Implications of Underwater Explosive Binder Systems on Slow Cook-off Violence and Interactions with Warhead Venting

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Slow Cook-Off and Underwater Explosives

- Slow Cook-off is a current identified IM shortfall for underwater explosives
- Slow cook-off mitigation approaches:

Physical Approach

- Reduce confinement through venting
  - Venting mechanism and actuation time
  - Vent size and location
  - Evacuation of material and gas
- Case material and design

Chemical Approach

- Decomposition reactions
  - Temperature of reaction
  - Time to reaction
- Mechanical properties during thermal ramp

- PROJECT OBJECTIVES: To develop an understanding of the thermophysical and thermochemical properties of underwater explosives and their melt-flow characteristics as they undergo SCO in order to
  - Design formulation approaches that can reduce SCO reaction violence
  - Provide design parameters for coupling warhead venting mechanisms with favorable explosive thermal decomposition chemistry opportunities to reduce SCO reaction violence.

Small Scale SCO Screening Protocol

Increasing amount of material and increasing test cost →

ARC & Rheology → VCCT → V-STEX → IM

ARC & Rheology
Accelerating Rate Calorimeter

- Scale: 0.1-0.5 g EM
- Material Characterization
- Self heating behavior
- Research quantities (neat and formulated)
- Binder properties at elevated temperatures

Material Properties

VCCT
Variable Confinement Cook-off Test

- Scale: ~50-60 g EM
- Material Characterization
- Reaction Violence vs. Confinement)
- Research quantities (formulated)
- 3.3°C/hr (slow)

Violence Under Confinement

V-STEX
Vented Scaled Thermal Explosion Test

- Scaleable
  - Small ~100 g
  - Large ~4 lbs
- Couples Venting with energetic materials
- For warhead design and packaging
- 3.3°C/hr

Physical Properties and Venting

IM
MIL-STD-2105C

- Munition scale
- IM Compliance
- Pass/Fail
- 3.3°C/hr

System Level Response

Underwater Explosives

Underwater explosives typically contain:

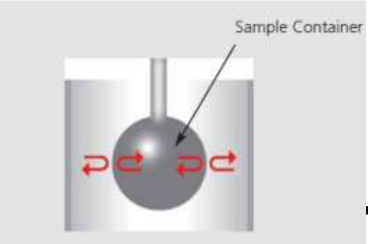
- Ammonium Perchlorate (40-50%)
- Aluminum (25-35%)
- RDX (7-20%)
- Binder System (polymer + plasticizer)
  - Baseline
    - HTPB = Hydroxyl-terminated polybutadiene
    - IDP = Isodecyl pelargonate
  - Binder System #2 (energetic plasticizer)
  - Binder System #3 (energetic plasticizer)

Studied: Explosives containing three chemically different binder systems

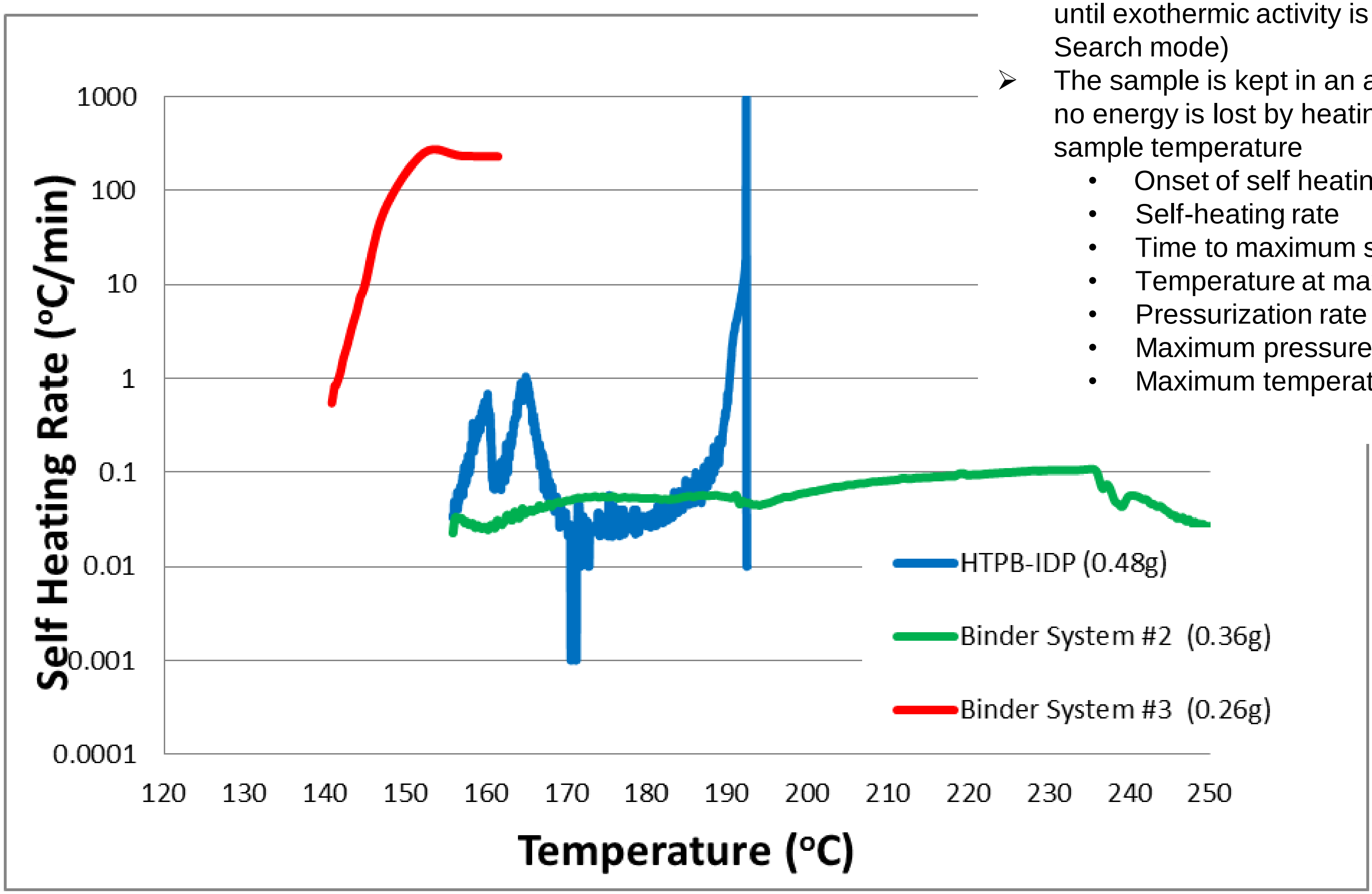
	HTPB - IDP	Binder System #2	Binder System #3
ARC	√	√	√
VCCT	√	√	√
Binder Rheology (inert gumstocks)	√	√	√
Small Vented STEX (~90 g)	√	√	√
Large Vented STEX (~4 lbs)	√	X	√

Increasing Energy Content →

Underwater Explosives ARC Results

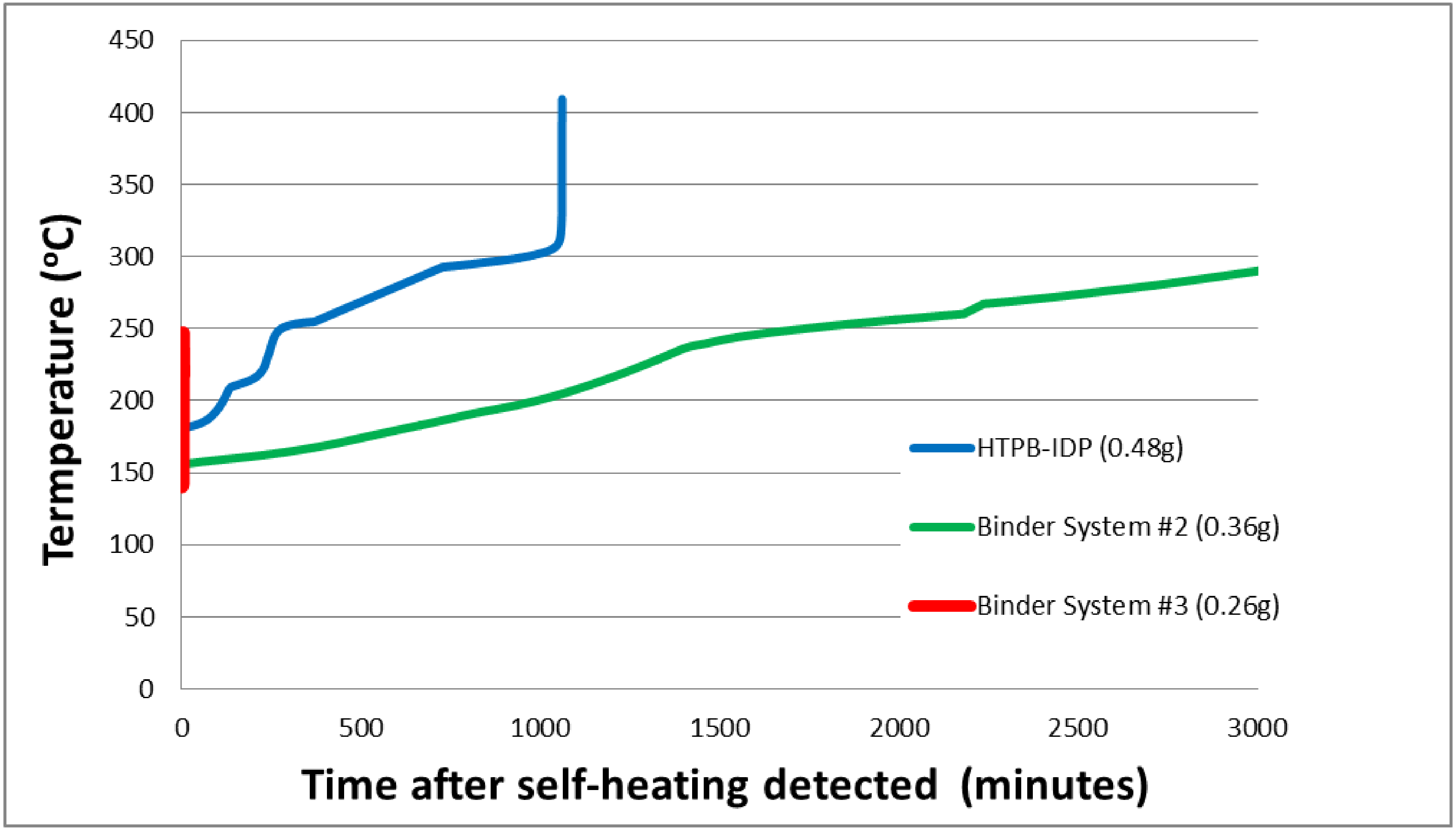


Adiabatic System: No heat out

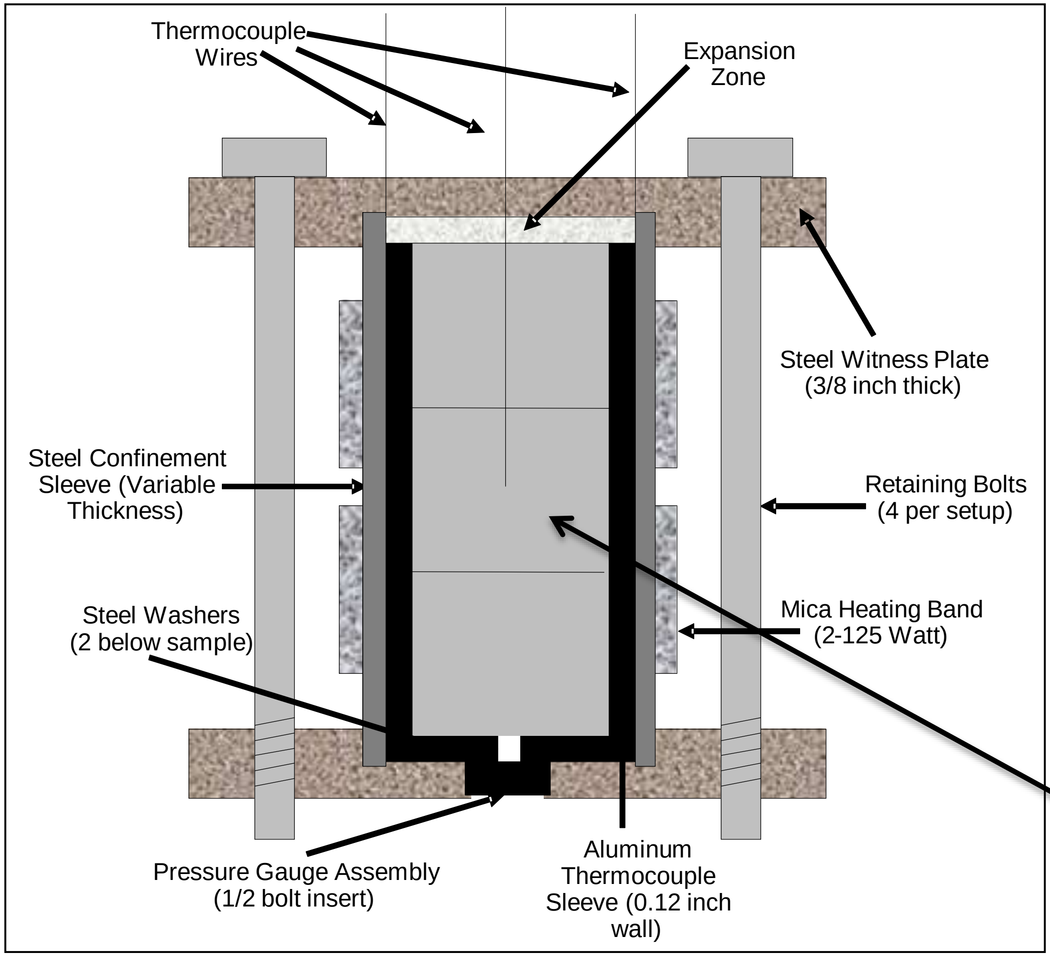


- Sample and surroundings are heated incrementally until exothermic activity is detected. (Heat-Wait-Search mode)
- The sample is kept in an adiabatic environment where no energy is lost by heating the calorimeter to the sample temperature
  - Onset of self heating
  - Self-heating rate
  - Time to maximum self-heating rate
  - Temperature at maximum self heating rate
  - Pressurization rate
  - Maximum pressure
  - Maximum temperature

Underwater Explosives ARC Results



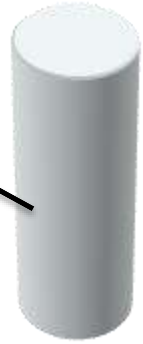
Testing Techniques
Variable Confinement Cook-off Test



- Constant Volume HE
- Variable Confinement Sleeves
- Set Rise Temperature (Heating Bands)

Diagnostics

- Recorded Wall Temperature + Internal HE Temperature (Optional)
- Video Coverage of Cook-off Cycle
- Hardware Inspection, post-test
  - Failure modes tracked to violence levels
  - Pressure Gauge on bottom end cap (optional)
  - Photographic evidence to preserve subtleties within violence levels



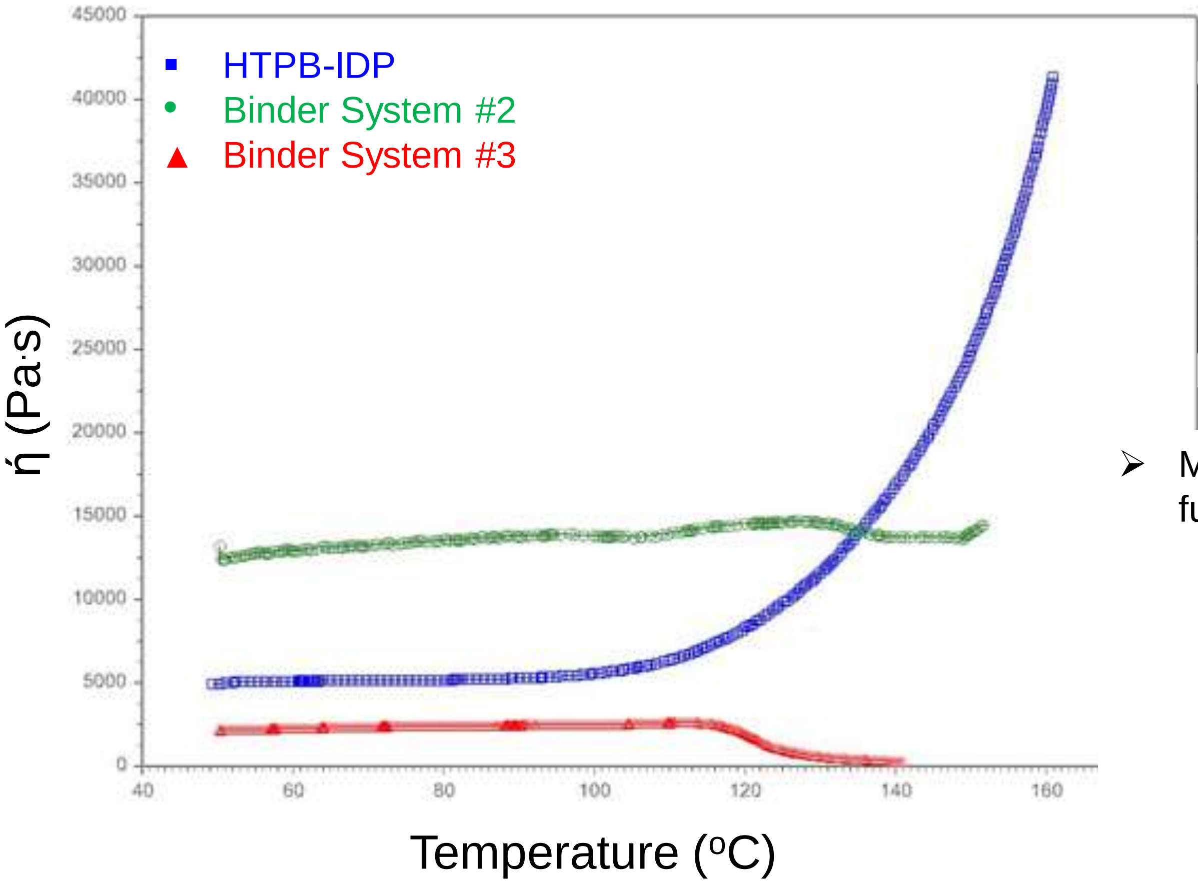
An energetic column 1-inch by 2.5 inches is placed / cast into Al sleeve.

Underwater Explosives
VCCT Results (Maximum Confinement)

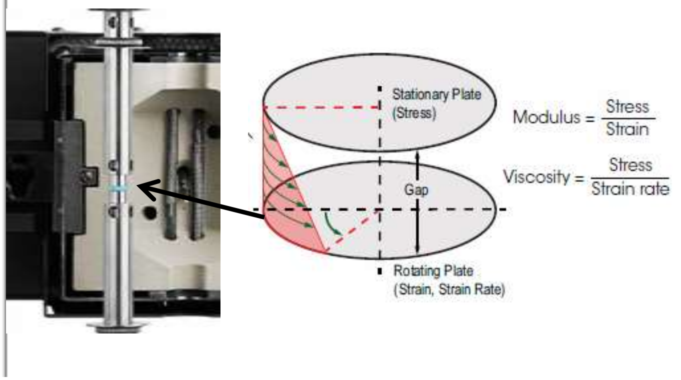
HTPB-IDP	Binder System #2	Binder System #3
		
Burn, No Damage to Tube	Burn, No Damage to Tube	Violent reactions at all confinement levels tested

Rheometer Data: Binder Gumstocks
(0.1ºC/minute, 100g force)

Complex Viscosity



TA - ARES-G2 Rheometer



- Measure the viscosity of a material as a function of temperature
  - -10° to 200°C
  - Independent measurements of stress and strain
  - Viscosity
  - Modulus

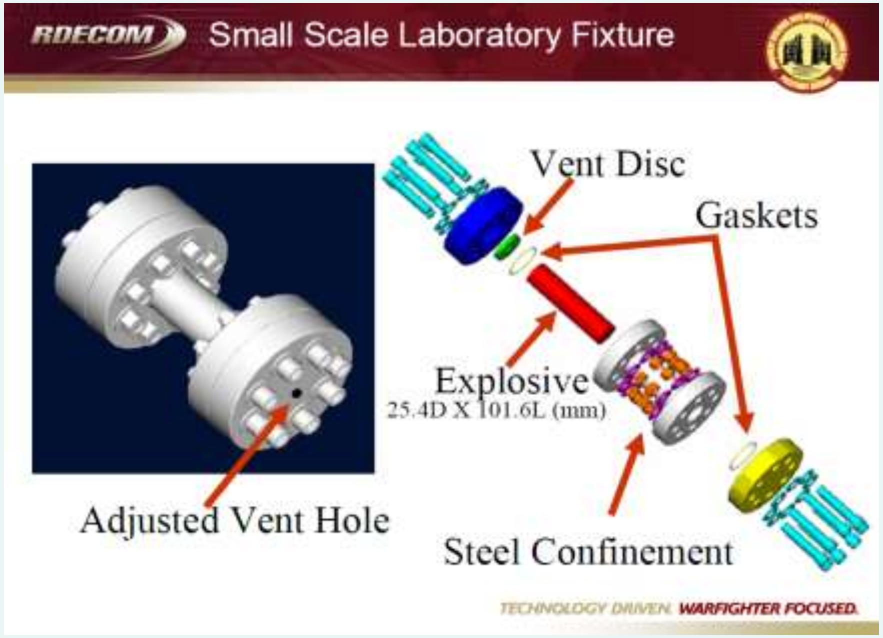
Rheology of Binder Gumstocks
(0.1°C/minute, 100g force)

	50°C	125°C	150°C	175°C
HTPB - IDP				
Binder System #2 ***(with energetic plasticizer)***				
Binder System #3 ***(inert – no energetic plasticizer)***				

Testing Techniques
Vented - STEX Tests

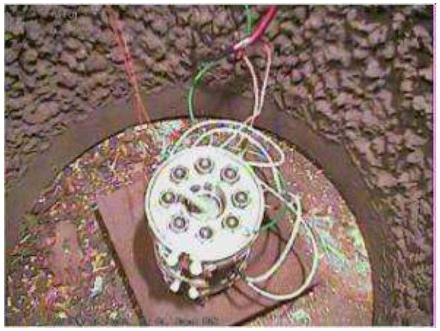
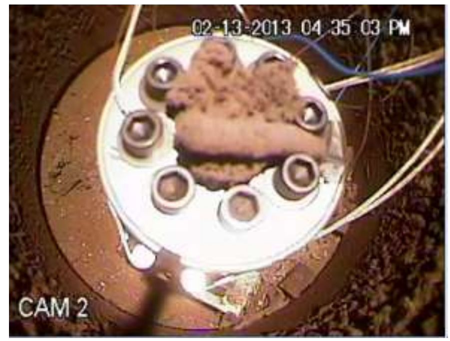
- ARDEC adapted original LLNL STEX
  - Venting characterization coupled with energetic material
  - Venting characterization as a function of vent area
  - Venting characterization as a function of heating rate
  - Warhead IM design technology
  - Small STEX hardware holds ~90 grams of energetics, high burst pressure (>20kpsi)

- ARDEC also developed a larger, low cost scale vented STEX
  - Off the shelf pipe parts
  - Low cost
  - Low burst pressure
  - ~4lbs of explosive



- S. DeFisher, et.al., "Confined Energetic Cook-off Mitigation as a Function of Heating Rate", 2007 Insensitive Munitions and Energetic Materials Technology Symposium,15th-18th October, 2007

Underwater Explosives (Small) Vented STEX SCO Results

	HTPB-IDP Binder	Binder System #2	Binder System #3
Venting of Mass Prior to Reaction			
Reaction Result			
	Burn	Burn	Explosion

Large vented STEX Results
HTPB – IDP (~4 lbs per tube)

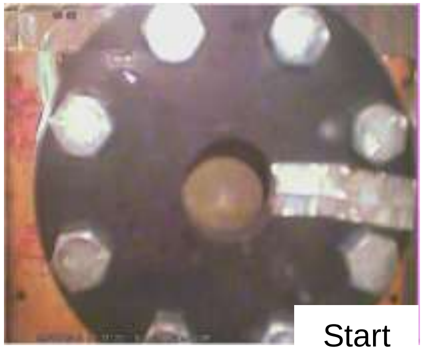
Vent Port Diameter (inches)	Cook-Off Time, hours	Cook-off Temperature °C	Reaction
0.75	32.6	177-183	Violent
1	31.2	179-182	Violent
1.5	32	182	Violent
2.0	32.7	183	Burn (2) Violent (1)

Large Vented STEX Results
Binder System #3 (~4 lbs per tube)

Vent Port Diameter (inches)	Cook-off Temperature °C	Reaction	Configuration
1.5	132°C	Violent disassembly, no material evacuation out of vent port	On side, heating bands
2.0	131.6°C	Less violent, no material evacuation out of vent port	On side, heating bands
2.0	135°C	Burn, material evacuated out of the vent port, large pieces of oven intact	On side, in oven
1.0	130°C	Burn, material evacuated out of the vent port, oven nearly destroyed	On side, in oven




Large STEX – VIDEO STILLS
Binder System #3



Start

127^{o}C

133^{o}C

133-134^{o}C

~135^{o}C

~135^{o}C

~135^{o}C
ignition

~135^{o}C cook-off
reaction

Small thermal window between material flow and ignition!

Summary and Conclusions

- 3 Similar explosives with chemically different binder systems --- 3 Quite different observed behaviors
  - Cook-off temperature
  - Self-heating characteristics and propensity for thermal runaway
  - Violence of reaction
  - Melt-flow and venting characteristics
  - ***Different mitigation/venting schemes would need to be tailored for each!***

- Pragmatic, inexpensive, small scale tests to study both the material decomposition and thermophysical properties can provide invaluable insight into the SCO behavior of energetic materials
  - Increasing scale and costs support formulation development efforts
  - Evaluate effects of formulation changes

- Binders have a profound effect on thermal decomposition mechanisms and violence
  - Avoid material combinations that are prone thermal runaway
  - Use binder chemistry to change the thermal decomposition profile of energetic materials from a rapid, self-accelerating event to a long time duration-low pressure history event
  - Use binder chemistry to complement venting opportunities
    - Binders that break down (via melting or scission) provide mechanism for evacuating the explosive mixture out of the confinement
    - Reduce the initial decomposition temperature of the energetic compositions
    - Provide ample time for venting schemes to mechanically/thermally actuate and allow system depressurization
    - Tailor thermophysical properties of the thermally softened material to assist with venting opportunities

Epilogue

- Subsequent larger tests were conducted (20-100lb scales) on HTPB-IDP and Binder System #3 explosives
  - Venting behavior of the explosive is consistent with small scale testing
  - Thermal gradients and warhead design (size of warhead, vent area and location, thermal conductivity of attached components, etc.) play a large role in:
    - hot spot location
    - effectiveness of venting (time to evacuate material)
    - reaction violence of the munition

- Continuing work:
  - Rheology studies
  - Conduct vented large STEX on Binder System #2 explosive
  - Utilize thermal profile modeling to characterize thermal gradients and hot spot location
    - Test configuration (oven, convection rate, case/liner materials, etc.)
    - Vary heating rate
    - Self-heating rate kinetics
  - Coupling of small scale tests and thermal models to assist test and warhead design efforts

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