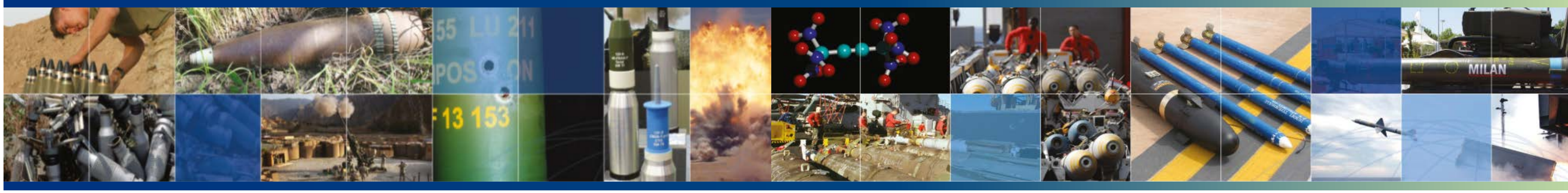
MSIAC

Munitions Safety Information Analysis Center

Supporting Member Nations in the Enhancement of their Munitions Life Cycle Safety



Insensitive Munitions Requirements, Technology, and Testing

May 2017

Presented by
Dr. Ernest L. Baker
Technical Specialist Officer
Warheads Technology
+32 (0)2 707 3844
e.baker@msiac.nato.int

Overview

- **IM Requirements: US vs. International**
- **Energetics Choice**
- **IM Warheads Design**
  - Shock Mitigation: TEMPER, PIMS
  - Venting
  - Packaging: Venting & Barriers
- **IM Propulsion Design**
  - Venting Devices
  - Active Mitigation
  - Intumescent coating
  - Casing composition
  - Packaging & Barriers
- **Conclusion: worst and best days**

US REQUIREMENTS

U.S. IM Law

- United States Code, Title 10, Chapter 141, Section 2389.

  § 2389. Ensuring safety regarding **insensitive munitions**. The Secretary of Defense shall ensure, to the extent practicable, that munitions under development or procurement are safe throughout development and fielding when subjected to unplanned stimuli.

DoD Policy

- DoD Directive 5000.1 The Defense Acquisition System May 12, 2003.

  All systems containing energetics shall comply with insensitive munitions criteria.

Joint Chiefs Policy

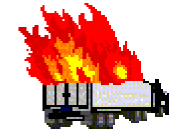
- Chairman, Joint Chiefs of Staff Manual 3170.01A, March 12, 2004

  Enclosure C, page C-5, para 2.b(2), **"Insensitive Munitions Waiver Requests._Insensitive munitions waiver requests require approval by the JROC.** Insensitive munitions waiver requests shall include a Component or agency approved insensitive munitions plan of action and milestones to identify how future purchases of the same system or future system variants will achieve incremental and full compliance.

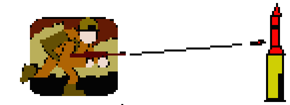
DoD Implementation through MIL-STD-2105

US vs. International

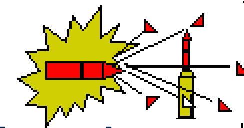
US DoD Insensitive Munitions: MIL-STD-2105D



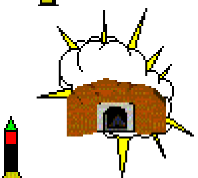
- FCO: STANAG 4240, logistical and operational



- SCO: STANAG 4382, logistical and operational
- BI: STANAG 4241, logistical and operational



- FI: STANAG 4496, logistical and operational
- SR: STANAG 4396, logistical confined and unconfined



- SCJI: STANAG 4526, Procedure 2, 81 mm LX-14 SC

International

- NATO: Policy for Introduction and Assessment of Insensitive Munitions (IM), STANAG 4439 covering AOP-39 Edition 3 (17 Mar 2010)
- However different countries have different national policies
- Several NATO and some MSIAC countries do not have national IM policies

IM Policy: History & Progress

- 1995:
  - Publication for ratification of STANAG 4439 (AOP 39)
    - Ratified in 1998
  - Existing National IM Policies: AUS, CA, FR, NL, UK, US
- 2016:
  - NATO:
    - STANAG 4439 covering AOP-39 Edition 3 (17 Mar 2010)
  - Ratification Status:
    - Ratified and Implemented: **CAN,** CZE(1), **DEU,** DNK, **ESP, FRA, GBR,** HUN, **NLD, NOR,** ROU, SVK, TUR, **USA, AUS(2)**
    - Ratified to be implemented: **BEL,** BGR, EST, **ITA,** LTU, SVN, **FIN(2)**, **SWE(2)**
    - Ratified not implemented:
    - No Response: ALB, GRC, HRV, LUX, POL, PRT,
    - Not Participating: LVA
  - UN
    - UN HD 1.6 and Test Series 7

(1): With comments (2): MSIAC member non-NATO nation

Two Overarching Approaches

- Progressive Approach
  - IM requirements determined by THA (Threat Hazard Assessment)
    - Some nations use pre-defined levels 1* 2* 3*
  - Assessment of risks, communication of risks, and decisions based on acceptability

OR

- IM Ultimate Goal Associated with a “Waiver” System
  - IM requirements = IM ultimate goal
  - High level decision board (2 to 4-star) to authorise “waivers” for any non-compliance
  - THA has been used as a means to:
    - Eliminate the less relevant threats
    - Tailor the tests
    - Evaluate risk of any non-compliance to inform waiver process
    - Require additional “IM” (Safety) tests beyond the standard STANAG 4439 required tests

IM Requirements Summary

Supporting Munitions Safety

			NATO		UK	DEU	Italy			France			USA	UN
			STANAG 4439											
Threat	Test Procedures		IM Requirements	AASTP-1 SsD 1.2.3	JSP 520	Fü S IV 3	DG-AT IM Guidelines 2000			Instruction No 211893 7/21/2011			MIL-STD-2105D	HD 1.6
	STANAG	Stimuli					Φ	ΦΦ	ΦΦΦ	*	* *	* * *[4]		
Magazine/store fire or aircraft/vehicle fuel fire	4240	FH	V	V	V	V	V	V	V	IV[2]	V[3]	V[3]	V	V[4]
Fire in an adjacent magazine, store or vehicle	4382	SH	V	V	V	V	V	V	V	III	V	V	V	V[4]
Small arms attack	4241	BI	V	V	V	V	V	V	V	III	V	V	V	V[4]
Most severe reaction of same munition in magazine, store, aircraft or vehicle	4396	SR	III	III	III	III	III	III	III	III	III	III	III	III[4]
Fragmenting munitions attack	4496	FI	V		V	V		I[1]	V		V	V	V	V[4]
		Heavy FI						I[1]	V		III[5]	III[5]		
Shaped charge weapon attack	4526	SCJI	III		III	III		I[1]	III		III	III	III	

[1] Type I or better as per THA

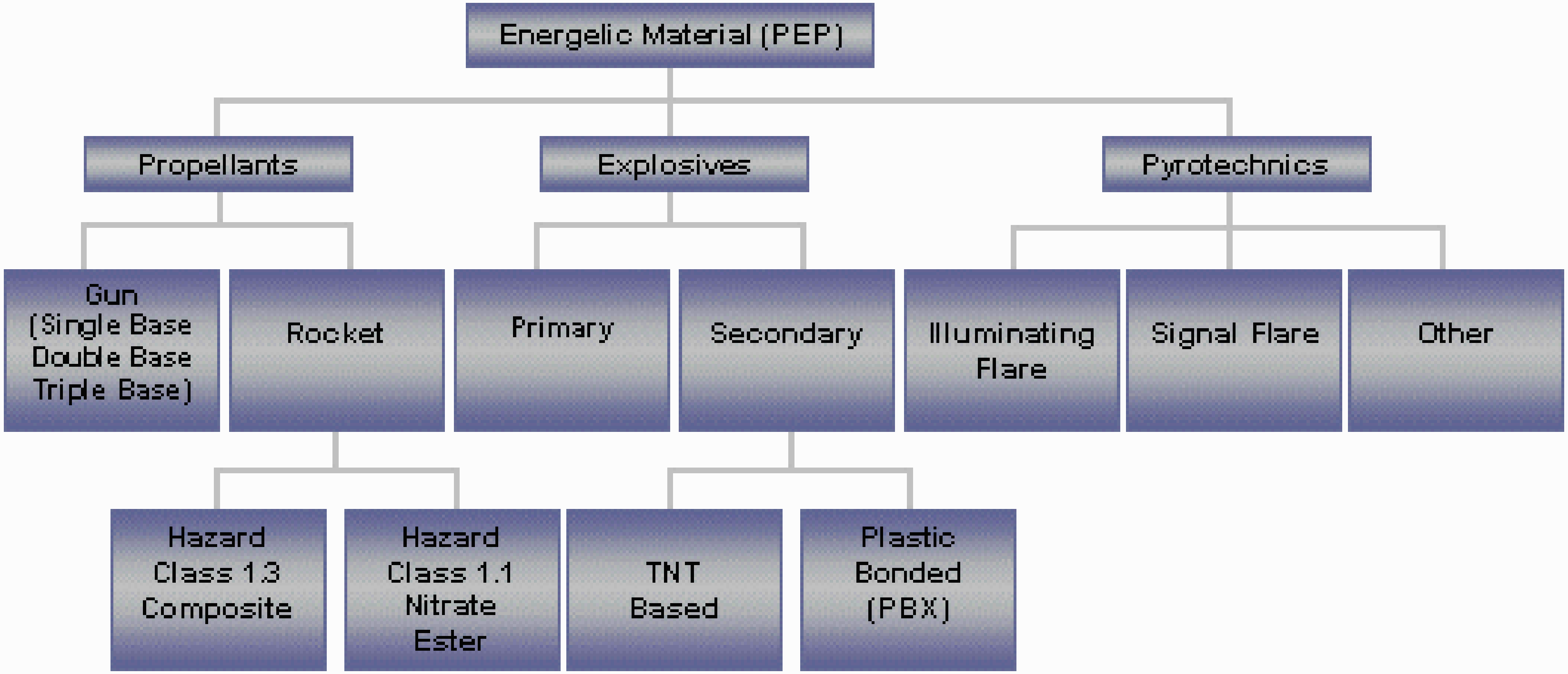
[2] Without Propulsion

[3] Only after 5 minutes

[4] Energetic materials required to meet substance criteria specified in UN orange Book TS7

[5] French National Standard NF T70-512

ENERGETICS CHOICE



Energetics choice based on application.

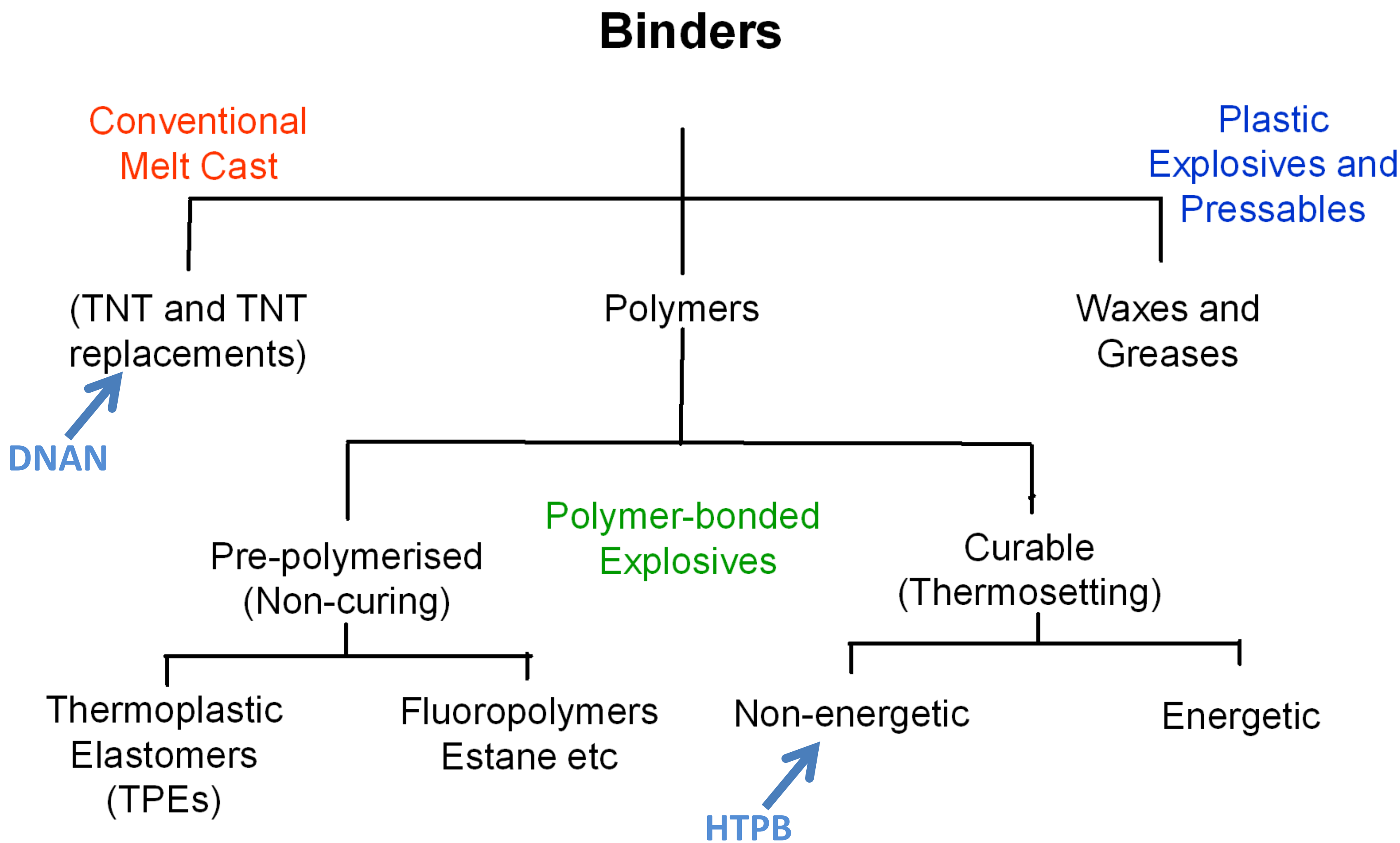
Secondary Explosives

- High energy explosive
  - Early energy output in work: most of work output by 7V/V0
  - Metal pushing: shaped charge, EFP, fragmentation
  - “Brisance” (now characterized by detonation pressure)
  - No aluminum in composition
- High blast explosive
  - Later energy output in work: work output after 10V/V0
  - Significant blast pressure and energy increases
  - Aluminum in composition (typically 15% - 30%)

	Density (gm/cc)	Relative Brisance	Relative Blast
TNT	1.60	100	100
Tritonal (TNT+Al)	1.75	93	124

Choice based on application.

ENERGETICS CHOICE

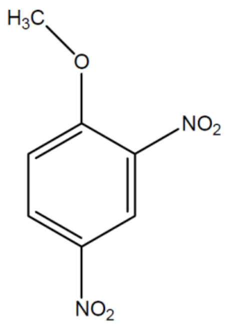


Choice based on a balance of performance vs. sensitivity.

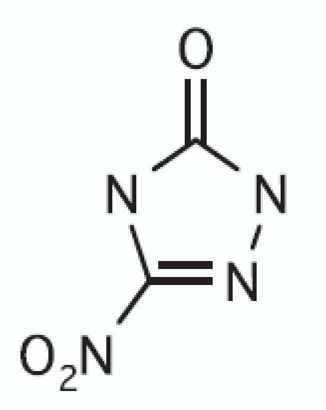
Recent IM Melt Pour

DNAN: 2,4-dinitroanisole, $C_7H_6N_2O_5$

- Melting point: 89 °C
- Molecular weight: 198.13 g/mol
- Detonation Velocity: 6200 m/s
- Density: 1.341 g/cc
- Typical Form: Fine Powder
- Color: Light Yellow
- First used in 2nd World War: AMATOL-40 – DNAN/AN/RDX for 'V Rockets'



- Nitrotriazolone (NTO)
- 5-nitro-1,2-dihydro-1,2,4-triazol-3-one, $C_2H_2N_4O_3$
- Melting Point 273°C (decomposition)
- Molecular weight: 130.013 g/mol
- Detonation Velocity: 8560 m/s
- Density: 1.93 gm/cc
- First prepared NTO in 1905

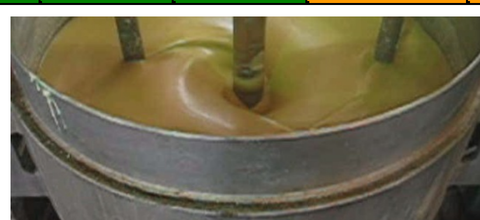


IMX-101 Melt Pour

Theoretical Maximum Density*:	1.67 g/cc
Velocity of Detonation:	6900 m/s
Detonation Pressure*:	20.56 GPa
Heat of Detonation*:	2.34 kJ/cc explosive
Gas Evolved on Detonation*:	0.462 cc/g explosive
Melting Point (DSC):	95.0 °C
Exotherm Onset (DSC):	207.0 °C
Efflux Viscosity @ 96°C:	< 4.0 seconds
Vacuum Thermal Stability (STANAG 4456):	0.115 ml/g
ERL Impact Sensitivity (STANAG 4489):	> 220 cm
Expanded Large Scale Gap Test (ELSGT)	59.0 - 60.0 kbar

IMX-101 IM Systems Test Result **

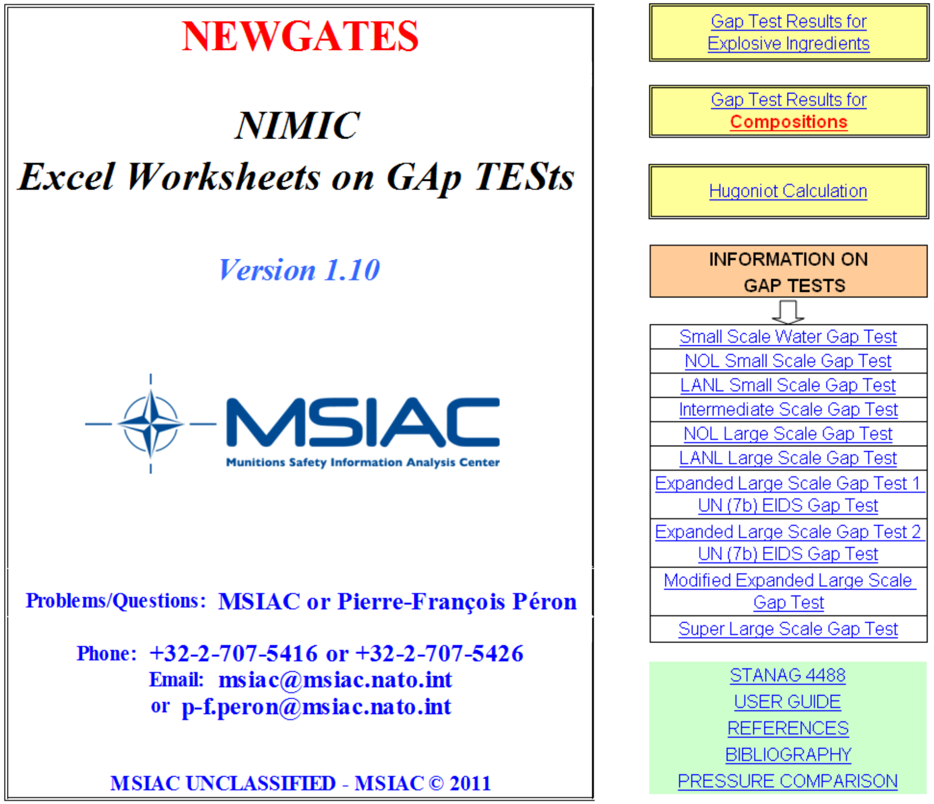
IM Tests	Fast Heating	Slow Heating	Bullet Impact	Fragment Impact	Sympathetic Reaction	Shaped Charge Jet Impact
Test Ref: (STANAG)	4240	4382	4241	4496	4396	4526
Passing Criteria	Type V	Type V	Type V	Type V	Type III	Type III
Baseline TNT	Type III	Type III	Type IV	Type IV	Type I	Type I
IMX-101	Type V	Type V	Type V	Type V	Type III	Type III



NEWGATES

SENSITIVITY: DATABASE OF GAP TEST DATA

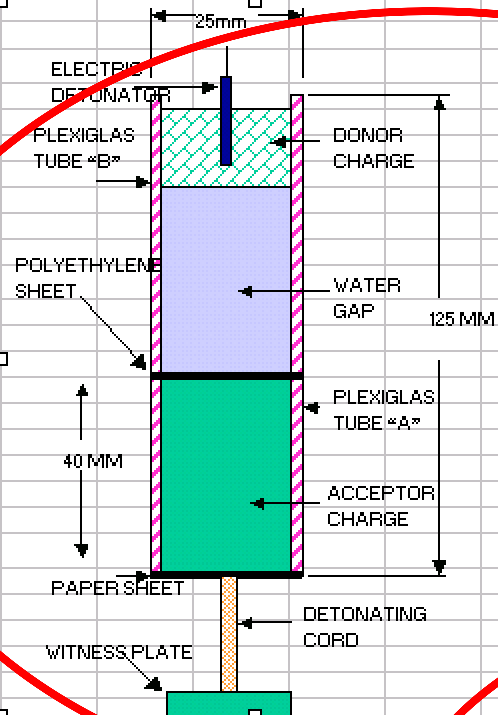
- NIMIC Excel Worksheet on Gap TESts (NEWGATES)
  - Most recent version 1.10: developed in Excel2003
  - Flexible research tool: References, data and calculations
  - 10 gap tests (dimensions, scop principles)
  - calibration curves: pressure, time and shock curvature
  - 1455 gap test results
  - Unreacted Hugoniots & mixtur Hugoniot calculation
- Wide range of:
  - Ingredients
  - Explosive composition
  - Gap tests
- Searchable:
  - Excel “Autofilter”

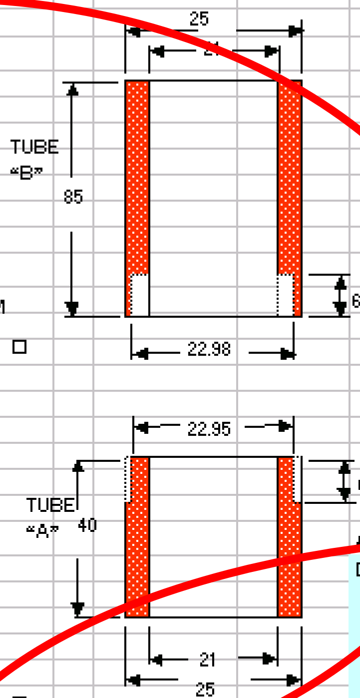


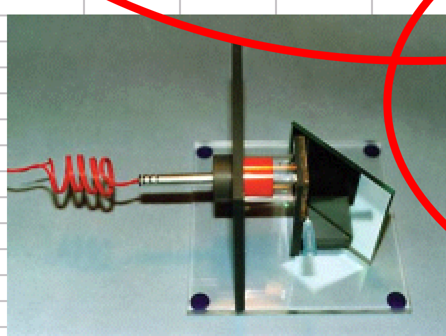
MSIAC
Supporting Munitions Safety

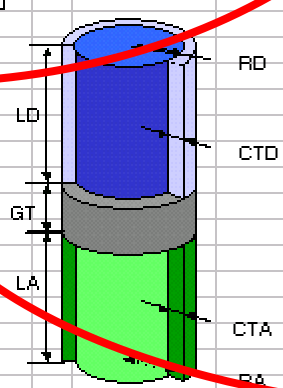
General Information on Gap Tests

Small Scale Water Gap Test









Scope

This method covers the test procedures to be used for the determination of the small-scale shock sensitivity of explosive materials. This technique is primarily designed to be used for booster and main charge explosives with critical diameters less than 20 mm.

Principle

Like other gap tests, this test is a measure of the shock required to initiate and propagate a high order detonation in the explosive being tested. The sensitivity of the acceptor explosive is determined as a function of the height of a water column which is used to attenuate the shock output of the donor explosive. Results are expressed as the height of the water column at which the acceptor is initiated 50% of the time.

Apparatus

Donor	Explosive	Radius	RD	mm	10.475
		Length	LD	mm	[illegible]
		Name			95% RDX, 5% Wa
		Density		g/cm3	1.6
		State			Solid
	Casing	Thickness	CTD	mm	2
		Name			Plexiglass
		Density		g/cm3	NA
Attenuator	Gap	Name			water
		Density		g/cm3	1
	Casing	Thickness	CTAt	mm	2
		Name			Plexiglass
		Density		g/cm3	NA
Acceptor	Explosive	Radius	RA	mm	10.5
		Length	LA	mm	40
	Casing	Thickness	CTA	mm	2
		Name			Plexiglass
		Density		g/cm3	NA

SSWGT / ISGT / NOL-LSGT / LANL-LSGT / ELSGT-1 (EIDS(7b)) / ELSGT-2 (EIDS(7b)) / modified ELSGT / SLS(

Examples of Gap Test Results

MSIAC
Supporting Munitions Safety

Pressure in the barrier at the interface with the acceptor explosive

Pressure in the acceptor explosive at the interface with the barrier

A	B	C	D	E	K	L	M	P	Q	R	S	W
Number of available gap tests results		1085			ISGT results				NOL-LSGT results			
INTRO Substance	Composition	rho0 [g/cm3]	C0 [km/s]	S	number of cards	gap length (mm)	Incident Initiation Pressure (GPa)	Critical Initiation Pressure (GPa)	number of cards	gap length (mm)	Incident Initiation Pressure (GPa)	Critical Initiation Pressure (GPa)
Octol 75/25	75HMX-25TNT	1,795										
Octol 75/25	75HMX-25TNT	1,815							220	55,88	1,68	NA
Octol 76/24	76HMX-24TNT	1,803										
Octol 76/24	76HMX-24TNT	1,810										
Octol 76/24	76HMX-24TNT	1,822										
Octol 78.6/21.4	78.6HMX-21.4TNT											
Octol 85/15	85HMX-15TNT	1,800	3,010	1,720					236	59,94	1,45	1,80
Octol 85/15	85HMX-15TNT	1,840							236	59,94	1,45	NA
ORA 86A	86HMX-14PU	1,710	2,346	2,180	150	28,50	4,86	5,97				
ORA 86A	86HMX-14PU	1,708	2,346	2,180	170	32,30	4,01	4,89				
ORA 86B	86HMX-14PU	1,700	2,346	2,180	160	30,40	4,42	5,39				
OSX-7	DNAN-RDX-NTO	1,728							110	[illegible]	[illegible]	[illegible]
OSX-8	DNAN-HMX-NTO	1,760							106	[illegible]	[illegible]	[illegible]
OSX-9		1,750							106	[illegible]	[illegible]	[illegible]
PAX-2A (pressed)	85HMX-9BDNPA/F-6CAB	1,735							168	[illegible]	[illegible]	[illegible]
PAX-2AR (pressed)	85HMX-9TNEB/DNEB-6CAB	1,736							169	[illegible]	[illegible]	[illegible]
PAX-2A	85HMX-9BDNPA/F-6CAB	1,780							139	[illegible]	[illegible]	[illegible]
PAX-2A	85HMX-9BDNPA/F-6CAB	1,770							161	[illegible]	[illegible]	[illegible]
PAX-2A	85HMX-9BDNPA/F-6CAB								137	34,80	4,47	NA
PAX-3 (pressed - class 5 HMX)	64HMX-20Al-9.6BDNPA/F-6.4CAB								129	32,77	4,70	NA
PAX-3 (pressed - class 5 HMX)	64HMX-20Al-9.6BDNPA/F-6.4CAB								124	31,37	4,87	NA
PAX-3 (pressed - class 5 HMX)	64HMX-20Al-9.6BDNPA/F-6.4CAB								120	30,48	4,99	NA
PAX-3A (pressed - class 5 HMX)	64HMX-20Al-9.6BDNPA/F-6.4	99.8% TMD							128	32,51	4,73	NA
PAX-11	79CL20-15AL-3.6BDNPA/F-2.	1,952							153	38,74	3,74	NA
PAX-12	90CL20-BDNPA/F-CAB								203	51,44	2,01	NA
PAX-12	[illegible]	[illegible]							137	34,80	4,47	NA
PAX-21	34[illegible]								155	39,37	3,62	NA
PAX-21	34DNAN-30AP-36RDX/MNA								161	40,89	3,34	NA
PAX-22	CL20-Binder	1,931							137	34,80	4,47	NA
PAX-25	DNAN/MNA-RDX-AP								134	34,04	4,55	NA

RDX Fluid Energy Mill Ground
RDX Class 1

99% TMD

"Next Generation IM Mortar Fill – Optimized PAX-33 Development and Characterization", C. Teague, A. Wilson, B. Alexander, V. Fung, IMEMTS 2007
"Development and filling of New Insensitive Melt Pour Explosives for 120 mm Direct Fire Ammunition", Alexander B., Fung V., Teague C., Gaines J., IMEMTS 2007

Intro | Database | Résultats | SSWGT | NOL-SSGT | LANL-SSGT | ISGT | NOL-LSGT | LANL-LSGT | ELSGT-

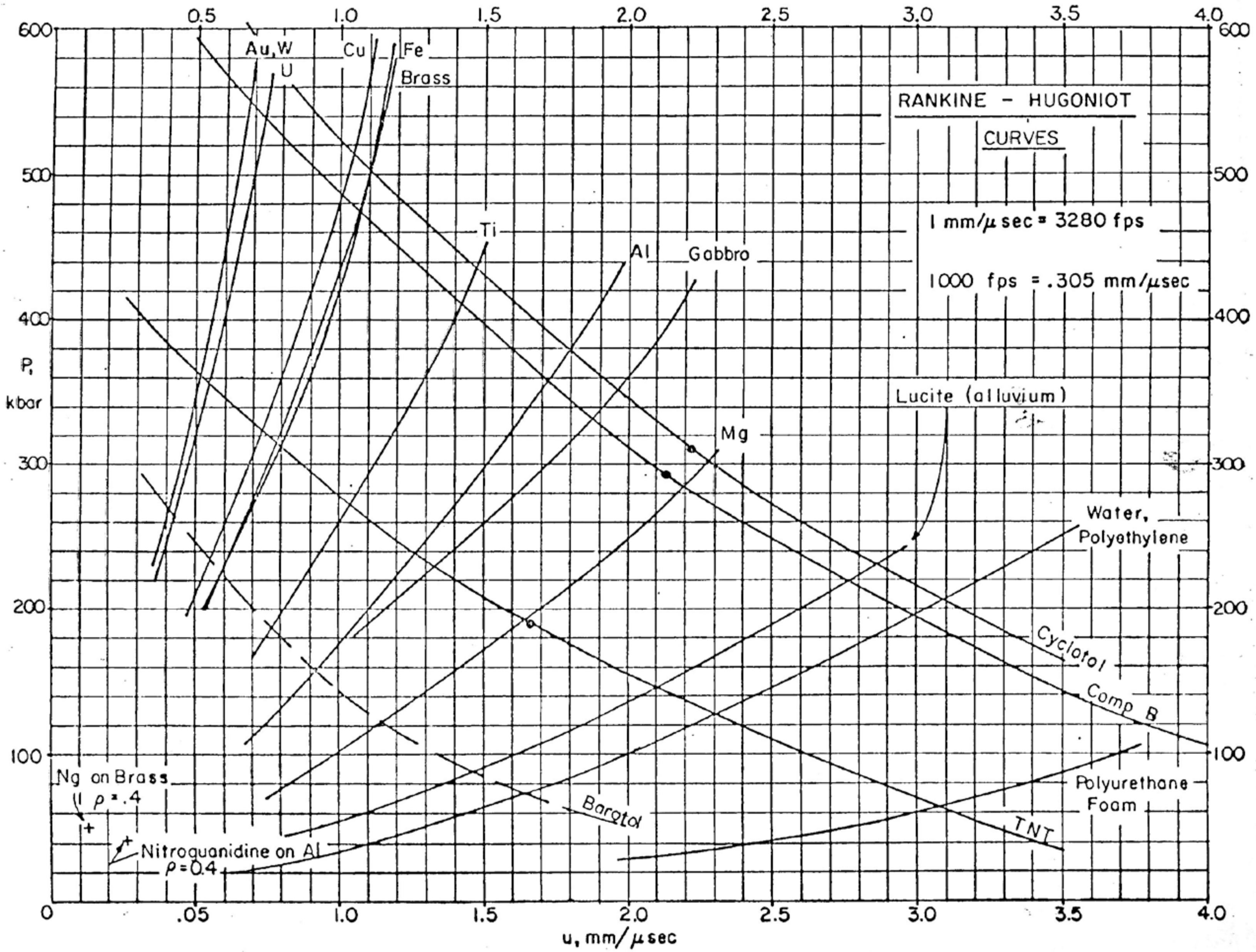
SHOCK MITIATION

Shock Mitigation

- Initial impact shock must be mitigated in order to prevent shock initiation
  - Barriers to slow or breakup fragments
  - Particle Impact Mitigation Sleeve (PIMS)
- Subsequent penetration mechanics needs to be mitigated
- Shock initiation calculations
  - Shock Hugoniot matching
  - TEMPER (version 2.3 available)
  - High rate continuum modeling

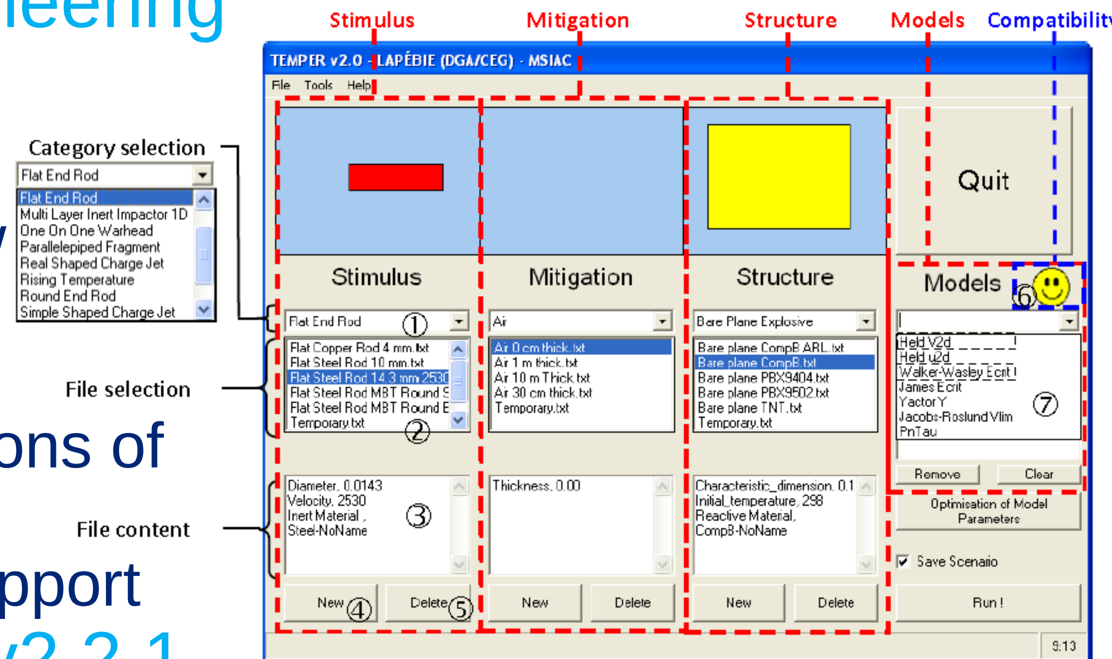
Shock Mitigation

MSIAC
Supporting Munitions Safety



TEMPER

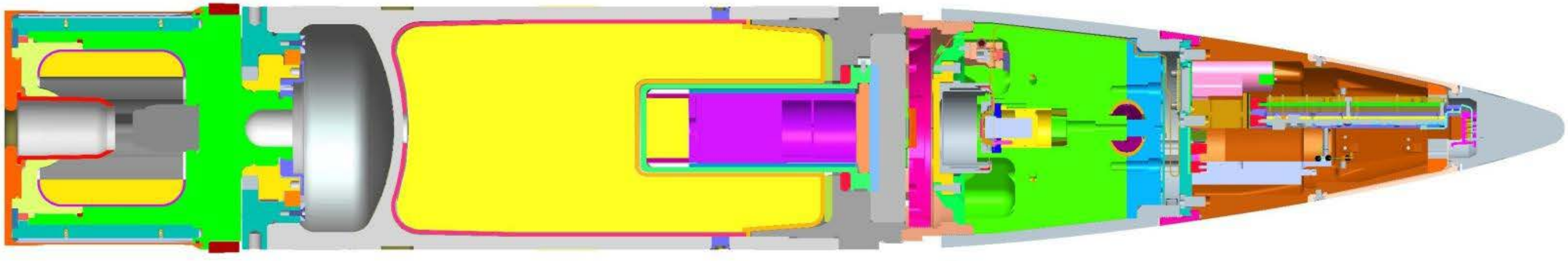
- The Toolbox of Engineering Models to Predict Explosive Reactions
  - TEMPER v2.3 is now available for use
  - Executable file
  - Runs on recent versions of Windows and Excel
  - Visual Basic 6: no support
- Replaces TEMPER v2.2.1
  - Not supported beyond Windows XP
- O-176: TEMPER Status and Recommendations
- TSO WT: Ernie Baker



- 2017
  - Porting TEMPER from antiquated Visual Basic 6 to a modern language
  - Currently scoping specs for an incremental Javascript rewrite.

PIMS

- Detonation behavior can be effected by barrier materials inserted between an incoming fragment or shock wave and an explosive material
  - Packaging materials used to ship and store munitions can be manipulated to help pass sympathetic detonation testing.
  - Low density liners around the warhead body, or between the explosive and warhead body can reduce fragment impact violence and provide a vent path for cook-off thermal events mitigation.
- As a practical application of this technology, low density liners, called Particle Impact Mitigation Sleeves (PIMS), were investigated to help reduce the violent response from fragment impact
  - Computationally modeled and shown to significantly reduce peak pressure in the explosive resulting from fragment impact
  - PIMS liners are now commonly used warhead configurations and are experimentally proven for IM response mitigation



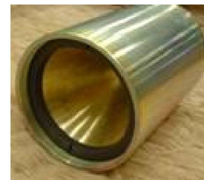
Internal and External PIMS

- PIMS liners can effect warhead performance
  - Shaped Charge/EFP liner collapse, warhead case fragmentation behavior and blast output
  - Need to be incorporated early on in the design process so that required warhead performance characteristics can be maintained, while mitigating fragment impact behavior
- External PIMS application
  - Modern missile warheads are often sub calibered in the missile airframe or can accommodate a wrap on the outside of the missile skin
  - The use of external sleeves allows the maximum interior diameter of the warhead to be used for the explosive charge for maximum munition effectiveness
- Internal PIMS application
  - Gun fired munitions are diameter constrained on the outside and also subjected to the high temperature gaseous products of the reacting propellant
  - The use of an internal PIMS may be used in conjunction with warhead venting techniques to mitigate the cook-off response of confined explosives

PIMS Fragment Impact Testing of High-G Launched Type Warheads

1929 m/s frag impact test setup

Internal PIMS Test Warhead

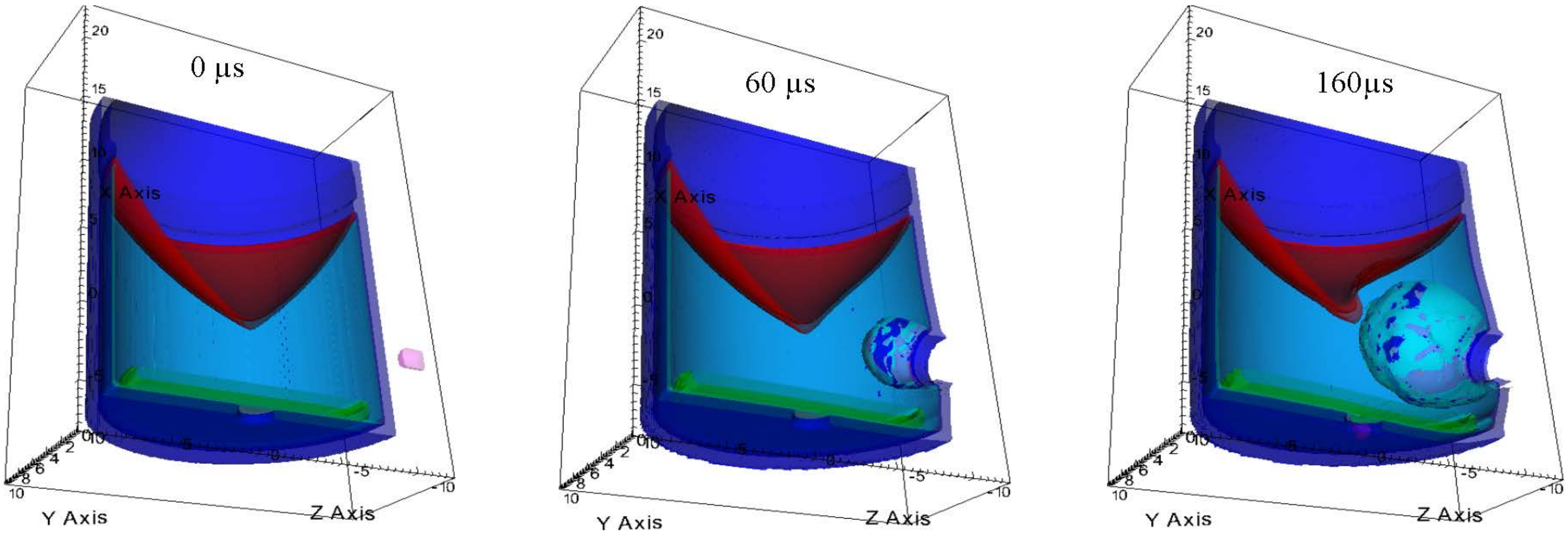


PIMS liners reduce shock transfer from Bullet/frag impact

- Evaluating Effect of PIMS on various explosives
- Evaluating effects of liner thicknesses

Fragment Impact M&S

- Fragment impact events were modeled using the high-rate continuum hydrocode ALE-3D.
- Maximum pressure in the explosive versus time was calculated for impact velocities of 1829-m/s and 2530-m/s.

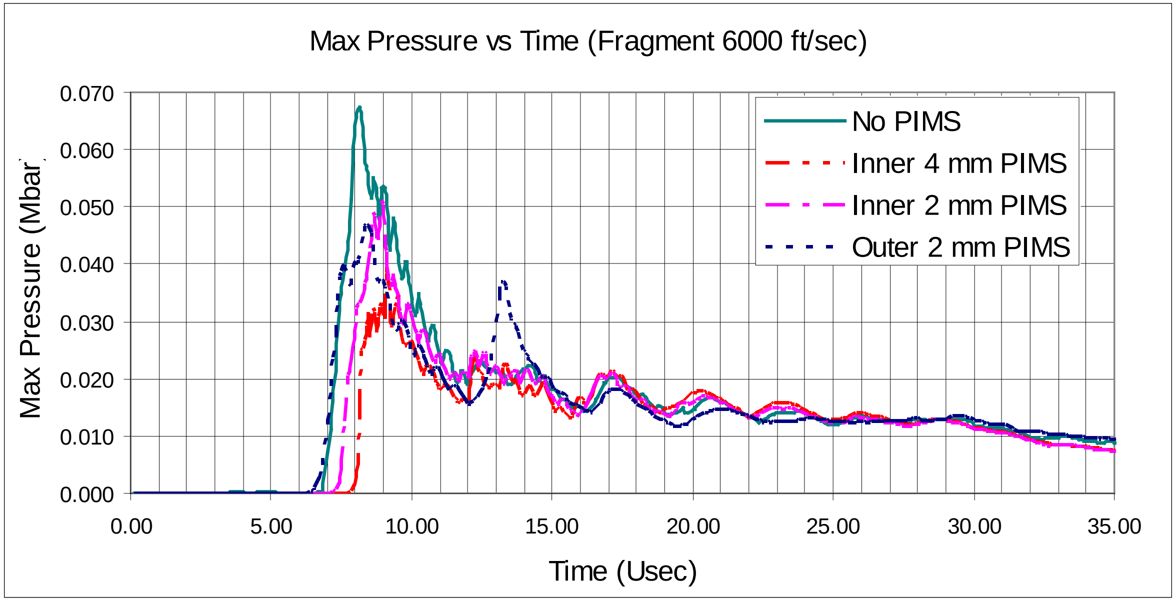


- Explosive replaced with mass matched inert material
- Tracer particles record pressure history

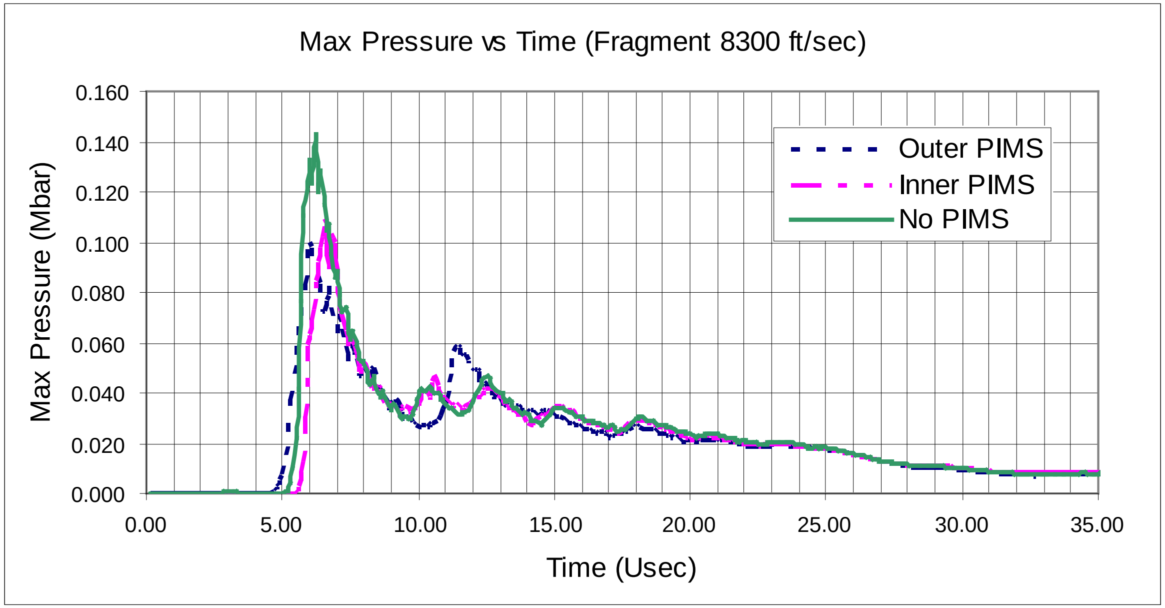
HEAVY CASED MUNITION

MAXIMUM PRESSURE PLOTS

1829 m/s



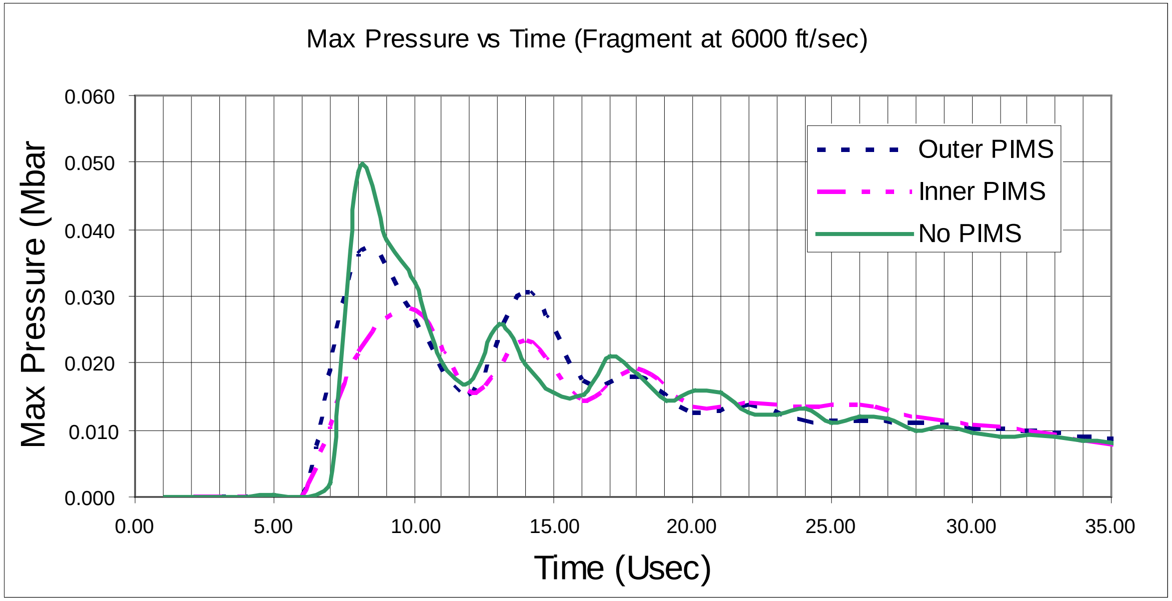
2530 m/s



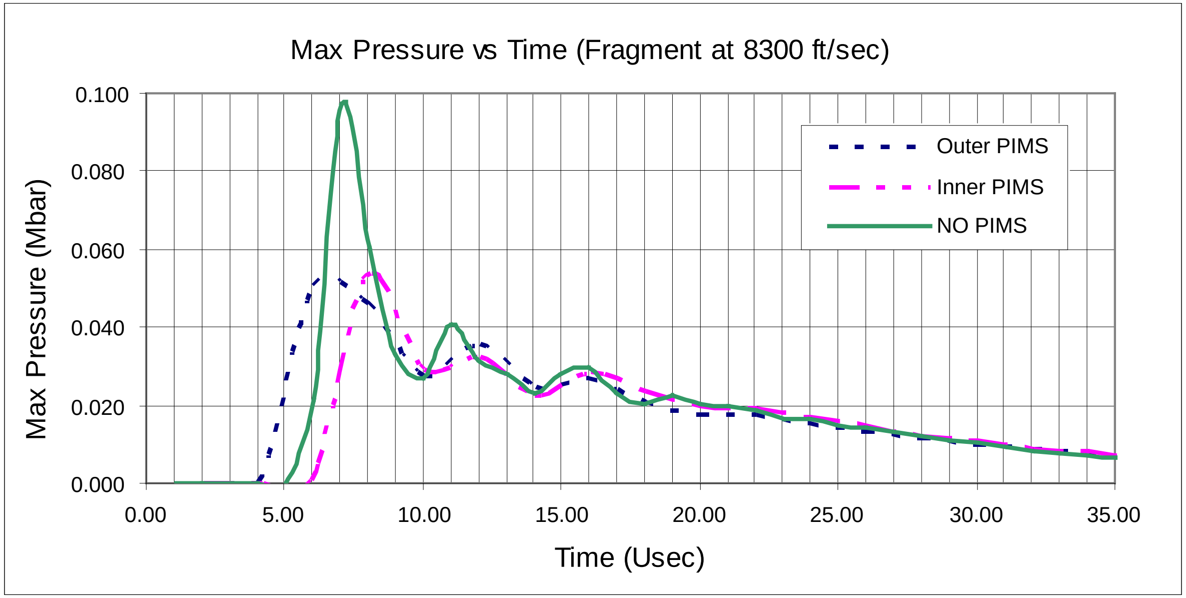
Lightly Cased Munition

Maximum Pressure Plots

1829 m/s



2530 m/s



Frag Impact Test Results

Explosive	No PIMS Reaction*	2mm PIMS Reaction	4mm PIMS Reaction
PBXN-9 (92% HMX)	Type 1	Type 1&4	Type 4
PAX-2A (85% HMX)	Type 1	Type 1	Type 4
PAX-3 (64/24% HMX/AL)	Type 2	Type 4	Type 4
PAX-42 (77/15% HMX/AL)	Type 1	Type 3	Type 3
PAX-30 (77/15% RDX/AL)	Type 1	Type 1	Type 3

* Baseline information provided by Raytheon and AMRDEC

TEST RESULTS

Typical type 4 reaction showing large chunks of un-reacted explosive

Witness plate after type 4 reaction

Witness plate after type 1 reaction

PIMS Fragment Impact Testing

Lightly Cased Warheads

External PIMS (4-mm) test hardware

1829 m/s frag impact test setup

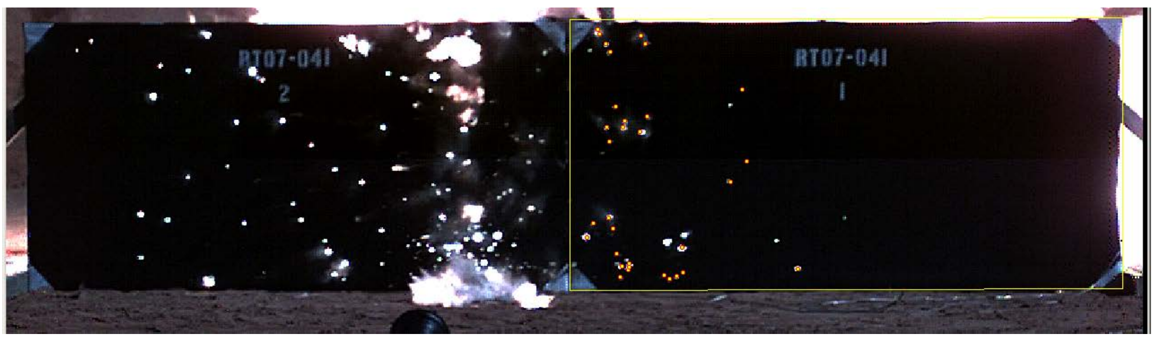
Type 4 test results for PAX-30 showing large case fragments and unreacted explosive

PIMS Warhead Performance

Setup

No change in shaped charge penetration performance from outer PIMS

No PIMS



With PIMS

Larger overall fragment size and more forward fragments with PIMS

WARHEAD VENTING

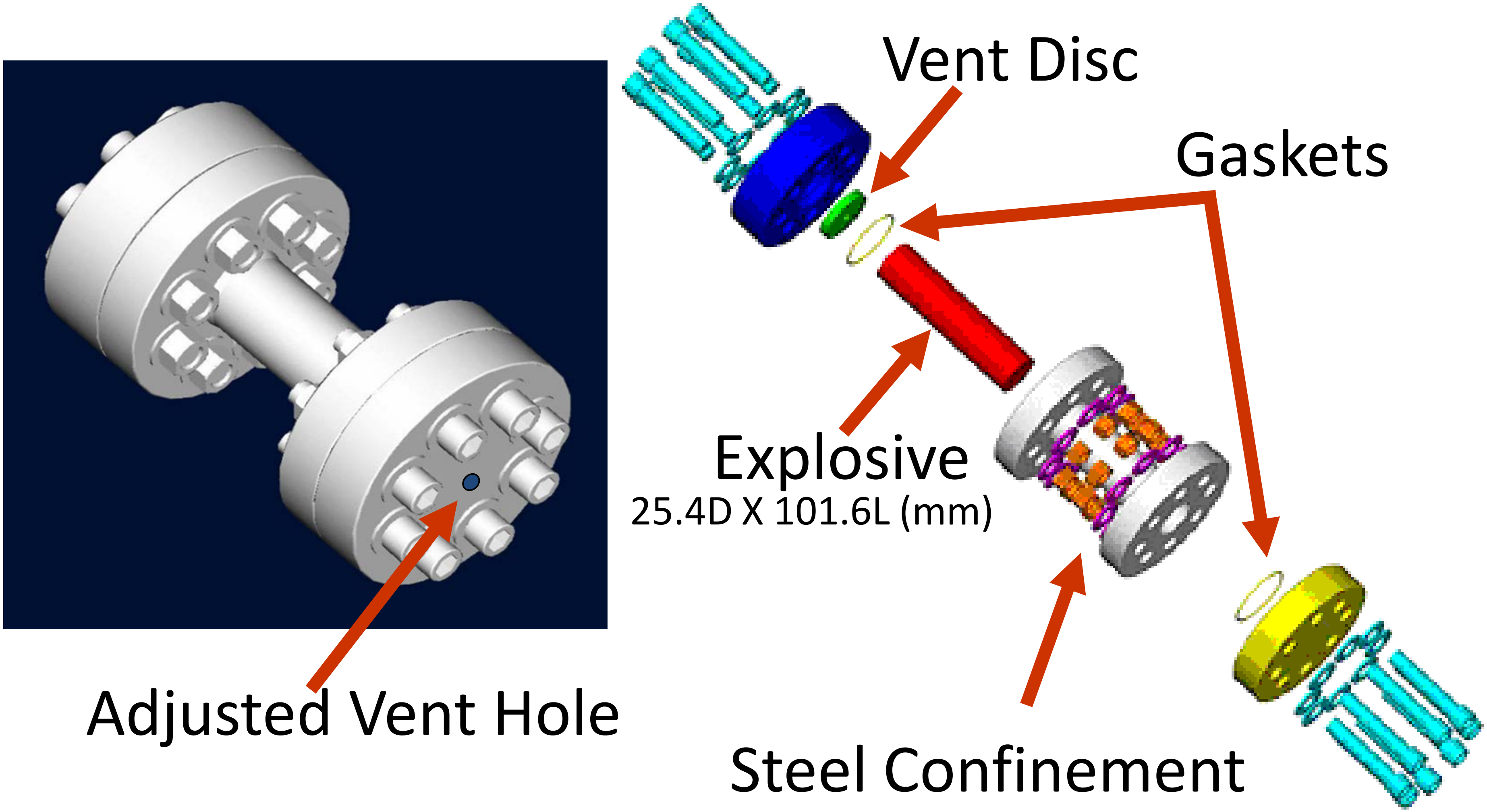
- Thermal threats are normally addressed using a venting technique in order to allow ignition products to escape therefore preventing over pressurization
- Venting techniques
  - Melt venting: plastics or eutechtics
  - Ignition venting: Typically 140˚ to 170˚C.
  - Pressure rupture: pressure blow-out
  - Shape memory alloys: metal or plastic
- Venting mechanisms
  - Vent plugs
  - Thread adaptors
  - Unlock mechanisms
  - Crushing or bursting

MSIAC

Supporting Munitions Safety

IM Warhead Venting

Small Scale Laboratory Fixture

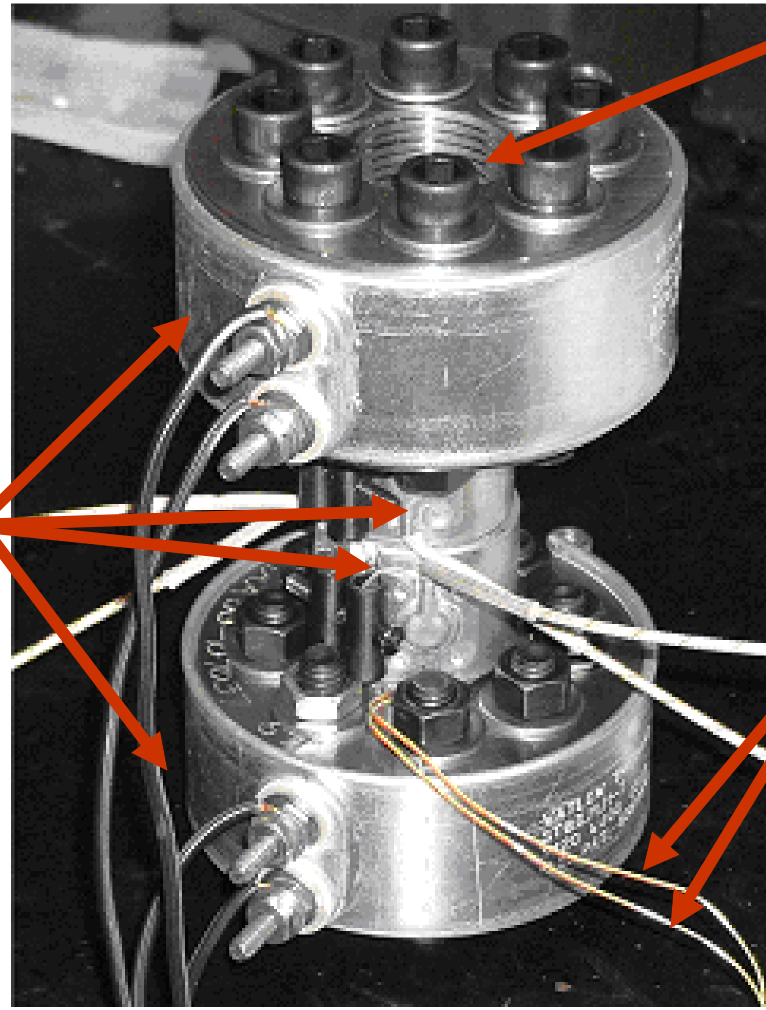


IM Warhead Venting

Small Scale Laboratory Fixture

Vent location

Heating bands

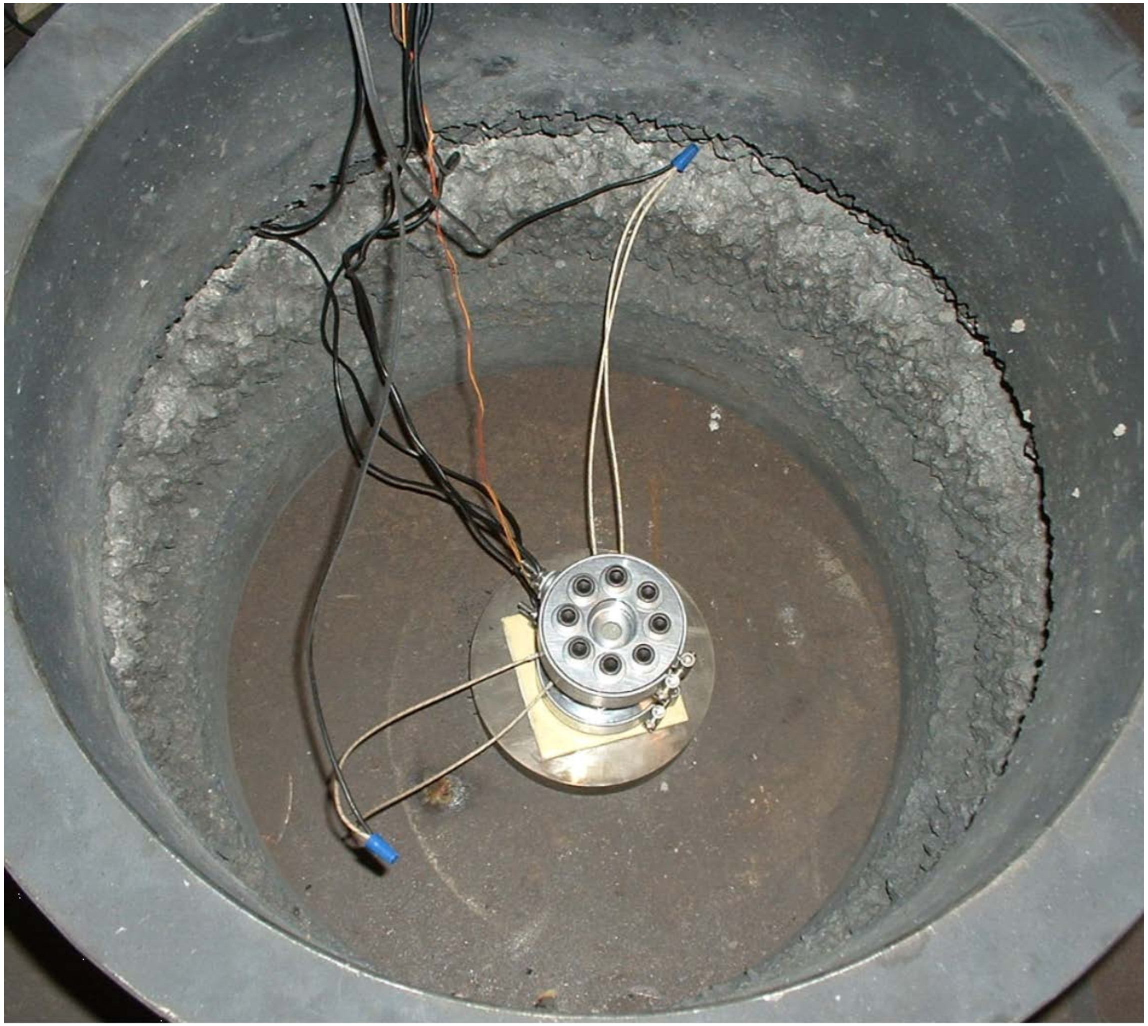


Thermocouple leads

Assembled fixture

IM Warhead Venting

Small Scale Laboratory Fixture

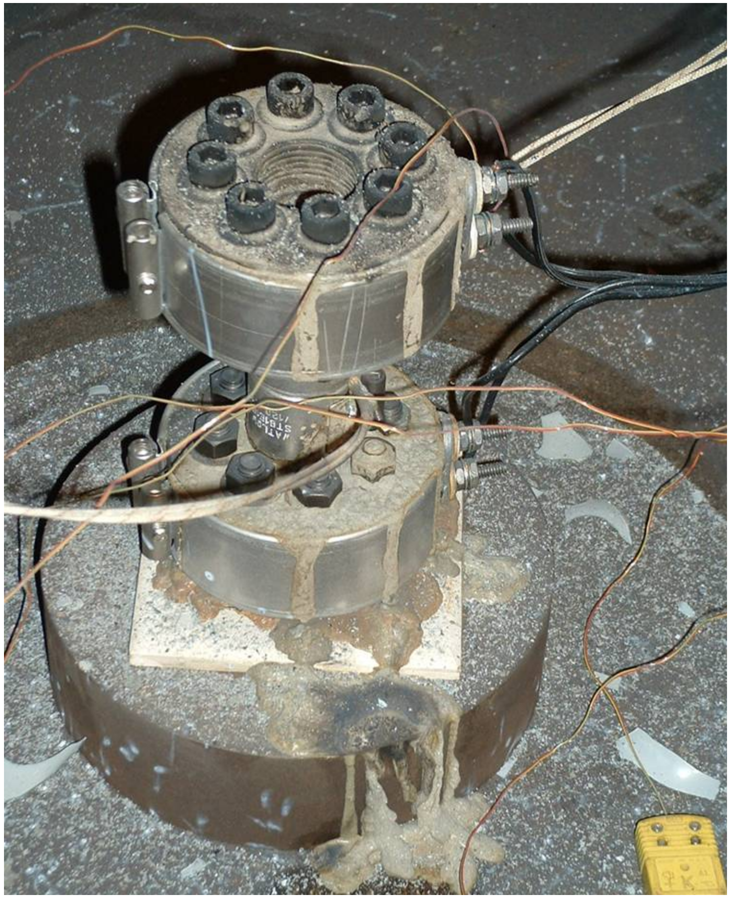


Assembled test fixture – ready for testing

IM Warhead Venting

Small Scale Laboratory Fixture

Violent Response



Non-Violent Response

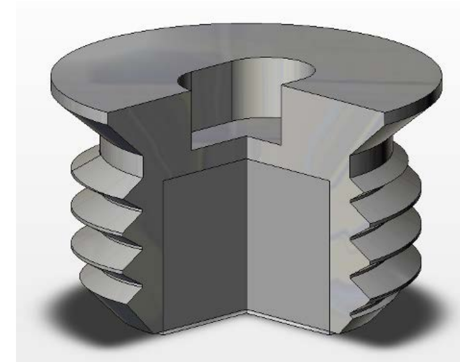
MSIAC

Supporting Munitions Safety

IM Warhead Venting

155mm Venting Lifting Plug

81mm Venting Adaptor



Reactive Vent Plug

Large Scale Laboratory Fixture
IM Liner Material Effects

PBXN-109 - AHM Liner Testing

Less viscous melt materials work better!

PBXN-109 - HDPE Liner Testing

Identical single hole vent:
AHM liner: not violent
HDPE liner: violent

EXCALIBUR SUB SCALE TEST RESULTS

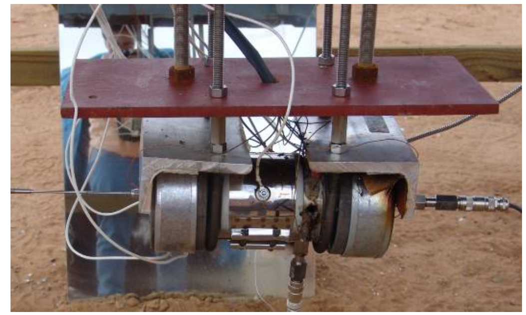
IM LINER THICKNESS EFFECT

Baseline XM982

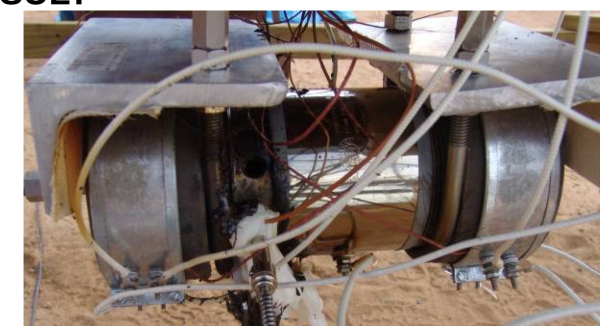
TYPE III

Double Thickness Liner

SETUP



RESULT



TYPE V

Double thickness liner resulted in Burn response

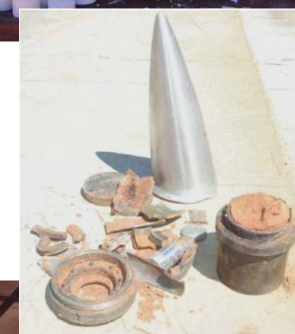
28C/hour

Excalibur Full Scale Test Results

28C/h: Type III & V

SETUP

RESULT



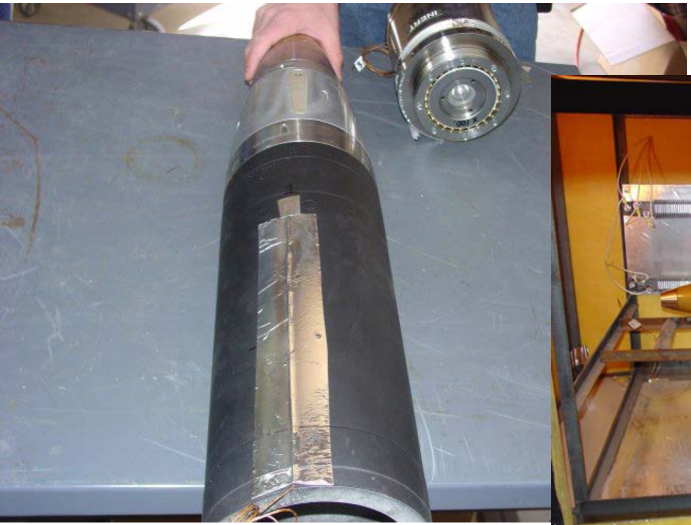
TYPE III

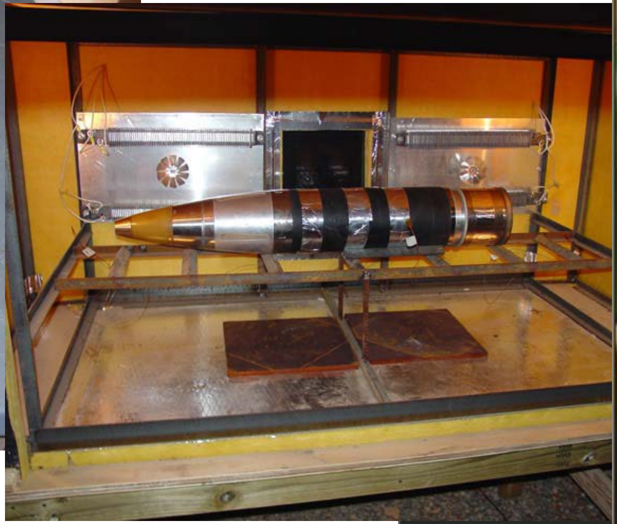
TYPE V

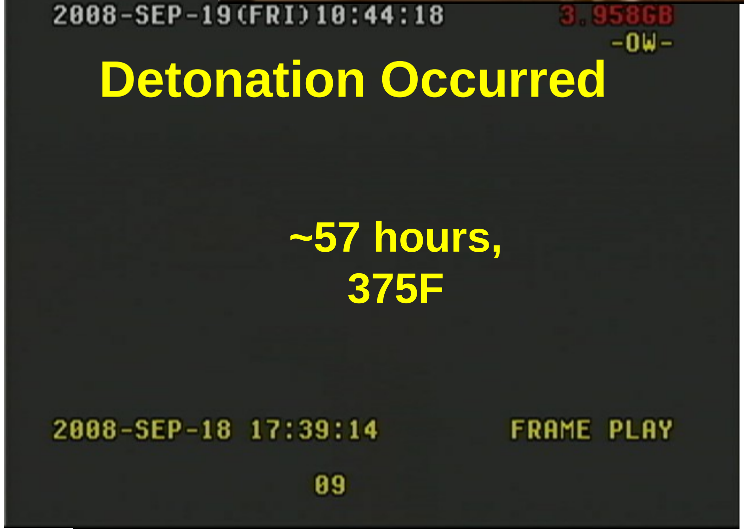
28C/hour

Excalibur Full Scale Test Results

3.3C/h: Type III & V

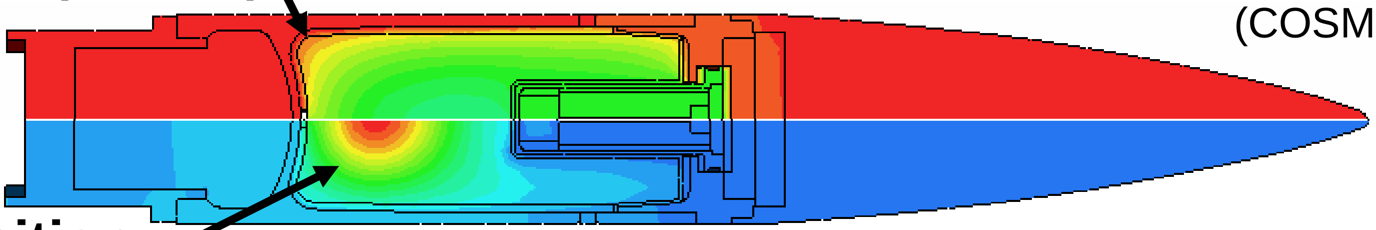






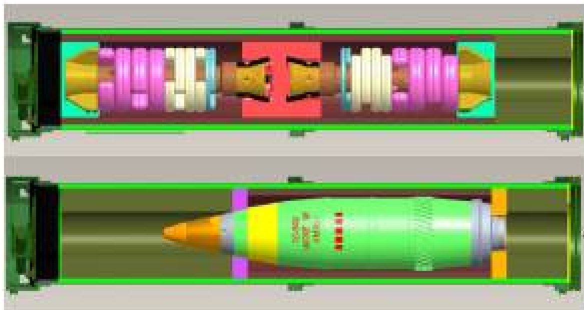
3.3C/hour

Excalibur Thermal Modeling

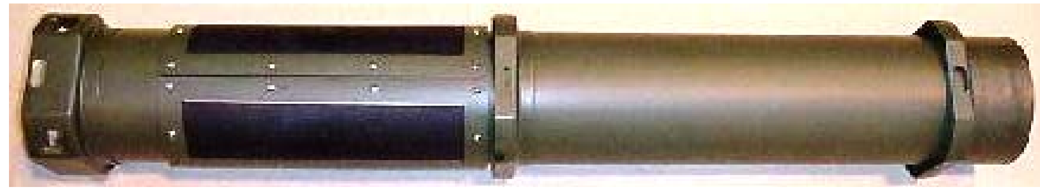


- Hotspot = where ignition occurs, i.e., explosive begins to burn in self sustaining reaction
- 28°C/hour
  - Hotspot forms on or near the surface
  - Surface burn allows gases to escape through vents
- 3.3°C/hour
  - Hotspot forms on billet centerline below the surface
  - Hot gases trapped inside the billet

Packaging Venting



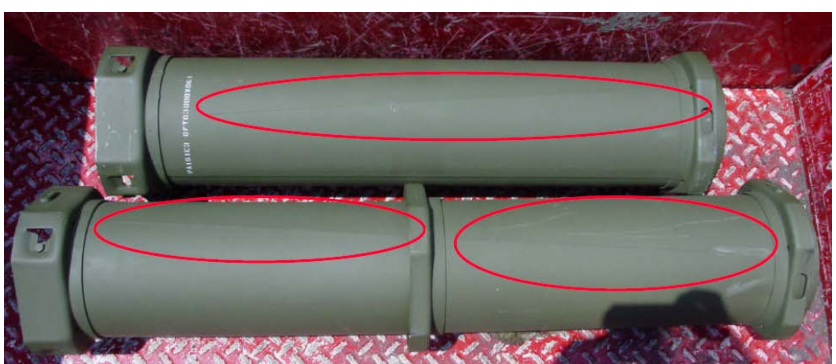
A Blowout Panel in the bottom of the container allows pressure release



120mm M829E3 Tank Cartridge
IM Container M171

Blowout Panels allow pressure release from inside the container

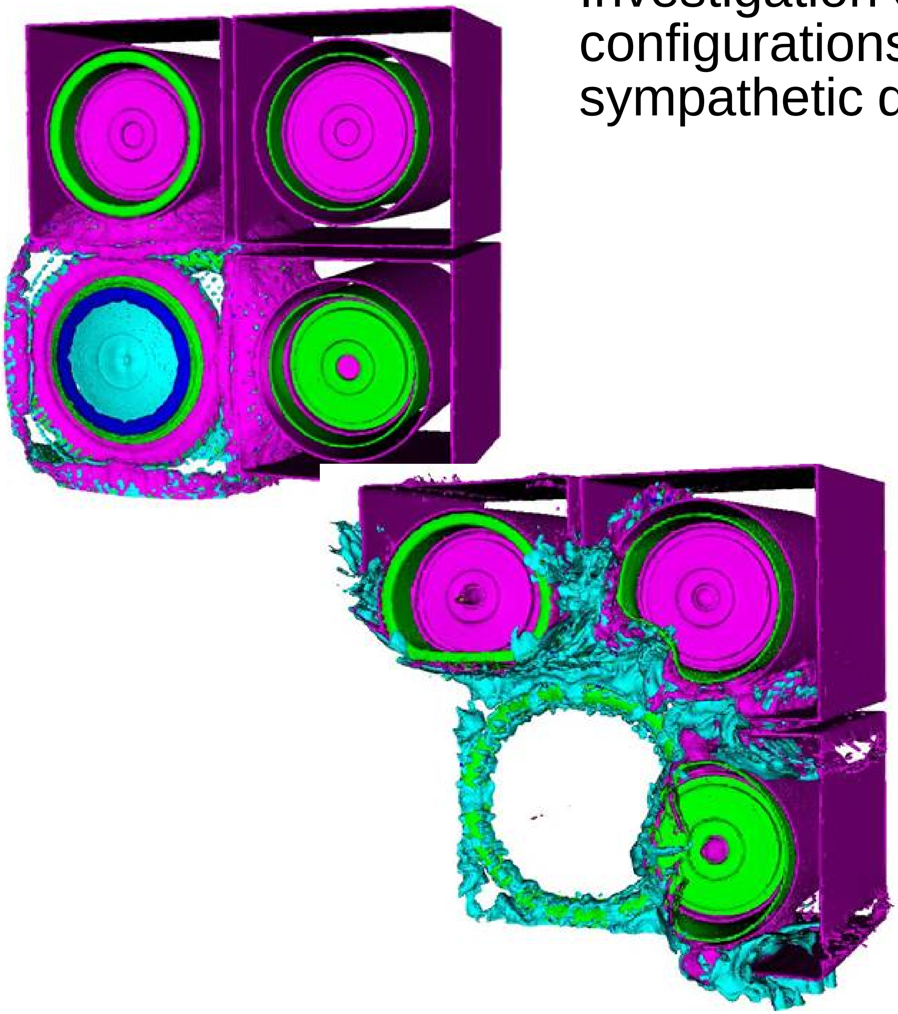
Foam cushions and sleeves melt and separate to prevent insulation of heat

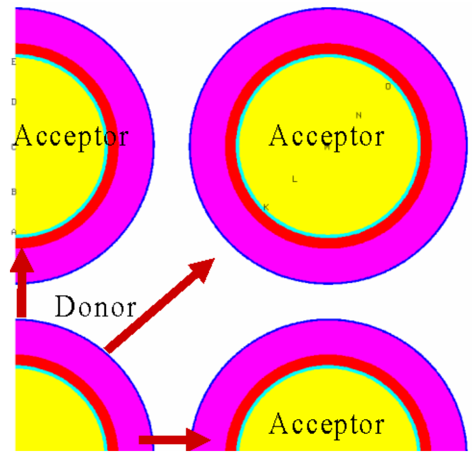


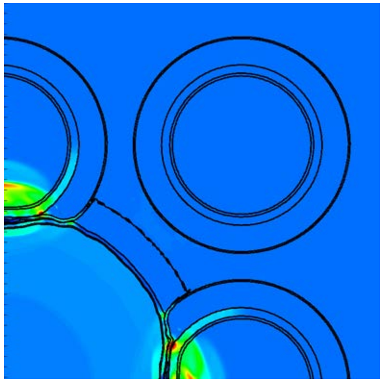
25mm IM Container

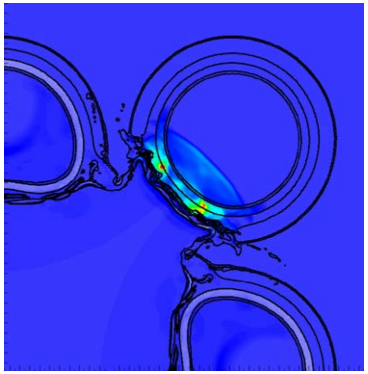
IM HIGH RATE CONTINUUM MODELING

Investigation of barrier materials and configurations in order to reduce and mitigate sympathetic detonation response of munitions.









SYMPATHETIC REACTION

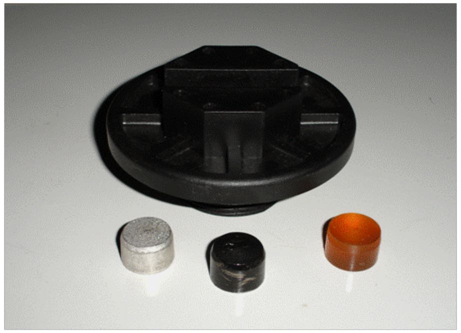
IM Testing

Original baseline test: Fail
After computational redesign: Pass

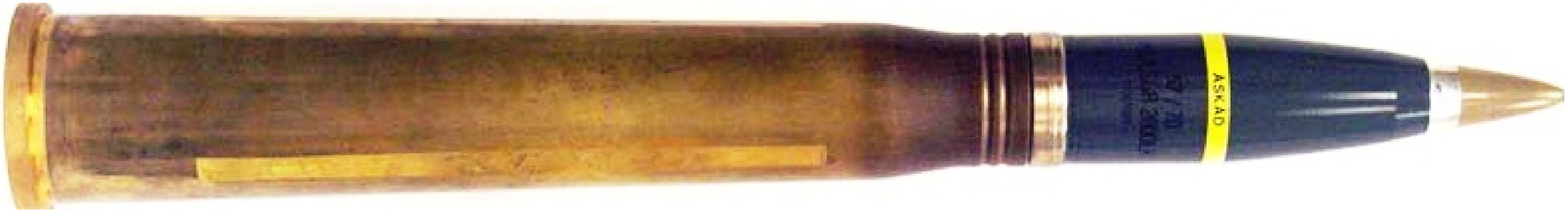
Using Computational Design to meet IM Requirements!

CARTRIDGE VENTING

- Mitigation technology for 105 mm to mitigate thermal threat: vent holes + meltable plug + primer heat protection



- Stress riser (example: 57 mm cartridge case)

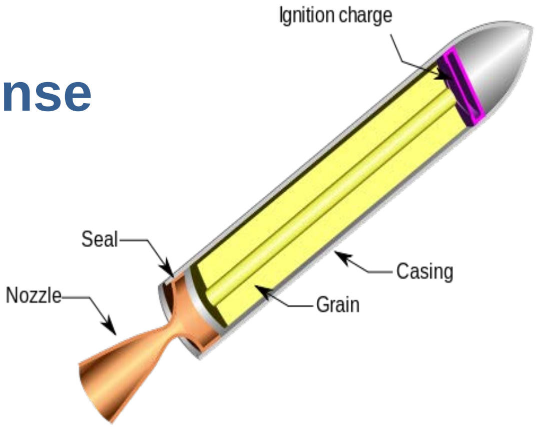


Different mitigation families

➢ Venting Devices	9 technologies identifies, 3 known as to be in use
➢ Active Mitigation	16 technologies identified, 3 known as to be in use
➢ Intumescent coating	14 painting identified, 3 known as to be in use
➢ Casing composition	8 technologies identified, 5 known as to be in use
➢ Barrier – Packaging – Arrangement	6 technologies identified, 3 known as to be in use

Other way to help reduce the rocket motor response

- ➢ Composition of the propellant



Solid Rocket Motor

Venting devices

To create a venting of the motor during heating. In case of ignition of the propellant it would permits a decrease of the pressure. Thus the reaction type stays a burning and does not change into a more violent reaction type.

<u>Threat</u>: Slow /Fast Heating

<u>Example</u>: Use of Shape Memory materials ; Partial insulation; Use of eutectic components…

Shape Memory Material to disengaged the end

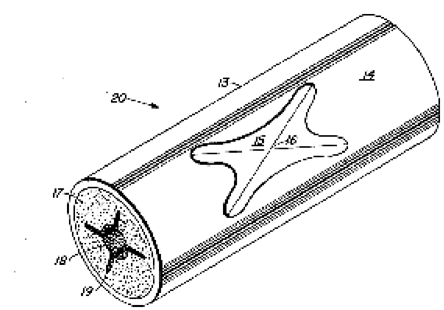


FIG. 3

Figure 5 : Partial Insulation Technique

Active Mitigation System

Use of Energetic Materials. Some active devices enable both venting and pre-ignition. Others only permits pre-ignition and had to be coupled with a venting device.
A pre-ignition enables a burning at a low/controlled burning rate

<u>Threat</u>: Slow /Fast Heating

<u>Example</u>:
- Venting and Ignition : Linear shaped charge; Explosive or thermite pellet…
- Pre-ignition: Additional Igniter; Chemical components; Propellant…

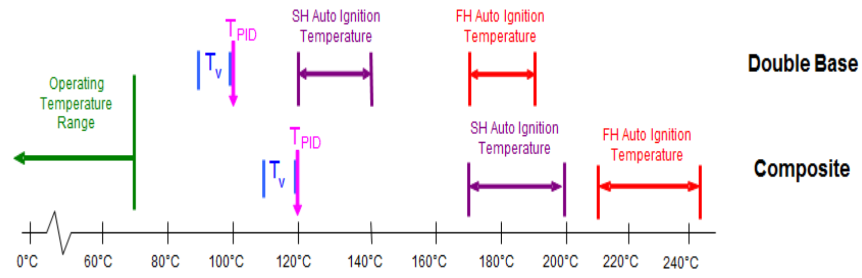


Figure 7 : SH and FH typical response temperatures

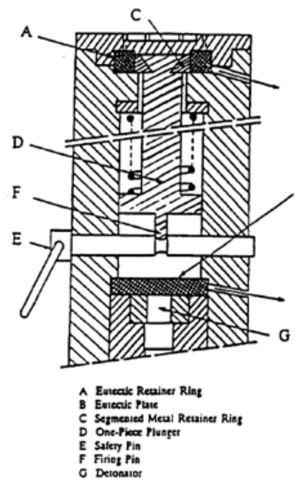


Figure 8 : Pre-ignition Device with eutectic

Figure 9 : Case Opened by a LSC

Intumescent coatings

Coating materials that swell when subjected to heat. They expand to several time their original thickness forming an insulating char which reduce thermal conductivity. It enables to delay the reaction but not always decreases the violence of the response.

<u>Threat</u>: Fast Heating

<u>Example</u>: FIREX 2390 ;LURIFER n°2; FM 26; CHARTEK 59...

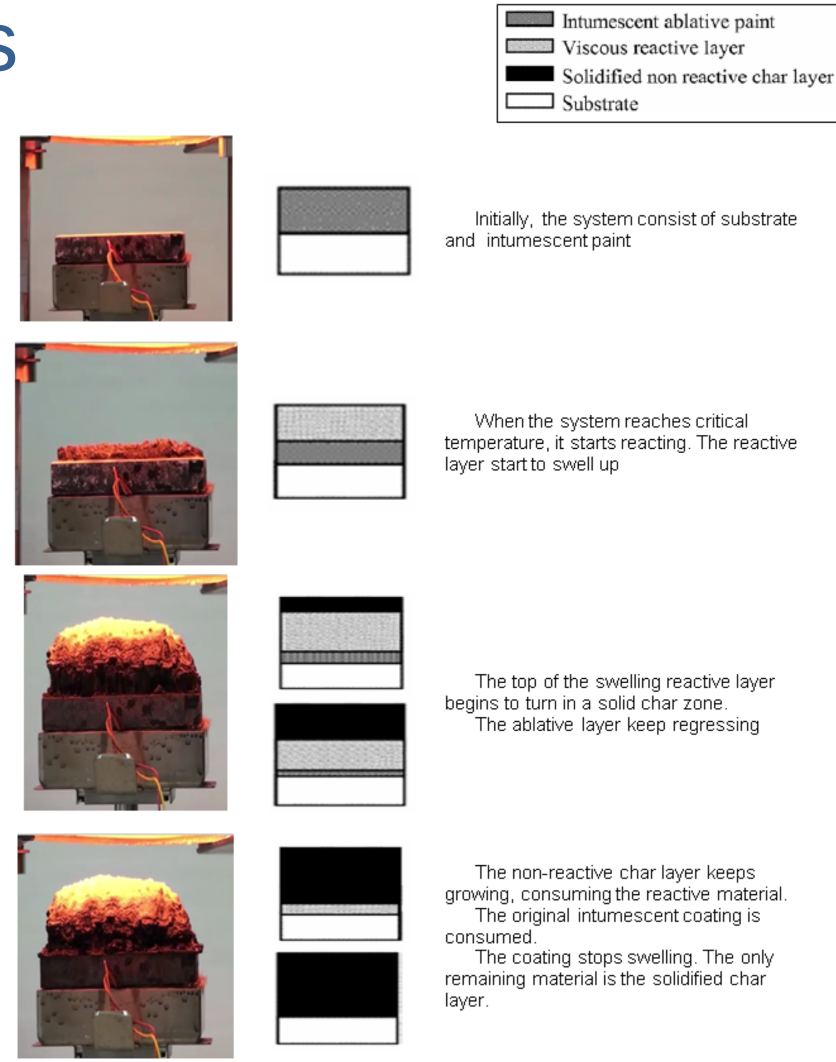


Figure 11 : Intumescing process

Casing Composition

Use of alternatives components which could permit a venting of the case during heating or impact.

Threat: Slow /Fast Heating, Fragment / Bullet Impact, Sympathetic Reaction

Example: Composite case, Steel strip laminated case, hybrid case…

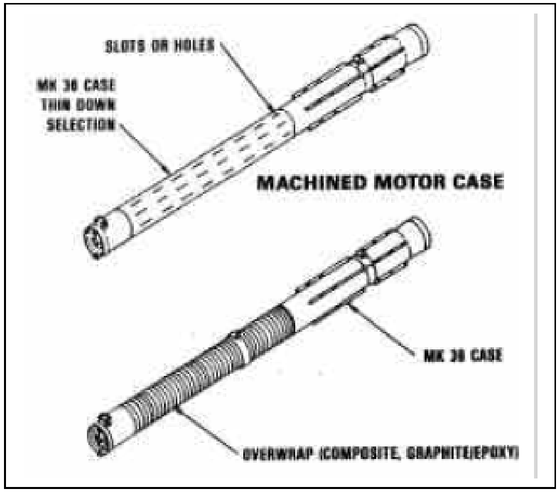


Figure 13 : Hybrid case

Figure 14 : Fragment impact result with a composite case

Barrier – Packaging – Arrangement

Use of barrier or change in the storage arrangement to decrease the severity of a response to sympathetic detonation.

Threat: Sympathetic detonation; Bullet / Fragment Impact

Example: Metallic plates, Deflector, Arrangement, Metallic container, Bore Mitigation

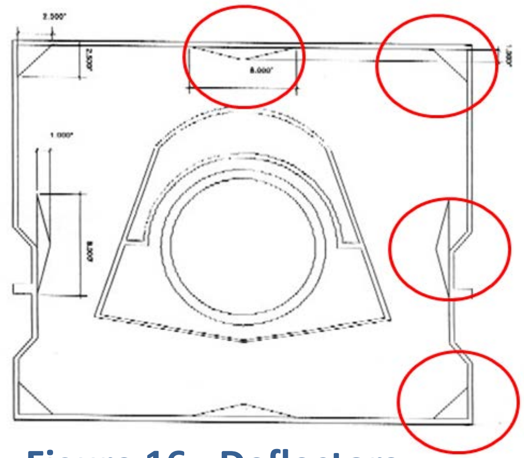


Figure 16 : Deflectors

Figure 17 : Bore Mitigation

AMERICAN ORDNANCE EXPLOSION




Fatal explosion occurred on 12 June 2006 killing two.
Justin Friedrichsen (24) , Steven Upton (48)

INSENSITIVE MUNITIONS SUCCESS

SPC Ng visits US Army PEO Ammunition on 5 OCT 2009

Exterior view of the MRAP

Interior view of the MRAP

Collected unexploded shell bodies and separated fuzes

Insensitive Munitions saves lives!

12 SEP 2009: Specialist Ng was travelling in a Mine Resistant Ambush Protected (MRAP) vehicle when it was hit by a very powerful Improvised Explosive Device (IED). The IED ruptured the vehicle’s hull and fuel tank, which engulfed the vehicle interior in flames-to include sixteen M768 60mm mortar cartridges that were carried inside the cabin with the seven-man crew. Although several soldiers were seriously injured in the ambush, all survived. Specialist Ng credited the Insensitive Munitions (IM) features of the M768 cartridges with averting a much greater disaster.

REFERENCES

Baker, E.L.;"Warhead Venting Technology Development for Cook-off Mitigation", 2006 Insensitive Munitions & Energetic Materials Technology Symposium, Bristol, United Kingdom 24-28 April 2006.
Daniels, A., J. Pham, K. Ng, and D. Pfau; "Development of Particle Impact Mitigation Sleeves to Reduced IM Response", 2007 Insensitive Munitions & Energetic Materials Technical Symposium, Miami, FL, October 15-17, 2007.
Ho, R., D. Pudlak; "Insensitive Munitions Integration Program Venting Technology", Insensitive Munitions & Energetic Materials Technical Symposium, San Francisco, CA, 15-17 November 2004.
N. Al-Shehab, T. Madsen, S. DeFisher, D. Pfau, E.L. Baker, B. Fuchs and B. Williamson; "Cook-Off Mitigation Scaling Effects", 2007 Insensitive Munitions & Energetic Materials Technical Symposium, Miami, FL, October 15-17, 2007.
N. Al-Shehab, E.L. Baker, J. Pincay, D. Hunter, J. Morris, M. Steinberg and J. Snyder; "Using Energetic Materials to Control Warhead Ignition During Slow Cook-Off", 2009 Insensitive Munitions & Energetic Materials Technology Symposium, Tucson, Arizona 11-14 May 2009.
Cook, J., A. Howard, L. Chandrasekaran, A.S. Kaddour and I.H. Maxey; "Mitigation of Thermal Threats Using Devices Based On Shape Memory Alloys",
C. Morales, T. Woo, L. Moy, A. Cohen and B. Ingold; "Cartridge Case Venting Technologies, 25mm M910 Cartridge Test Vehicle", 2010 Insensitive Munitions and Energetic Materials Technology Symposium, Munich, Germany 11-14 October 2010.

Available to MSIAC Nations:

Software – IM Design: Toolbox of Engineering Models for the Prediction of Explosive Reactions (TEMPER)

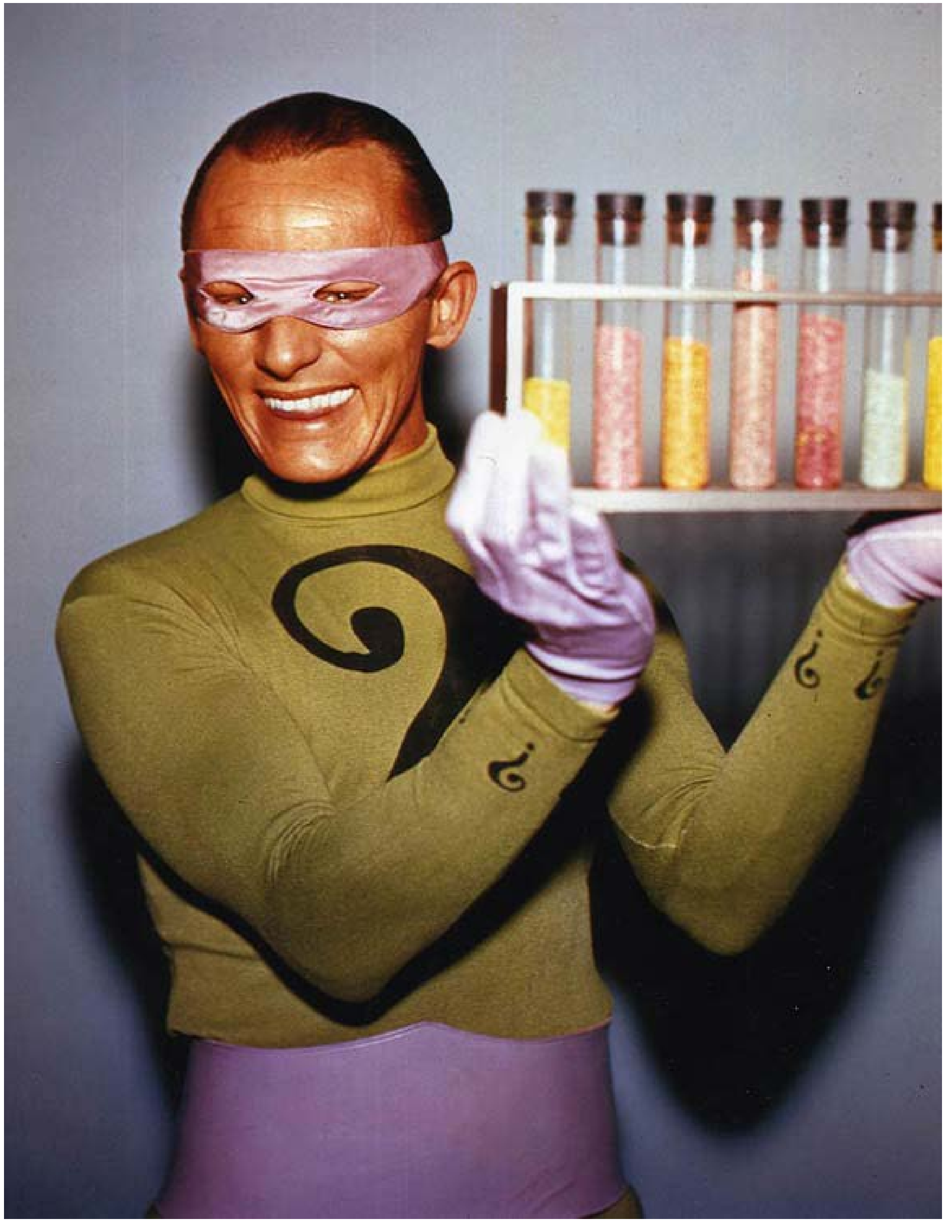
Datatbase Tool – NIMIC Excel Worksheets on GAp TESts (NEWGATES)

Database Tool, Software - Mitigation Technologies for Munitions (MTM)

MSIAC

Supporting Munitions Safety

Questions?



LA-4167-MS

Selected Hugoniots

Prepared by Group GMX-6

Los Alamos Scientific Laboratory

University of California

Los Alamos, New Mexico 87544

May 1, 1969

Pages 2-4 - Supplemental Data
Page 5 (17 x 24 Graph) Hugoniots

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

GMX-6 Hugoniot data fitted by the equation, $u_s = c_0 + s\,u_p + q\,u_p^2$. All data were analyzed using standards of January 1969.

Material	ρ_0 (g/cm^3)	c_0 (km/sec)	s	q (sec/km)	γ_0	Comments
Elements						
Antimony (4)	6.700	1.983	1.652		0.60	
Barium (10)	3.705	0.700	1.600		0.55	Above P = 115 and u_s = 2.54
Beryllium (3,9)	1.851	7.998	1.124		1.16	
Bismuth (3,4)	9.836	1.826	1.473		1.10	
Cadmium (3,4)	8.639	2.434	1.684		2.27	
Calcium (10)	1.547	3.602	0.948		1.20	
Cesium (6)	1.826	1.048	1.043	.051	1.62	
Chromium (3,4,9)	7.117	5.173	1.473		1.19	
Cobalt (3,4)	8.820	4.752	1.315		1.97	
Copper (3,4,9)	8.930	3.940	1.489		1.99	
Germanium (9)	5.328	1.750	1.750		0.56	Above P = 300 and u_s = 4.20
Gold (3,4,9)	19.240	3.056	1.572		2.97	
Hafnium (9)	12.885	2.954	1.121		0.98	Below P = 400 and u_s = 3.86
Hafnium (9)	12.885	2.453	1.353		0.98	Above transition
Indium (3)	7.279	2.419	1.536		1.80	
Iridium (9)	22.484	3.916	1.457		1.97	
Iron (3,4,9)	7.850	3.574	1.920	–.068	1.69	Above u_s = 5.0
Lead (3,4)	11.350	2.051	1.460		2.77	
Lithium (6)	0.530	4.645	1.133		0.81	
Magnesium (3)	1.740	4.492	1.263		1.42	
Mercury (1)	13.540	1.490	2.047		1.96	
Molybdenum (3,4,9)	10.206	5.124	1.233		1.52	
Nickel (3,4,9)	8.874	4.602	1.437		1.93	
Niobium (3,9)	8.586	4.438	1.207		1.47	
Palladium (3,9)	11.991	3.948	1.588		2.26	
Platinum (3,9)	21.419	3.598	1.544		2.40	
Potassium (6)	0.860	1.974	1.179		1.23	
Rhenium (9)	21.021	4.184	1.367		2.44	
Rhodium (3,9)	12.428	4.807	1.376		1.88	
Rubidium (6)	1.530	1.134	1.272		1.06	
Silver (3,4)	10.490	3.229	1.595		2.38	
Sodium (6)	0.968	2.629	1.223		1.17	
Strontium (10)	2.628	1.700	1.230		0.41	Above P = 150 and u_s = 3.63
Sulfur (10)	2.020	3.223	0.959		-	
Tantalum (3,9)	16.654	3.414	1.201		1.60	
Thallium (3,4)	11.840	1.862	1.523		2.25	

Material	ρ_0 (g/cm^3)	c_0 (km/sec)	s	q (sec/km)	γ_0	Comments
Elements						
Thorium (3,4)	11.680	2.133	1.263		1.26	
Tin (3,4)	7.287	2.608	1.486		2.11	
Titanium (3,4,9)	4.528	5.220	0.767		1.09	Below P = 175 and u_s = 5.74
Titanium (3,4,9)	4.528	4.877	1.049		1.09	Above transition
Tungsten (4,9)	19.224	4.029	1.237		1.54	
Uranium (10)	18.950	2.487	2.200		1.56	
Vanadium (4,9)	6.100	5.077	1.201		1.29	
Zinc (3,4)	7.138	3.005	1.581		1.96	
Zirconium (3,9)	6.505	3.757	1.018		1.09	Below P = 260 and u_s = 4.63
Zirconium (3,9)	6.505	3.296	1.271		1.09	Above transition
Alloys						
Brass (3,4)	8.450	3.726	1.434		2.04	
2024 Aluminum (3,9)	2.785	5.328	1.338		2.00	
921-T Aluminum (9)	2.833	5.041	1.420		2.10	
Lithium-Magnesium Alloy (10)	1.403	4.247	1.284		1.45	
Magnesium Alloy AZ-31B (9)	1.775	4.516	1.256		1.43	
Stainless Steel (304) (9)	7.896	4.569	1.490		2.17	
U-3 wt % Mo (9)	18.450	2.565	2.200		2.03	
Synthetics						
Adiprene (9)	0.927	2.332	1.536		1.48	
Epoxy Resin (9)	1.186	2.730	1.493		1.13	Below P = 240 and u_s = 7.0
Epoxy Resin (9)	1.186	3.234	1.255		1.13	Above transition
Lucite (9)	1.181	2.260	1.816		0.75	
Neoprene (9)	1.439	2.785	1.419		1.39	
Nylon (10)	1.140	2.570	1.849	–.081	1.07	
Paraffin (9)	0.918	2.908	1.560		1.18	
Phenoxy (9)	1.178	2.266	1.698		0.55	
Plexiglas (9)	1.186	2.598	1.516		0.97	
Polyethylene (9)	0.915	2.901	1.481		1.64	
Polyrubber (9)	1.010	0.852	1.865		1.50	
Polystyrene (9)	1.044	2.746	1.319		1.18	
Polyurethane (9)	1.265	2.486	1.577		1.55	Below P = 220 and u_s = 6.5
Silastic (RTV-521) (9)	1.372	0.218	2.694	–.208	1.40	
Teflon (9)	2.153	1.841	1.707		0.59	
Compounds						
Periclase (MgO) (8)	3.585	6.597	1.369		1.32	Above P = 200 and u_s = 7.45
Quartz (5)	2.204	0.794	1.695		0.90	Stishovite above P = 400
Sodium Chloride (7)	2.165	3.528	1.343		1.60	Transition ignored
Water (2)	0.998	1.647	1.921	–.096	-	

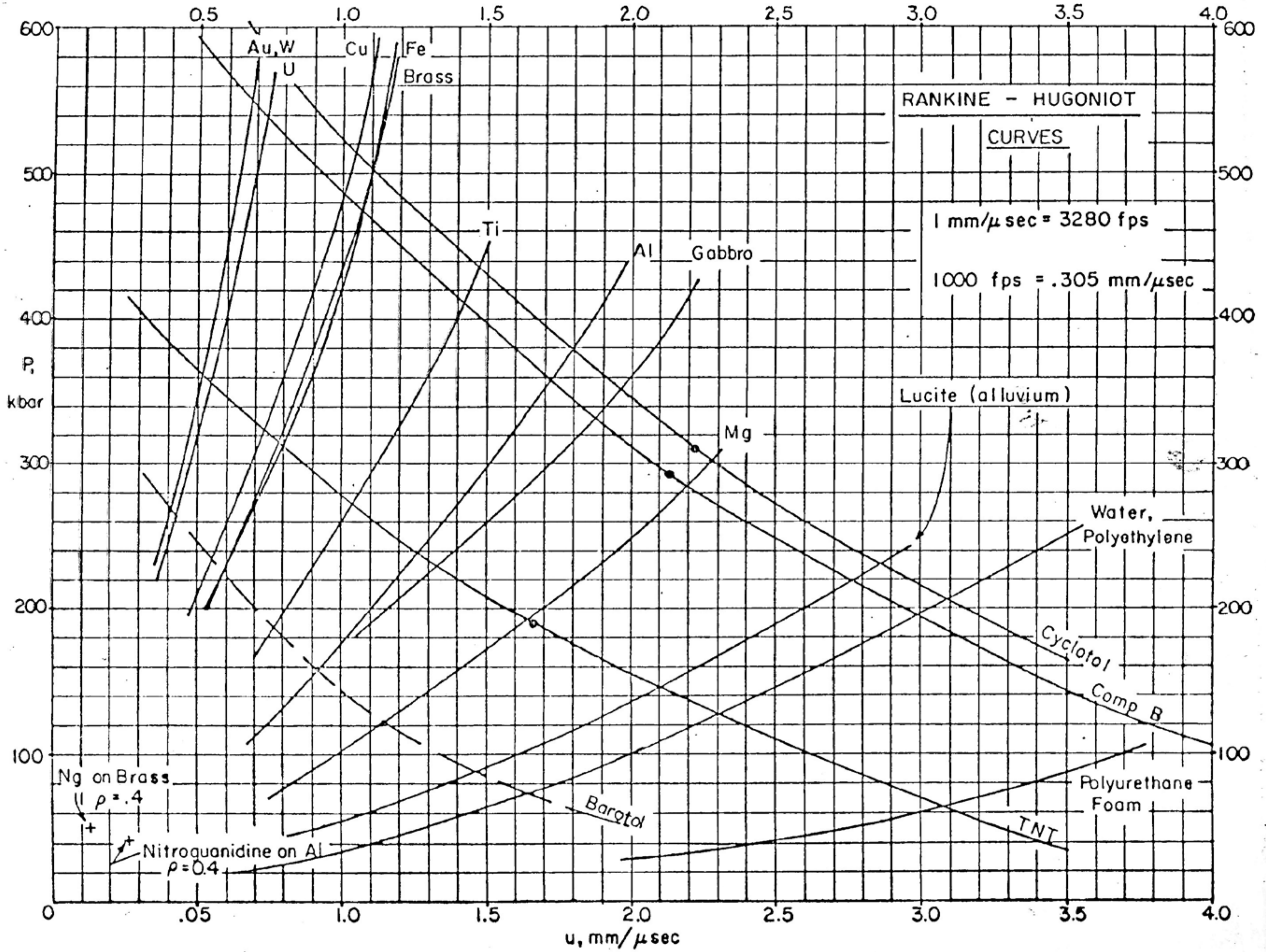
Hugoniot data have been fitted by the equation $u_s = c_0 + s\,u_p + q\,u_p^2$, where u_s is the shock velocity and u_p the associated particle velocity. All data have been reanalyzed using the standards listed in Ref. (9). Grüneisen parameters have been obtained from best estimates of zero pressure thermodynamic parameters, which are sometimes of dubious value. The pressures and velocities describing the valid range of the fits do not necessarily indicate the onset or completion of a transition.

The u_s-u_p fits have been transformed to the pressure-particle velocity plane. For obvious reasons, the region in the lower left hand corner has not been filled in. For many materials the data extend considerably above one megabar.

The dotted segments represent the region of two-wave structure for those materials exhibiting transitions; the lines have been drawn on the basis of the shock velocity of the first wave. The dashed curves represent reflected shocks and rarefaction release loci from the 2024 Al Hugoniot at the pressures listed. The three heavy curves are the Hugoniots of 2024 Al, Cu and U-3 wt. % Mo alloy which were determined independently. These were used as standards to determine the Hugoniots of the other materials.

REFERENCES

1. J. M. Walsh and M. H. Rice, J. Chem. Phys. 26, 815 (1957).
2. M. H. Rice and J. M. Walsh, J. Chem. Phys. 26, 824 (1957).
3. J. M. Walsh, M. H. Rice, R. G. McQueen and F. L. Yarger, Phys. Rev. 108, 196 (1957).
4. R. G. McQueen and S. P. Marsh, J. Appl. Phys. 31, 1253 (1960).
5. J. Wackerle, J. Appl. Phys. 33, 922 (1962).
6. M. H. Rice, J. Phys. Chem. Solids 26, 483 (1965).
7. J. N. Fritz, S. P. Marsh, W. J. Carter, and R. G. McQueen, "The Hugoniot Equation of State of Sodium Chloride in the Sodium Chloride Structure," LA-DC-9989, (Los Alamos Scientific Laboratory, 1968).
8. W. J. Carter, S. P. Marsh, J. N. Fritz, and R. G. McQueen, "The Equation of State of Selected Materials," LA-DC-9990, (Los Alamos Scientific Laboratory, 1968).
9. R. G. McQueen, S. P. Marsh, W. J. Carter, J. N. Fritz, and J. W. Taylor, High Velocity Impact Phenomena, edited by E. V. Cohen (Academic Press, Inc., New York), in press.
10. Preliminary data.


RANKINE - HUGONIOT
CURVES
1 mm/μ sec = 3280 fps
1000 fps = .305 mm/μsec
P, kbar
u, mm/μsec
Au, W
U
Cu
Fe
Brass
Ti
Al
Gabbro
Mg
Lucite (alluvium)
Water, Polyethylene
Cyclotol
Comp B
Polyurethane Foam
Baratol
TNT
Ng on Brass
ρ = .4
Nitroguanidine on Al
ρ = 0.4