM-EW

Distribution Statement A: Approved for public release, distribution is unlimited

OUTLINE

- Typical Medium Caliber Baseline CO Response
  - Bare warhead
  - Logistical Configuration
- Successful Demonstration of IM Mitigation Technology
- Logistical Response Challenges and Potential Issues with Medium Caliber Ammunition
- Burn Model
- 6F/h versus 27F/h
- Potential Solutions
- Successful Cook-Off Mitigation
- Conclusions

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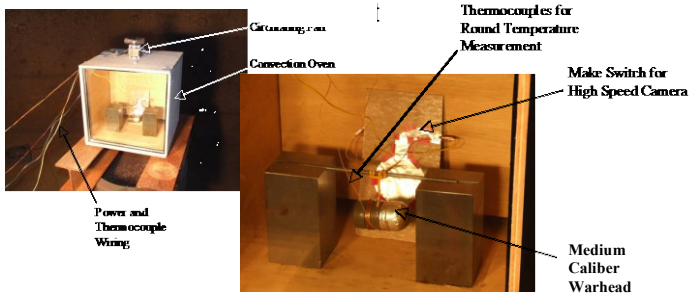
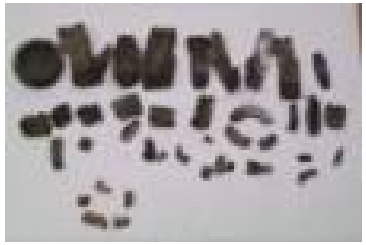
TYPICAL BASELINE RESPONSE – WARHEAD ONLY

Medium caliber warheads reacts violently when subjected to Cook-off tests as defined in MIL-STD-2105C



M430A1 Baseline SCO (6F/h)[1]

XM25mm Baseline SCO (6F/h)[2]



30mm Baseline SCO

XM25mm Baseline FCO[2]

Type II

Notes:
1. IMEMTS, "TESTING OF AN IM UPGRADED M430A1 40 mm GRENADE," Las Vegas, NV, 14-17 May 2012
2. IMEMTS, "IM Baseline Testing of the XM25 HEAB Cartridge," Rome, Italy 18-21 May 2015

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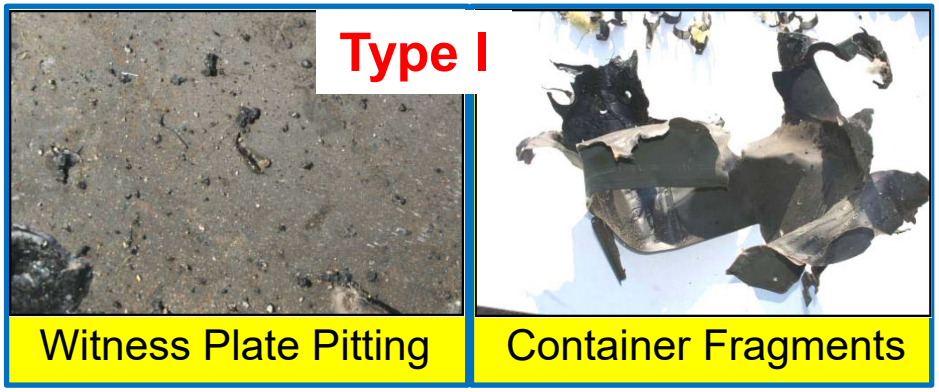
TYPICAL BASELINE RESPONSE – PACKAGED

Logistical configuration of medium caliber cartridges react violently when subjected to Cook-off tests as defined in MIL-STD-2105C

40mm Baseline SCO (6F/h)

XM25mm Baseline SCO (6F/h)[1]



30mm Live Warhead Baseline SCO (6F/h)

Notes:

1. IMEMTS, "IM Baseline Testing of the XM25 HEAB Cartridge," Rome, Italy 18-21 May 2015

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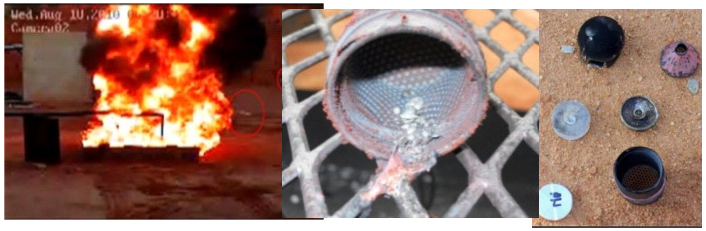
SUCCESSFUL DEMONSTRATION OF INDIVIDUAL IM TECHNOLOGY

Warhead Venting

- Successful SCO tests of bare projectiles with warhead venting melt rings (6F/h)

- Successful FCO tests of bare projectiles with warhead venting melt rings



- Successful packaged SCO Tests of 8 linked rounds with warhead venting– front and aft confinement
  - Live warheads with inert cartridge cases

Notes:
1. IMEMTS, "TESTING OF AN IM UPGRADED M430A1 40 mm GRENADE," Las Vegas, NV, 14-17 May 2012

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SUCCESSFUL DEMONSTRATION OF INDIVIDUAL IM TECHNOLOGY

Cartridge Case Venting

Vented and unvented cartridge cases were testes with inert warheads and plates simulating front and aft confinement

- Unvented cases cause projectile to decrimp from cartridge case; significant damage to end plates

Vented case SCO (6F/h)

Unvented case SCO (6F/h)

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SUCCESSFUL DEMONSTRATION OF INDIVIDUAL IM TECHNOLOGY

Packaging Venting

Vented Containers with modified 40mm Cartridges

- Simulated Warhead Venting - Threads Removed and Fuze Just Set in Place. Allows Venting of HE.
- Simulated Cartridge Case Venting - Base Plug Modified; 3 Kidney Shaped Holes Filled with Wax.

SCO (6F/h)

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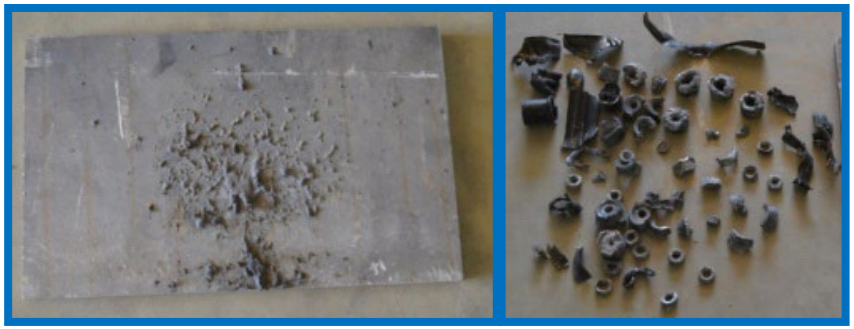
LOGISTICAL RESPONSE CHALLENGES

Violent response of single container SCO tests of combined warhead, cartridge case and packaging venting technologies

SCO 1



SCO 2

Potential Issues – Medium Caliber

- Multiple round per container (30 to 110) – heightened risk of at least one violent reaction
- Linked rounds versus unlinked rounds
- Round orientation: horizontal versus vertical
- Melted HDPE dunnage material coats rounds causing slumping and prevents release of venting mechanism

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INTEGRATED COOK-OFF TEST

Testing conducted to identify cause/location of violent reaction in system level Cook-off Environment

Test Configuration	SCO	FCO
Full Inert, Glass Container	X	
Single Round, Live IM Cartridge Case 1		(V)
Single Round, Live IM Cartridge Case 2		(V)
Full Inert, Full Standard Container		X
Bottom Layer Live - Warhead Only 1		(I)
Bottom Layer Live - Warhead Only 2		(V)*
Second from Bottom Live - Warhead Only		(V)
Third from Bottom Live - Warhead Only		(V)
Top Layer Live - Warhead Only		(V)
All Live Cartridge Case Only 1		(V)
All Live Cartridge Case Only 2		(V)
Bottom Layer Live - Warhead Only - No Dunnage		(V)
Bottom Layer Live - Warhead Only - "wine-rack"		(V)
Bottom Layer Live - Warhead Only	(I/II)	
Second from Bottom Live - Warhead Only	(IV/V)	
Third from Bottom Live - Warhead Only	(IV/V)	
Top Layer Live - Warhead Only	(I)	
Bottom Layer Live - Warhead Only - "wine-rack"	(V)	
Bottom Layer Live - Warhead Only - No Dunnage	(III)	
Bottom Layer Live - Warhead Only - Mod Dunnage	(I)	
Top Layer Live - Warhead Only - "wine rack"	(II)	
Top Layer Live - AUR - "wine rack"	(II)	

Notes:	Key:
1. Reactions shown in parenthesis ( ) are assessed, and not based on formal system-level tests.	FCO = Fast Cook-off
	SCO = Slow Cook-off
	BI = Bullet Impact
2. Reactions shown in brackets [ ] are official assessments made by the Army IM Board.	FI = Fragment Impact
	SD = Sympathetic Detonation
3. * Considered no-test due to high wind conditions and resultant thermal profile	SCJ = Schaped Charge Jet
	Type VI: No Reaction
4. Unless otherwise noted, applicable tests were conducted with standard dunnage material	Type V: Burn
	Type IV: Deflagration
	Type III: Explosion
	Type II: Partial Detonation
	Type I: Detonation

"Wine Rack" Test Configuration

Bottom Live Layer – Warhead Only

Dunnage potential cause of violence in bottom row

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LIMITED 25MM PACKAGED SCO TEST SET UP

- **Purpose: To determine the temperature and severity of reaction of cartridges in the interior of the shipping container**

Hardware:

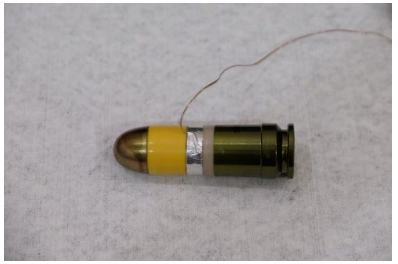
- Six cartridges with live warheads + fuze, no propellant
- Standard container and dunnage
- Inert aluminum slugs in unoccupied positions in cartons

Test Setup:

- 8 Thermocouples (6 on cartridges, 1 in air, 1 between cartons)
- Temperature soaked with 6ºF/hr ramp

Container in Oven

Aluminum Slug



Cartridge with Thermocouple

Thermocouple between Cartons

Top Tray

Bottom Tray

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LIMITED 25MM PACKAGED SCO TEST RESULTS

Recovered hardware:

- 5 cartridge cases with Aft Warheads
- 1 damaged cartridge case, piece of Aft Warhead (far right)
- 5 Forward Warheads
- No HE

Damaged cartridge case and piece of Aft Warhead identified as Cartridge #1

- One Forward Warhead missing, likely from this cartridge

Container deformed, bottom shows indents from the 3 bottom tray cartridges

- Bottom indents show no evidence of frags

Two perforations in container below live cartridge 1

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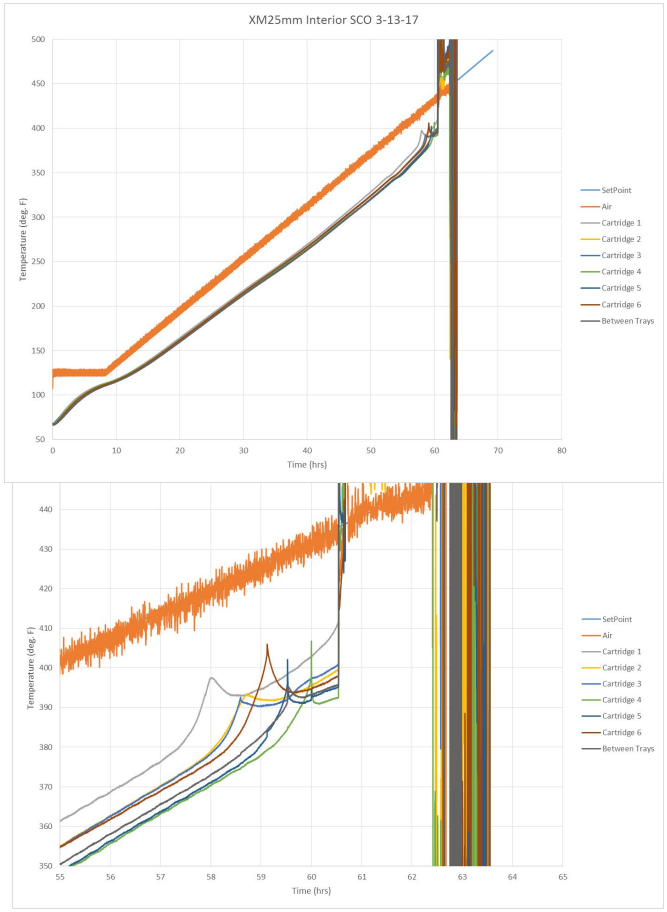
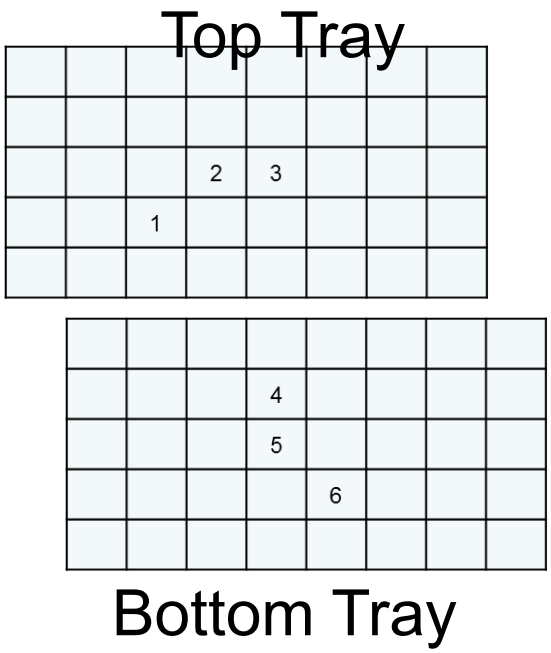
LIMITED 25MM PACKAGED SCO TEST RESULTS





- Each thermocouple shows a spike prior to terminal reaction
  - Previous testing and recovered hardware indicate each spike corresponds to the Aft Warhead deflagrating
- **Cartridge 1** likely reacted violently
  - First to show temp spike
  - Recovered hardware shows this cartridge to have most damage →Aft warhead and cartridge case damaged

Distribution Statement C: Distribution authorized to U.S. Government Agencies and their Contractors, Administrative/Operational Use, March 2017. Other requests shall be referred to Armament Research, Development, and Engineering Center, Picatinny Arsenal, New Jersey.

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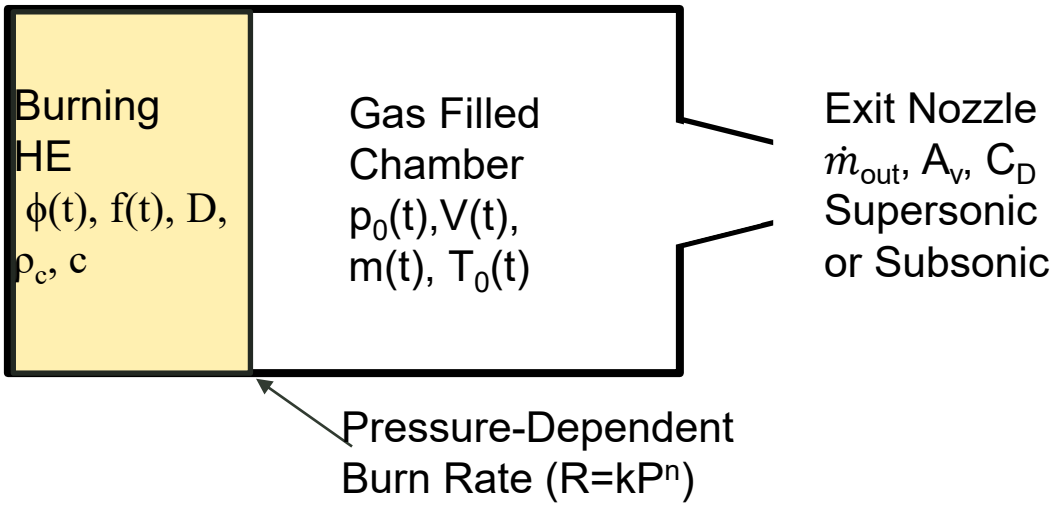
BURNING AND VENTING PHENOMENOLOGY



$$\frac{dm}{dt} = \dot{m}_{gen} - \dot{m}_{vent} \qquad R = \beta p_0^n \qquad p_0 V = mRT_0$$

- Energetics burning/venting can be described as shown above
- Most medium caliber ammunition have pressed explosives – "porous-like" burning and damage effects as well
- Burning products pressurize chamber and vent through nozzle
- The burning, venting, and gas buildup are all coupled
- This is exactly the situation in a solid propellant rocket motor

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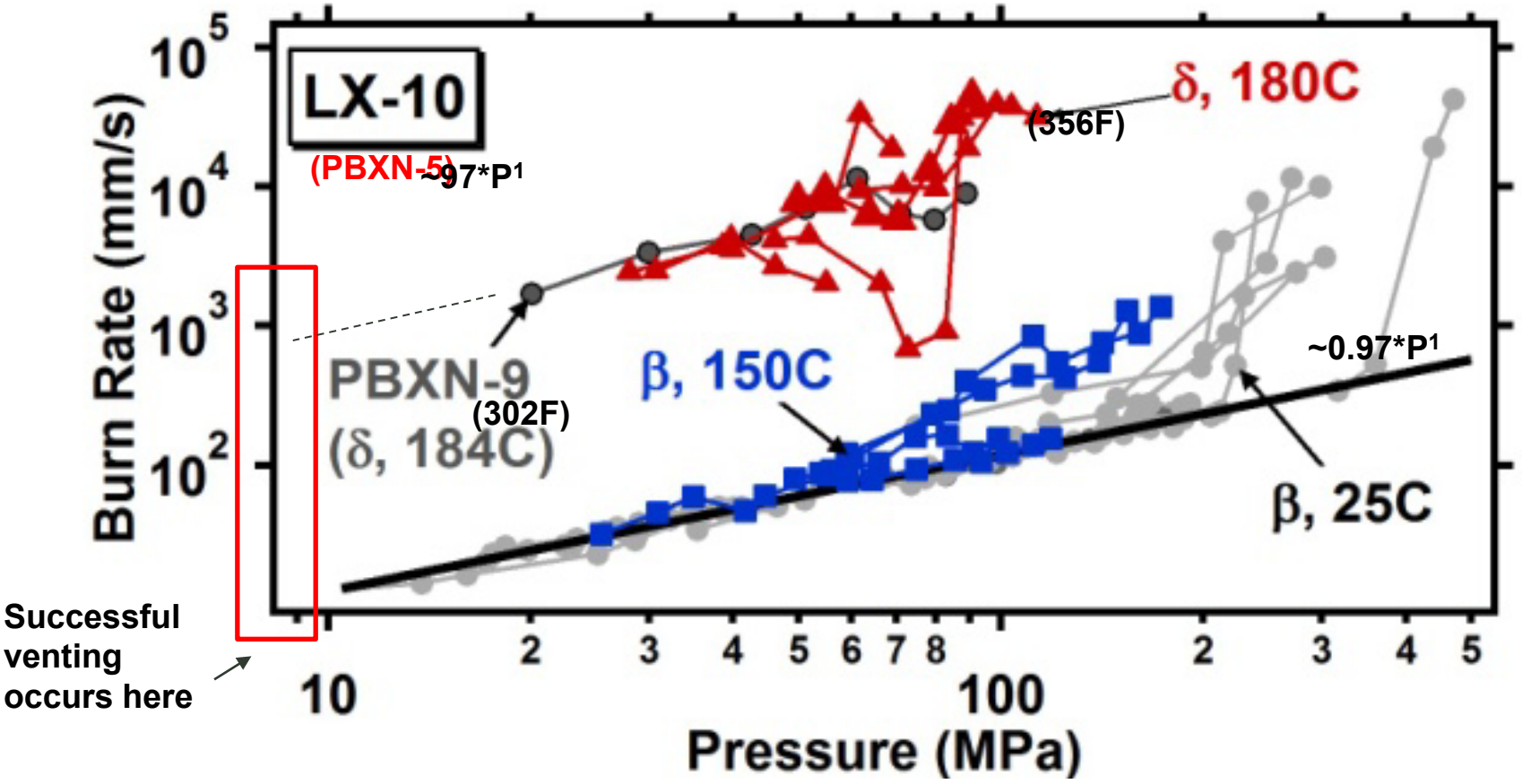
PRESSURE-DEPENDENT BURN RATES

- Explosives: $R \sim kP^2$, large T dependence. Deconsolidative burn



Hot HE → higher burn rates → more reaction violence!

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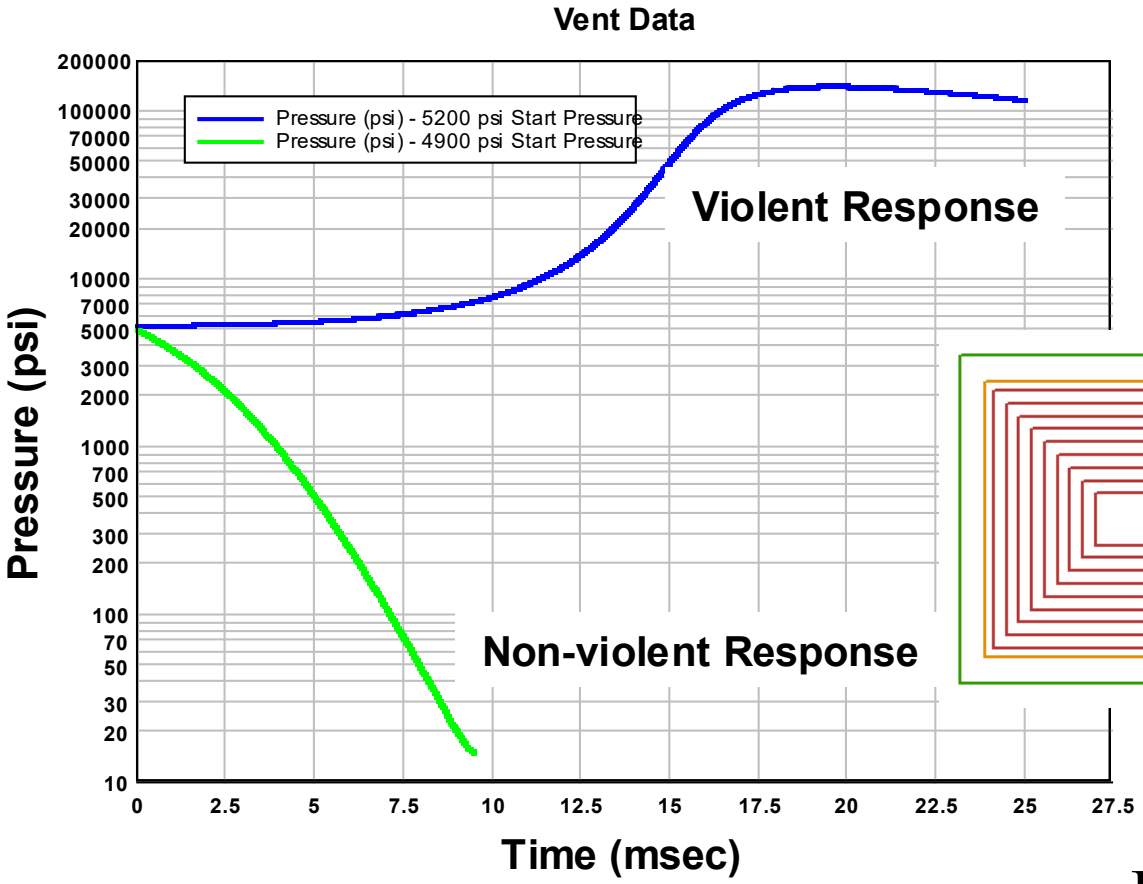
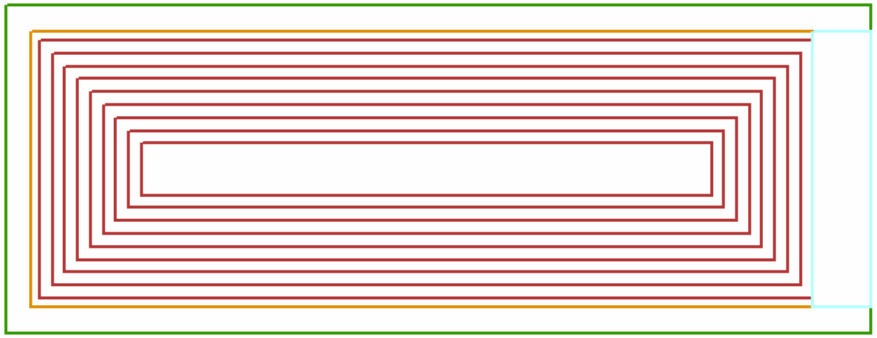
PBXN-109 ANALYTIC BURN MODELING

Analytic Burn Modeling of PBXN-109



Pressure Response



Billet Burn Profiles

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6 VERSUS 27F/H

- **For single round testing:**
  - The melt ring temperature is adequately uniform at both rates and tracks with the warhead skin temperature
  - At both 27F/h and 6 F/h the pre-ignition hotspot is expected to remain closer to the center of HE (for small munitions)
  - Cartridge case venting required for large propellant charge

- **For packaged round configuration:**
  - Each round will see the same temperature history starting at different times (latency) – (E. Baker, private communications)
  - Significant temperature gradients within container
  - Venting works for individual rounds at either rate, unless interior rounds are significantly cooler when the outer ones ignite
  - Clear vent path and sufficient vent areas required to keep pressures low once ignition occurs (slumping, deformation)
  - Gun propellant reacts significantly earlier than HE – starts as SCO, ends as FCO
  - Exact steady packaging temperature gradient challenging to model

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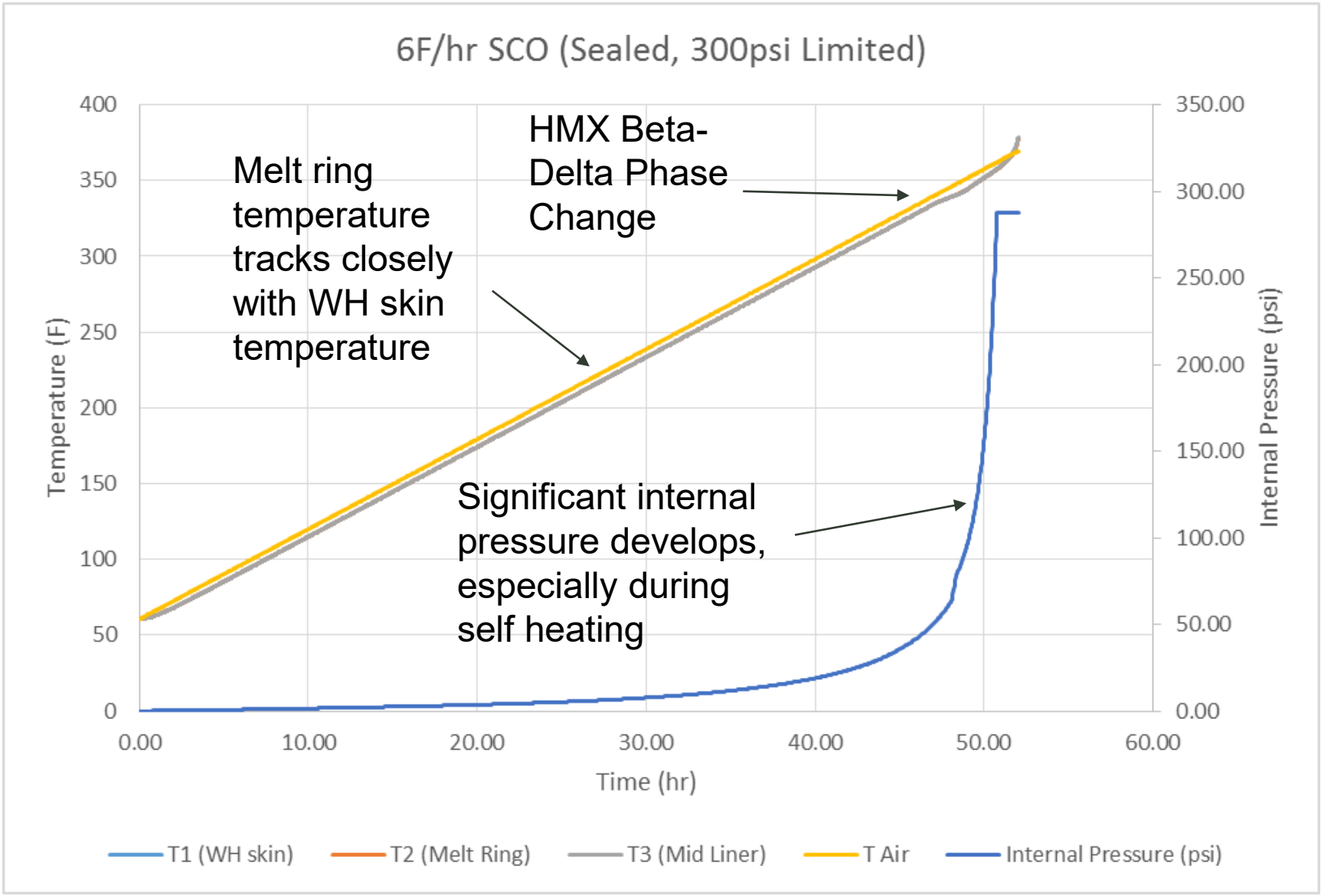
6F/HR RESULTS



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27F/HR RESULTS

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POTENTIAL SOLUTIONS

- **Effective warhead, cartridge case and container venting, as required**
- **Dimensionally stable dunnage that does not obstruct vent path**
- **Sufficiently conductive internal packaging to ensure venting features function**
- **Rudimentary mostly intractable modeling, need to test to success**
- **Couple mechanical solutions with less sensitive, higher performing energetic formulations for improved IM mitigation solutions**

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RECENT MEDIUM CALIBER VENTING

Internal View

Close-Up View

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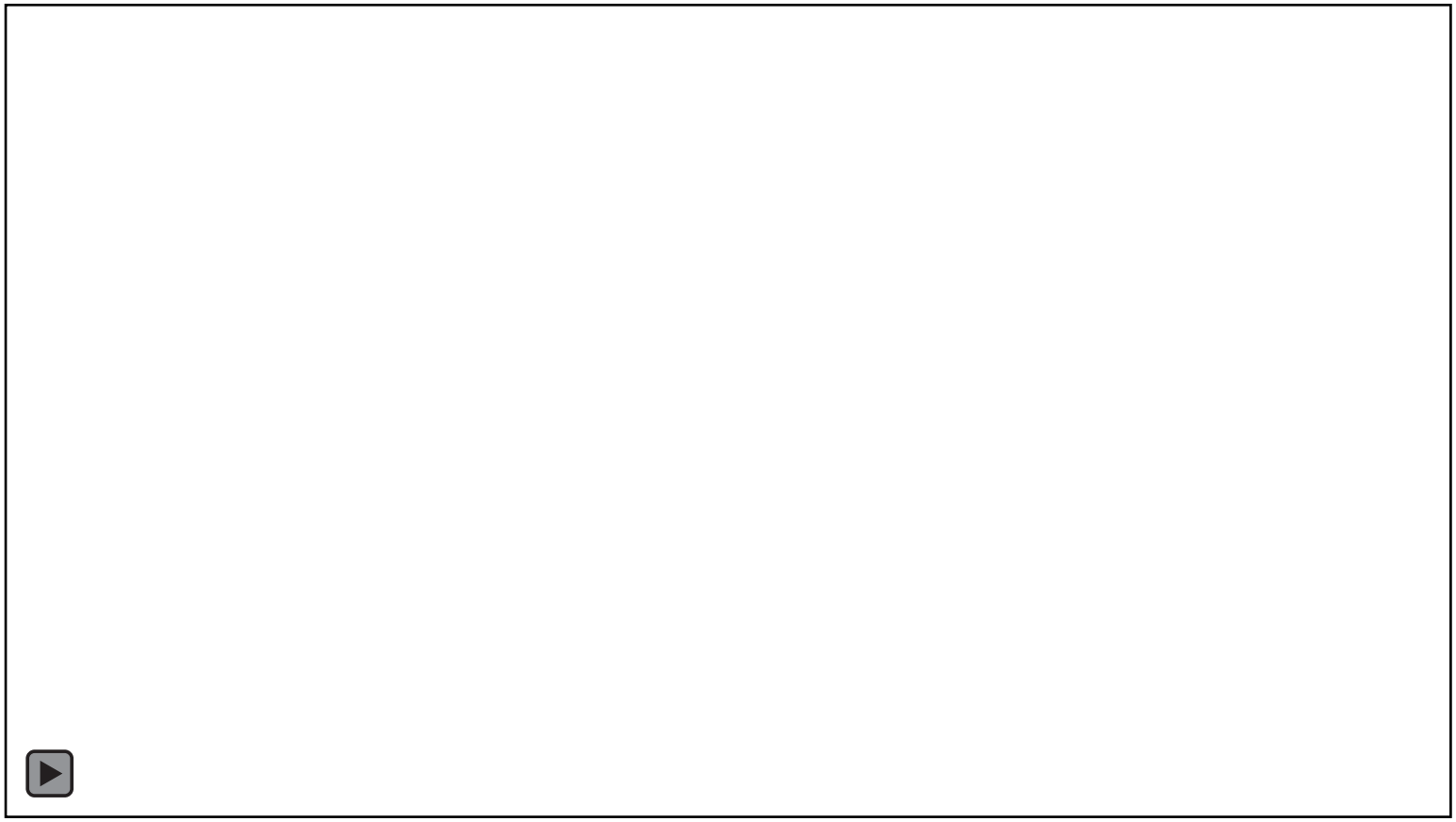
MEDIUM CALIBER VENTING INTERNAL VIEW



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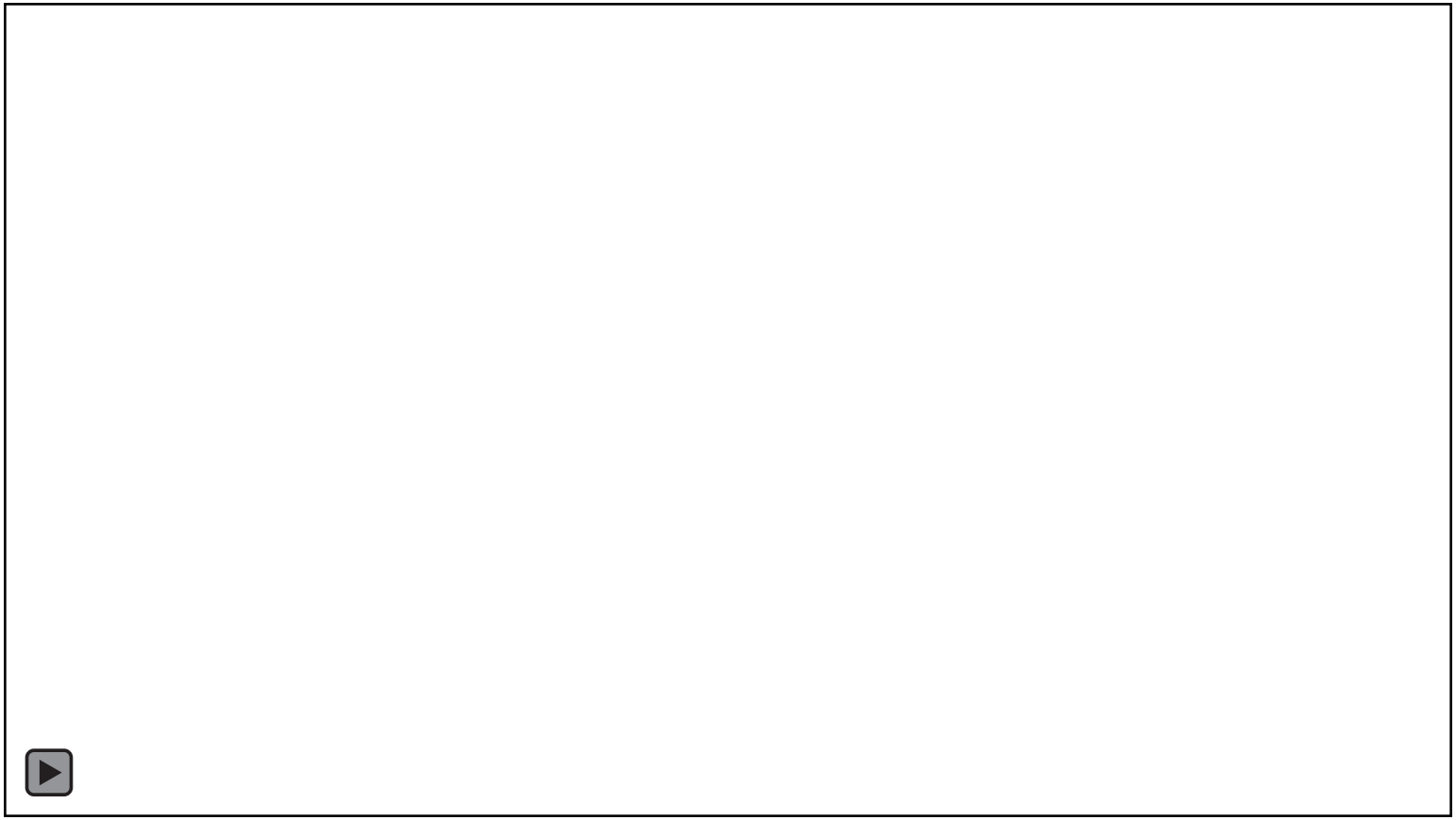
MEDIUM CALIBER VENTING CLOSE-UP VIEW



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CONCLUSIONS

- Unique challenges to medium caliber cook-off mitigation uitilizing only mechanical solutions
  - Clear vent path and sufficient vent areas required to keep pressures low once ignition occurs (slumping, deformation)
  - Container heat management required to address potential large thermal gradients within the container
    - Need to actuate internal round vent features prior to outer rounds initiating
- Exact steady packaging temperature gradient challenging to model
- Need to couple mechanical solutions with less sensitive higher performing energetic materiel
- Encouraging recent results for 27F/h heating rate, however, need to be aware of large temperature gradients within containers

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