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

Cook-Off Mitigation for Medium Caliber Ammunition

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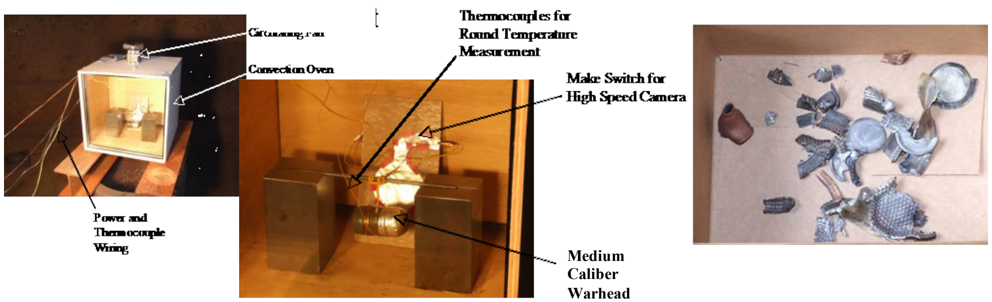
OUTLINE

- 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

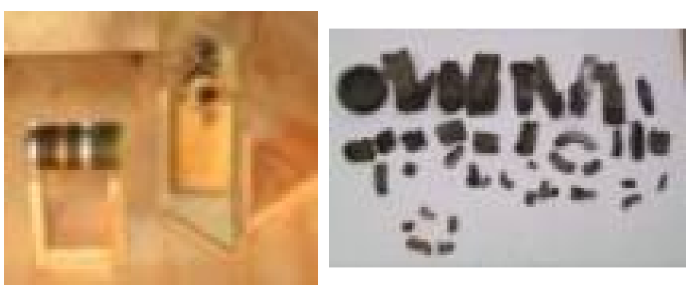
TYPICAL BASELINE RESPONSE – WARHEAD ONLY

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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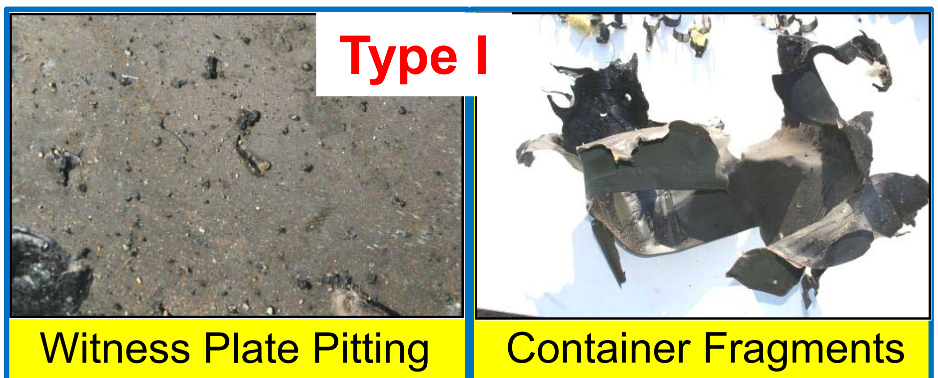
TYPICAL BASELINE RESPONSE – PACKAGED

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

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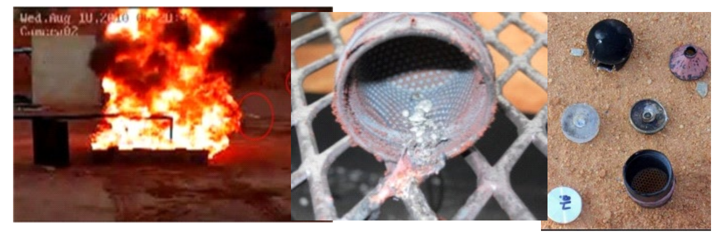
Warhead Venting

- 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

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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)

SUCCESSFUL DEMONSTRATION OF INDIVIDUAL IM TECHNOLOGY

Packaging Venting

Vented Containers with modified 40mm Cartridges

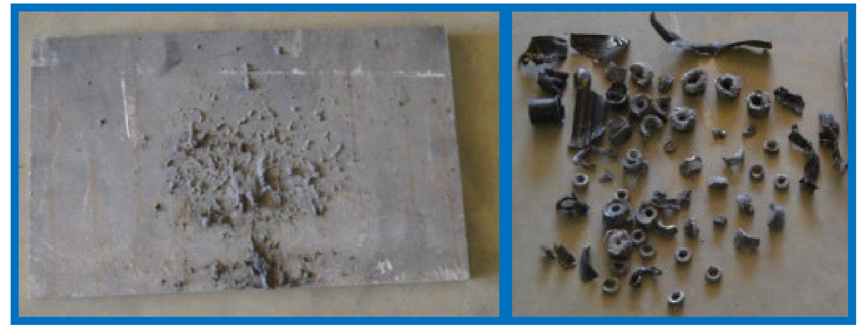
- Simulated Warhead Venting - Threads Removed and Fuze Just Set in Place. Allows Venting of HE.
- Simulated Cartridge Case Venting - Base Plug Modified; 3 Kidney Shaped Holes Filled with Wax.

SCO (6F/h)

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

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

Dunnage potential cause of violence in bottom row

"Wine Rack" Test Configuration

Bottom Live Layer – Warhead Only

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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:

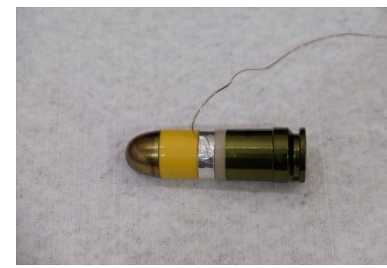
- Six cartridges with live warheads + fuze, no propellant
- Standard container and dunnage
- Inert aluminum slugs in unoccupied positions in cartons

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

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

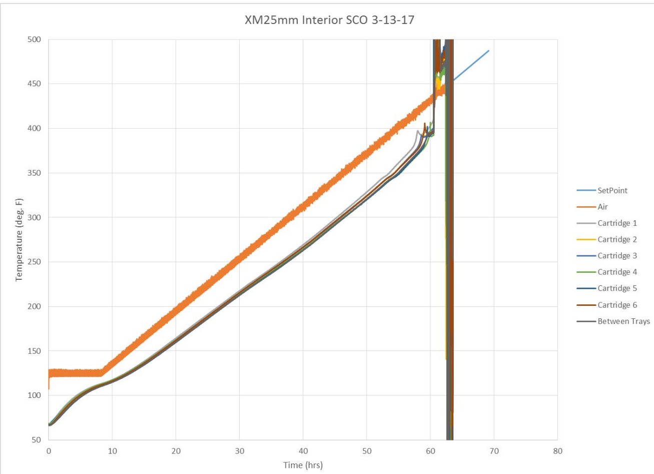
- One Forward Warhead missing, likely from this cartridge

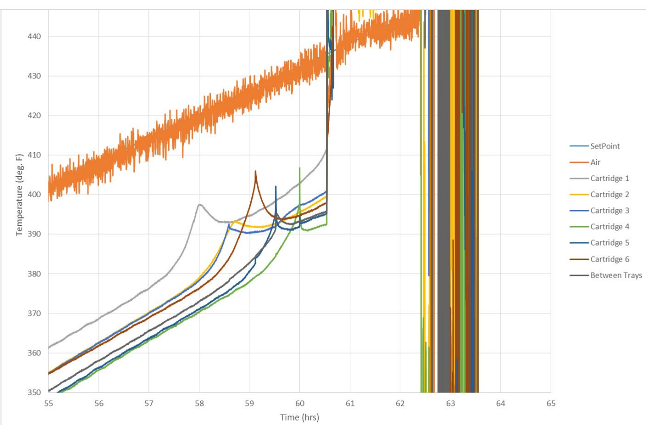
Container deformed, bottom shows indents from the 3 bottom tray cartridges

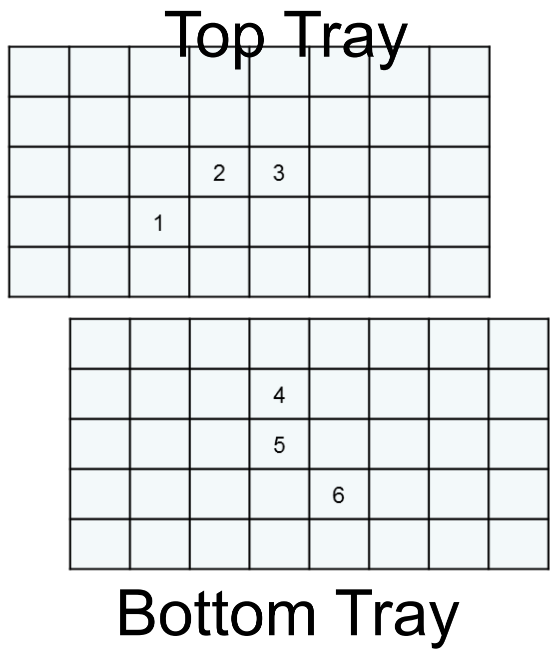
- Bottom indents show no evidence of frags

Two perforations in container below live cartridge 1

LIMITED 25MM PACKAGED SCO TEST RESULTS

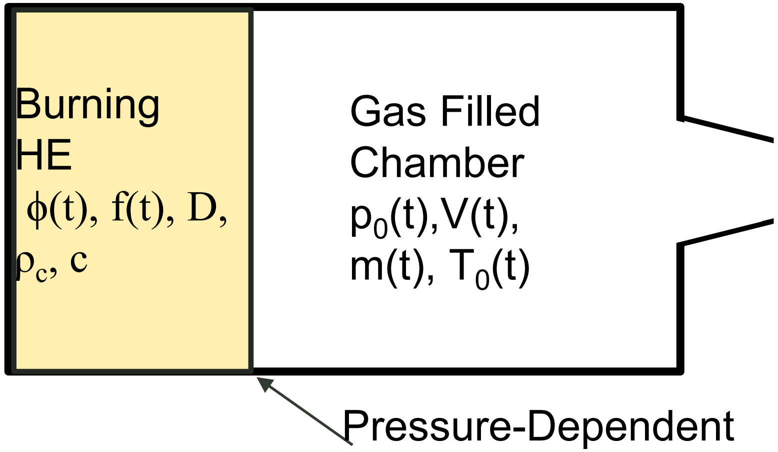






- Each thermocouple shows a spike prior to terminal reaction
  - Previous testing and recovered hardware indicate each spike corresponds to the Aft Warhead deflagrating
- **Cartridge 1** likely reacted violently
  - First to show temp spike
  - Recovered hardware shows this cartridge to have most damage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

BURNING AND VENTING PHENOMENOLOGY

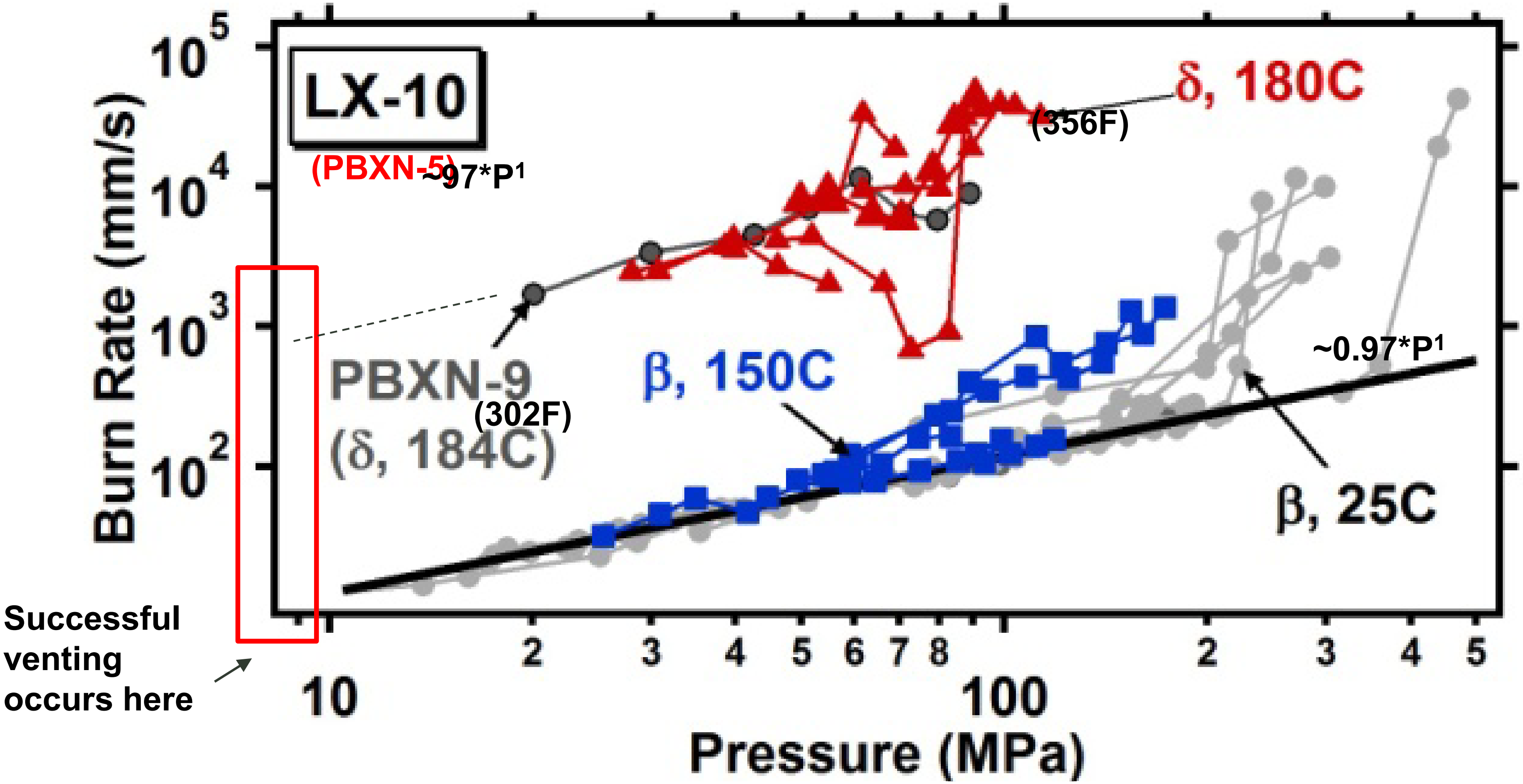


$$\frac{dm}{dt} = \dot{m}_{gen} - \dot{m}_{vent} \qquad R = \beta p_0^n \qquad p_0 V = mRT_0$$

- 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

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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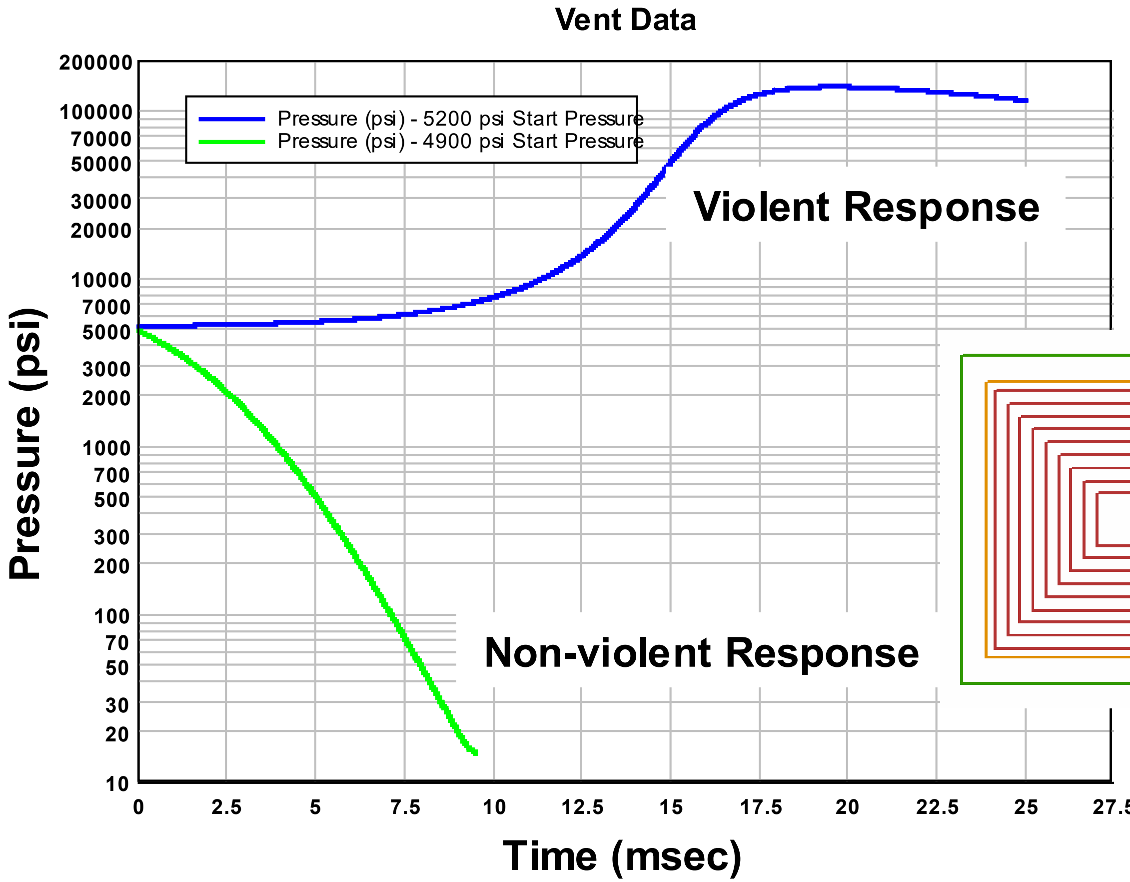
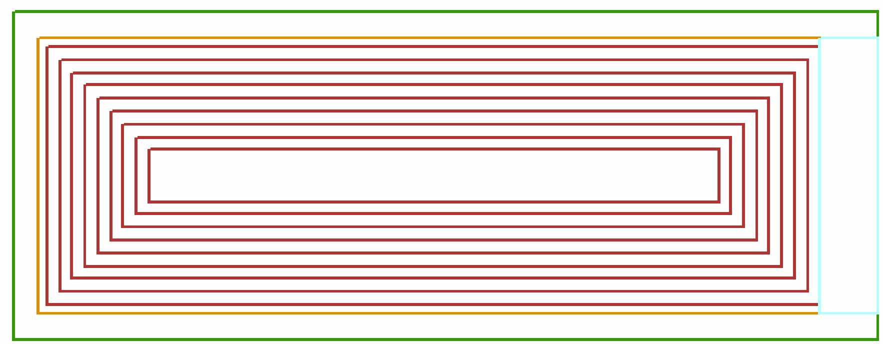
PBXN-109 ANALYTIC BURN MODELING

Analytic Burn Modeling of PBXN-109



Pressure Response



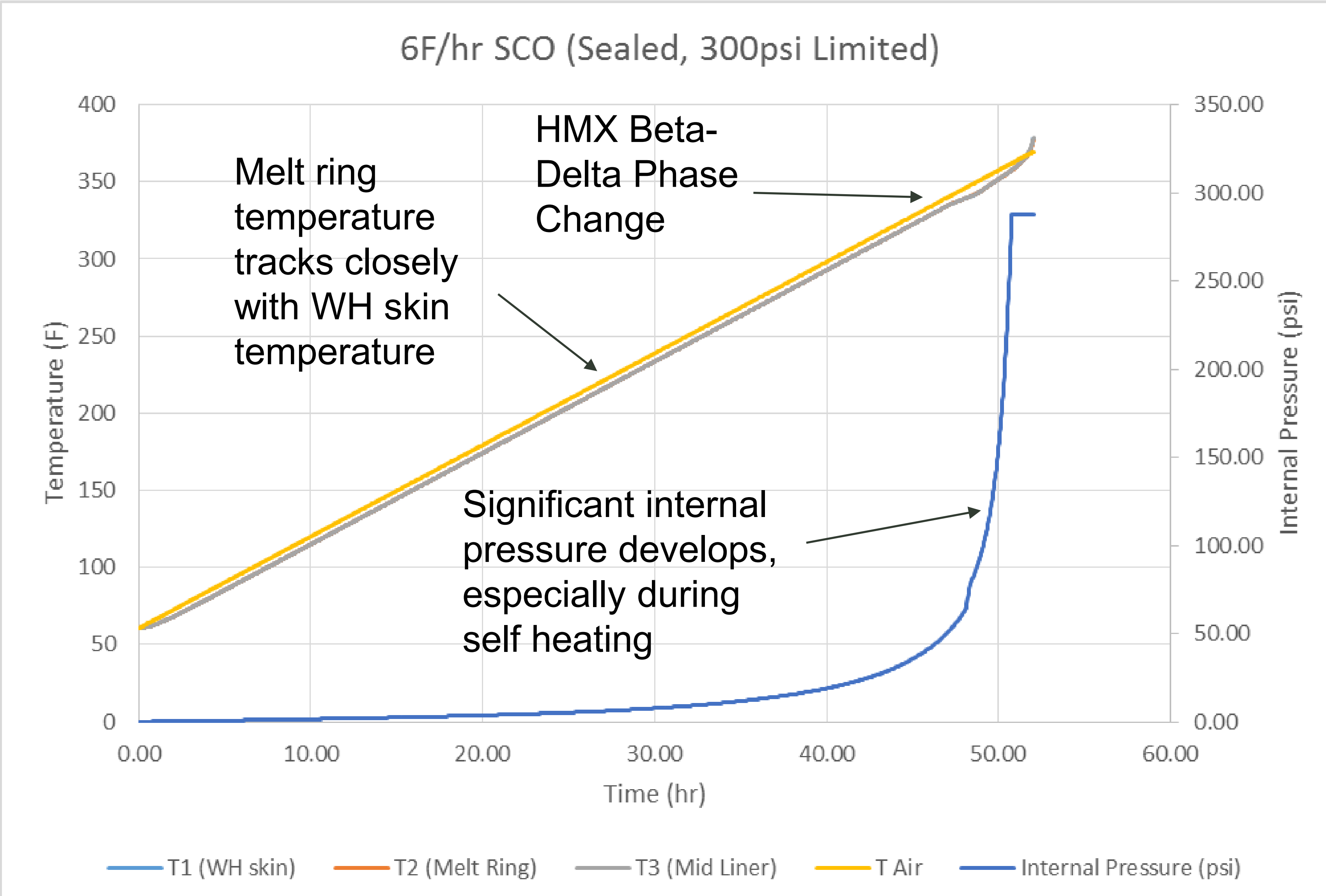
Billet Burn Profiles

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

6F/HR RESULTS



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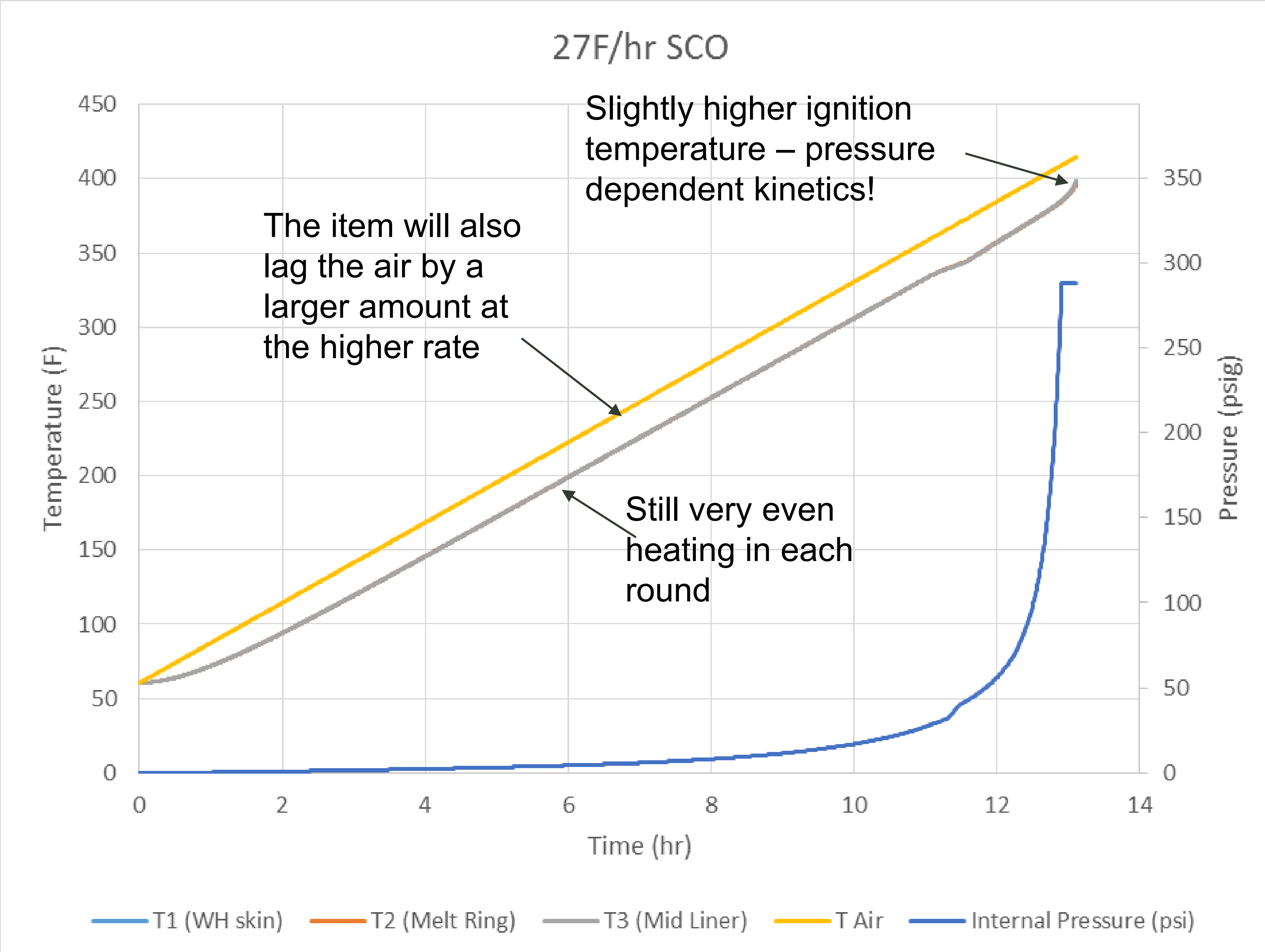
27F/HR RESULTS



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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

RECENT MEDIUM CALIBER VENTING

Internal View

Close-Up View

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MEDIUM CALIBER VENTING INTERNAL VIEW

MEDIUM CALIBER VENTING CLOSE-UP VIEW

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