# *Development of Small-Scale Slow Cook-Off (SCO) Testing Protocol for Granular Propellants*

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# Project Background

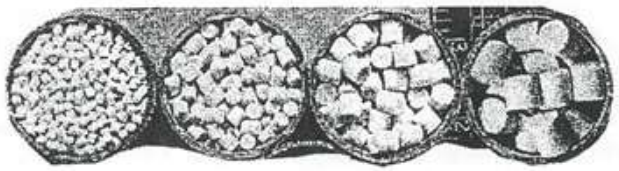
- **Existing Technology Gap**
  - General need for small-scale tests that are available to the gun community to assess/predict the slow cook-off behavior of granular propellants
- **Current assessments/predictions of SCO behavior are trial and error**
  - Indicators aren't realized until full-scale testing
  - Full-scale testing is expensive and time consuming
- **Technical Barriers**
  - Granular propellants are more complex than monolithic systems when it comes to determining their vulnerabilities to external stimuli
  - Understanding and measuring the burning rate of thermally-damaged material which has increased surface area
  - Complexities associated with the accurate modeling and simulation of a bed of granular propellants

# Project Background

- **Point of Departure: JIMTP Task 07-2-7 (Ms. Lori Nock - PI)**
- Protocol was developed for the scale-up of cook-off testing for AP containing explosives (containing both energetic and non-energetic binder systems) by correlating ARC, VCCT and STEX results to the results of full scale IM testing
  - Reported out at the February 2011 TTCP Sub-Scale Slow Cook-Off Testing Workshop

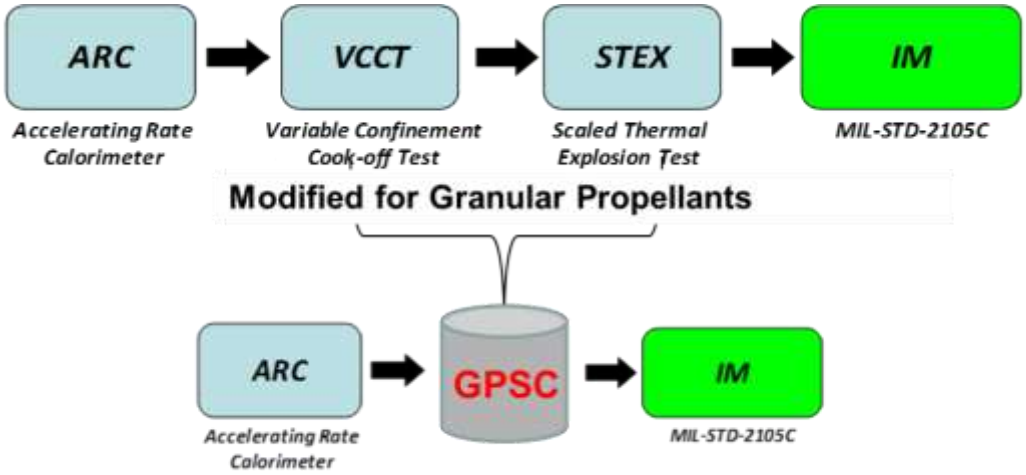
| ARC | → | VCCT | → | STEX | → | IM |
|---|---|---|---|---|---|---|
| *Accelerating Rate Calorimeter* | | *Variable Confinement Cook-off Test* | | *Scaled Thermal Explosion Test* | | *MIL-STD-2105C* |
| • Scale: ***0.5gm EM*** | | • Scale: ***50gm EM*** | | • Scale: ***100gm - 4 lb charge*** | | • Munition scale |

- **Similar approach (i.e. sub-scale protocol development) envisioned for gun propellants, but requires MODIFICATIONS to existing tests to <u>accommodate granular propellant configuration</u>**

Bed of propellant  versus  Monolithic configuration

# Technical Approach

- **Experimental: Apply small-scale tests (ARC and GPSC) to validate proposed SCO test protocol that will be used as a screening tool in gun propellant formulation development**
  - ***Primary Task:*** **Develop slow cook-off device suitable for granular propellants – Granular Propellant Slow Cook-off Device (GPSC)**




**Full-scale SCO data exists for these propellants**

**Small-scale SCO data will be validated with full-scale SCO data**

ALPI – Prop A, Low Energy, Poor in IM
AHPI – Prop A, High Energy, Poor in IM
BLII – Prop B, Low Energy, Improved IM
BHII – Prop B, High Energy, Improved IM

| | | IM Response (Thermal) | |
|---|---|---|---|
| | | Poor | Good |
| ENERGY | Low | ALPI | BLII |
| | High | AHPI | BHII |

# Technical Approach

## ➢ Modeling

- **Leverage existing IB model to simulate a SCO event corresponding to executed small-scale testing confinement configurations (pristine and thermally damaged), validate model with GPSC experimental results**
  - Ignition criteria are the same as those methods used for interior ballistics models at present; and propellant gas reaction is one-step
  - Includes thermal conductivity assumptions for the propellant; does not incorporate self heating
- **Leverage previously developed Navy granular propellant Finite Element models/simulations that mimic results of SCO, validate model with GPSC experimental results**
  - Incorporates experimentally determined decomposition kinetics/material properties of propellant
  - Self heating

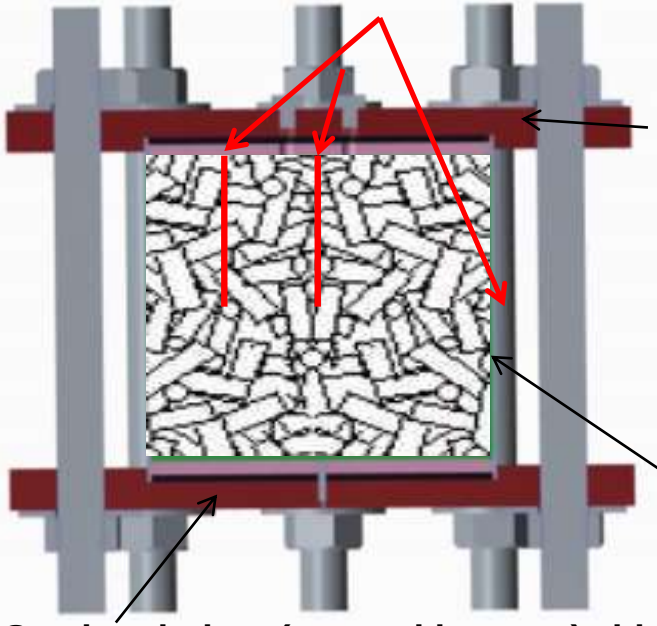
# Granular Propellant Slow Cook-off (GPSC)Test Assembly Design

SCO Tube - DSTO

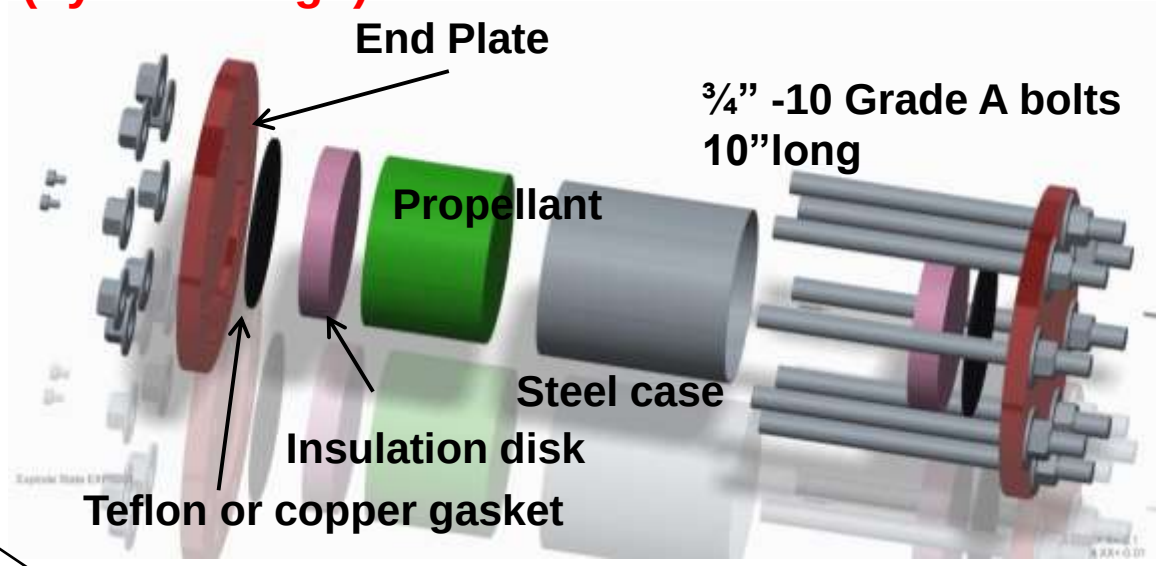
(hybrid design)

VCCT - IHEODTD

Thermocouple locations



Steel end-plate (top and bottom )with male gland O-ring seal, 8 thru holes for 3/4" diameter bolts

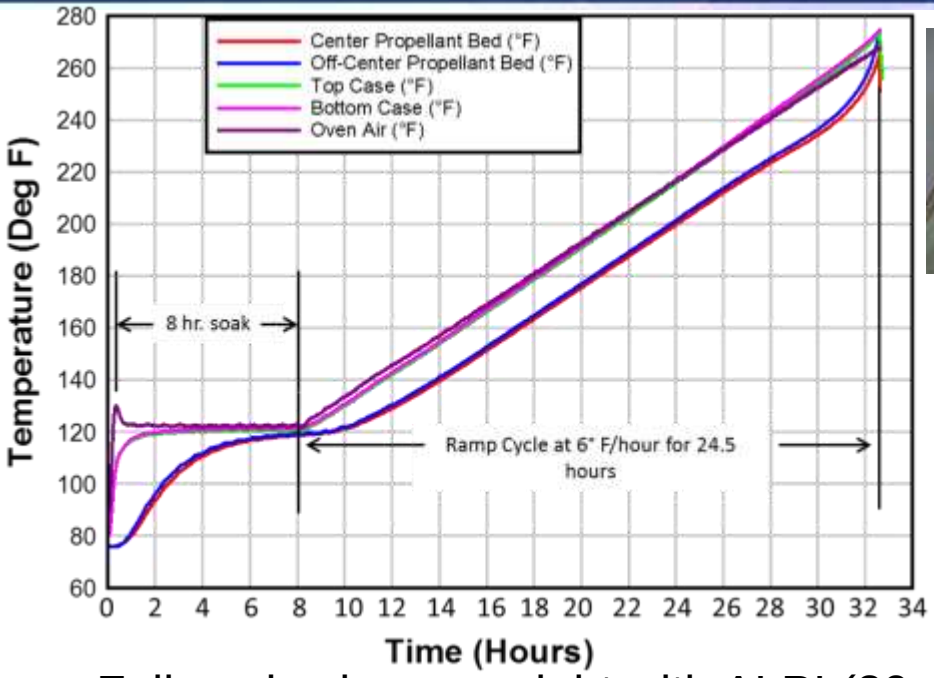



Steel Case
5.4882" OD X 6" long
0.070" thick wall

# GPSC Test Assembly Trial Shots

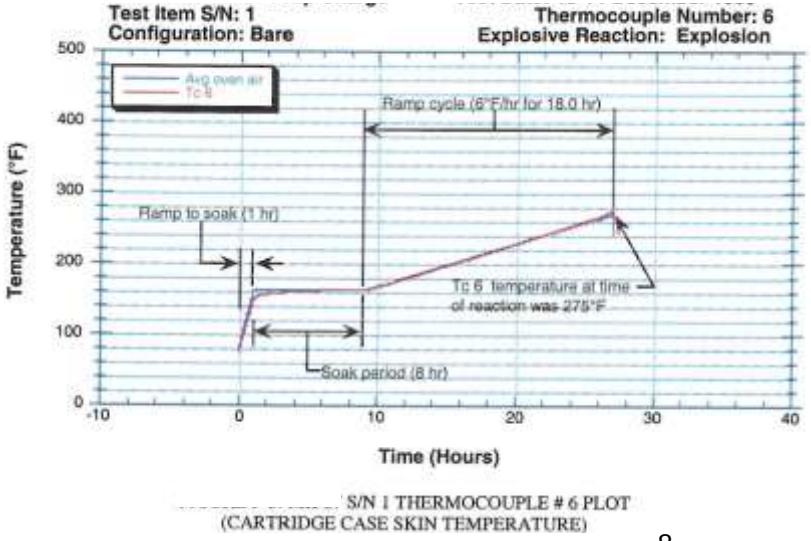
- **Trial shots conducted Q1FY14 at NSWC IHEODTD bomb proofs**
- **Thermocouple data collected at various locations**
  - Axis of GPSC (center of propellant bed), off-axis, GPSC cartridge wall (exterior), oven open air
- **GPSC test assembly exposed to a thermal soak in a toaster oven at 122°F for 8 hours, oven temperature is then increased 6°±1°F per hour until the test item reacts**
  - STANAG 4382, "Slow Heating, Munitions Test Procedures"
- **Digital photographs of test set-up and test results**
- **Upgrades being considered**
  - Closed circuit high speed video systems
  - Quantifiable means of assessing reaction (pressure, strain gages, force probes)

# Sub-Scale vs Full-Scale SCO Trends for ALPI (Low Energy, Poor in IM)



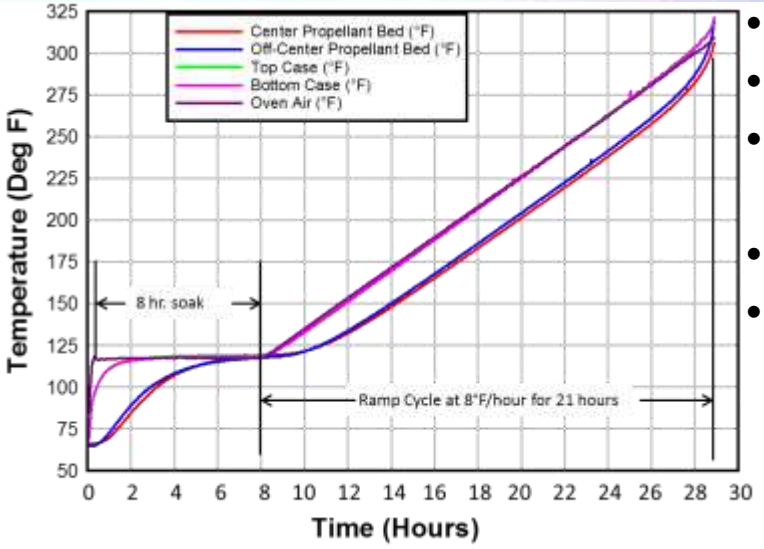

- GPSC (4 lbs. sample) – propellant only
- Thermal soak for sub-scale at 122°F
- 275°F cook-off/at ~ 25 hours
- Propellant bed temperature lags case and oven air by about ~20°F

- Full-scale charge weight with ALPI (20.4 lbs. sample) and primer
- Thermal soak for full-scale tests at 160°F
- Case skin temperature ~274°F at cook-off /18 hours
- ***Hypothesize ALPI cooks off faster at full scale as a result of higher thermal soak temperature* (160°F vs 122°F)**



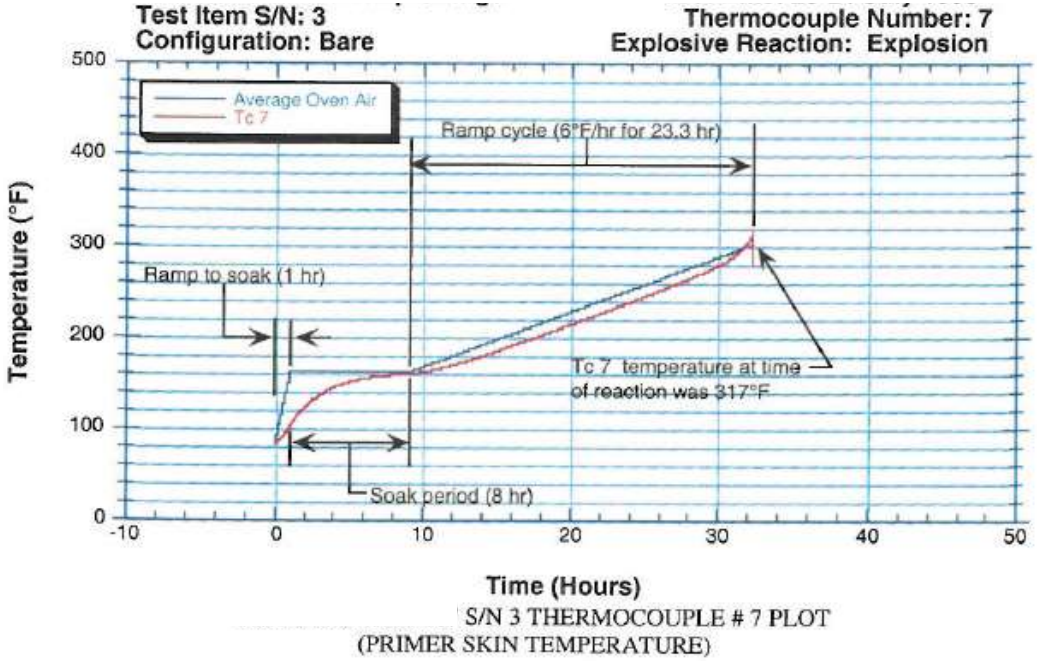

S/N 1 THERMOCOUPLE # 6 PLOT
(CARTRIDGE CASE SKIN TEMPERATURE)

# Sub-Scale vs Full-Scale SCO Trends for AHPI

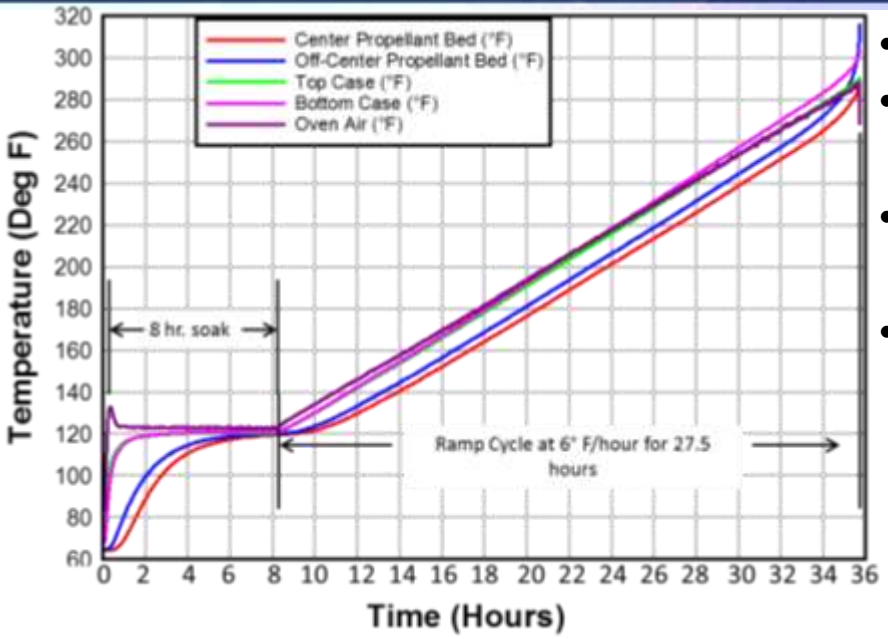



- ***High energy propellant, poor in IM***
- GPSC (4 lbs. sample) – propellant only
- Thermal soak for sub-scale at 122°F/higher than intended ramp, 8°F/hr versus 6°F/hr
- 320°F cook-off/21 hours
- Similar thermal behavior observed in that internal propellant temperatures lags case temperature by about 15-20°F

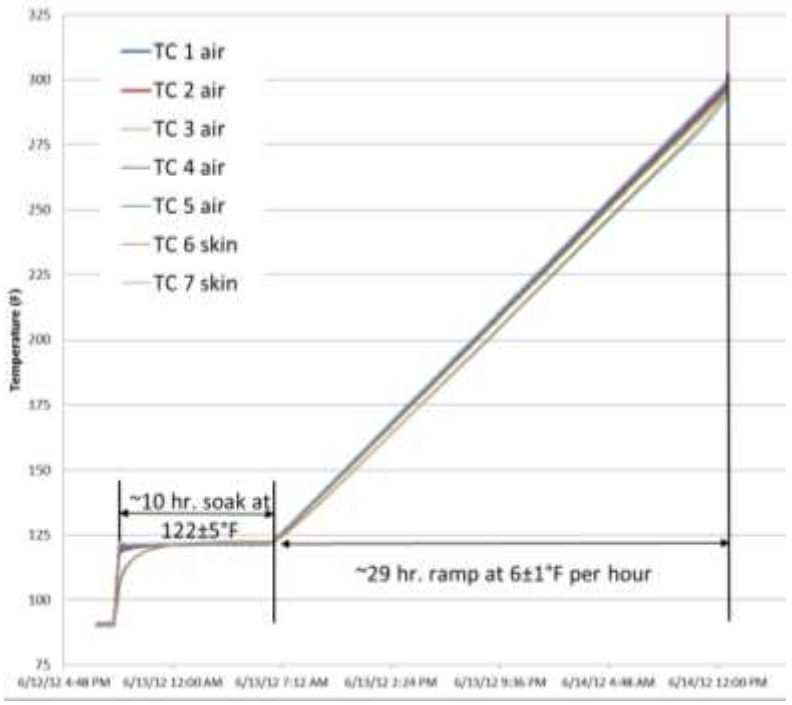
- Full-scale charge weight with AHPI (24.6 lbs. sample) and primer
- Full-scale thermal soak at 160°F
- Case temp ~305°F and primer temp ~320°F at cook-off temperature/23.3 hours
- **Higher heating at sub-scale (8°F/hr versus 6°F/hr) may counter effects of higher temp thermal soak**



# Sub-Scale vs Full-Scale SCO Trends for BLII

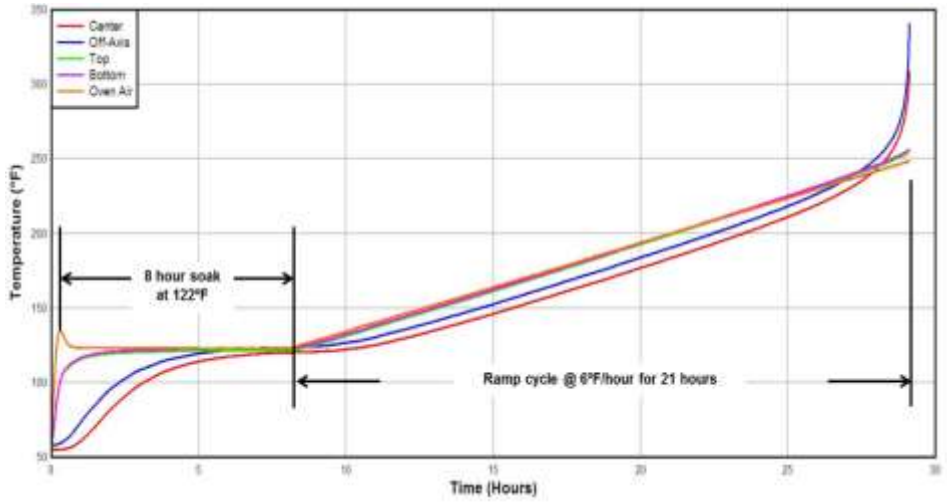



- ***Low energy propellant with improved IM***
- Propellant bed lags case and oven air temperature during ramp by ~ 10 ºF
- Near cook-off, bottom of the case deviates from top of case (hot spot location?)
- 320F/160°C cook-off temperature, time to cook-off ~ 27.5 hours



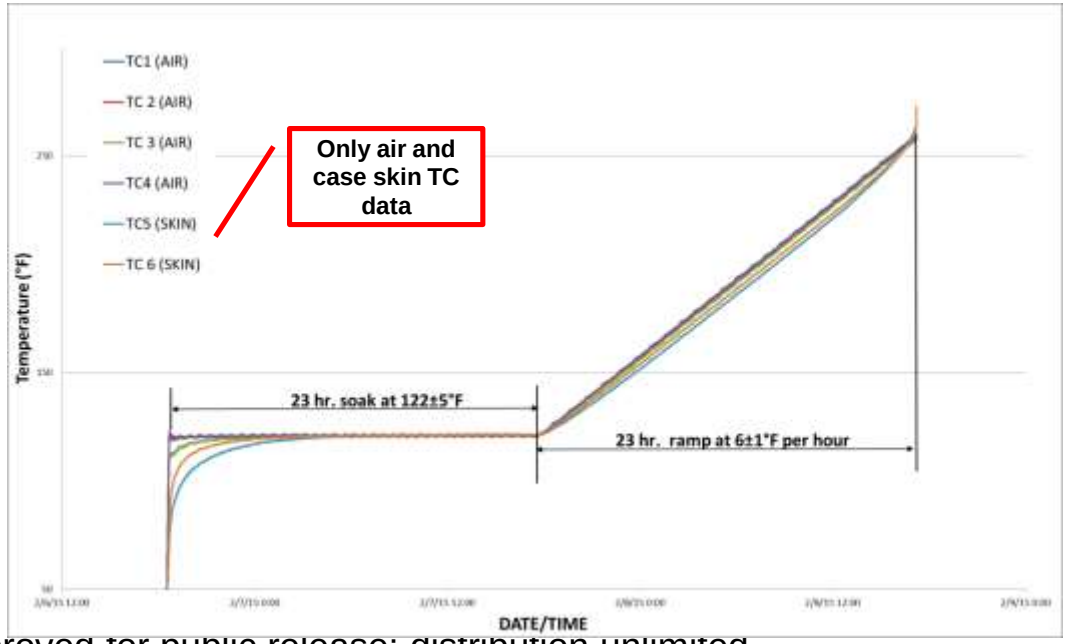

- Full-scale charge weight with BHGI (4 lbs. sample – mortar ) and primer
- Full-scale thermal soak at 122°F for 10 hours (soak duration ensure reaction during daylight)
- Case cook-off temp 299°F/29 hours
- Case skin temperature ~6ºF less than measured air temperature in oven

# Sub-Scale vs Full-Scale SCO Trends for BHII

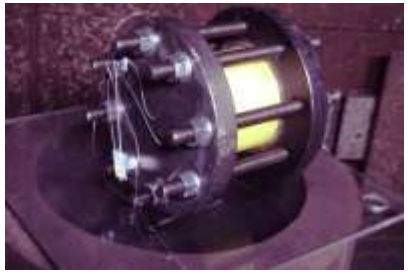



- ***High energy propellant, improved IM***
- GPSC (4 lbs. sample), propellant only
- Sub-scale thermal soak at 122°F
- 255°F @ cook-off/21 hours
- More pronounced thermal gradient between center of propellant and off-axis
- Thermal lag temperature delta not as large with BHII as others tested

- Full-scale charge weight with BHII (22 lbs. sample) and NO PRIMER
- Full-scale thermal soak at 122°F for 23 hours (ensuring reaction during daylight dictates soak duration)
- Case cook-off temp 265°F/23 hours
- Case skin temperature ~5ºF less than measured air temperature in oven



# GPSC Test Results Damage Comparison
# ALPI - AHPI - BLII - BHII Propellants



| | ALPI | AHPI | BLII | BHII |
|---|---|---|---|---|
| **Impetus (J/g)** | 891 | 1153 | 896 | 1186 |
| **T flame (K)** | 2450 | 3008 | 2145 | 3024 |
| **DSC (ºF) Onset** | 325 | 383 | 428 | 365 |
| **ARC (ºF) Onset** | 284 | 347 | 311 | 293 |
| **GPSC Cook-off temp*/time to event (°F/hr)** | ~275/25 | 320/21 | 290/27.5 | 255/21 |
| **Full Scale Cook-off temp*/time to event (°F/hr)** | 275/18 (160°F soak) **Type (III)** | 305/23 (160°F soak) **Type (III)** | 299/29 (105mm, 122°F soak) **Type (V)** | 265/23 (122°F soak) **Type (V)** |

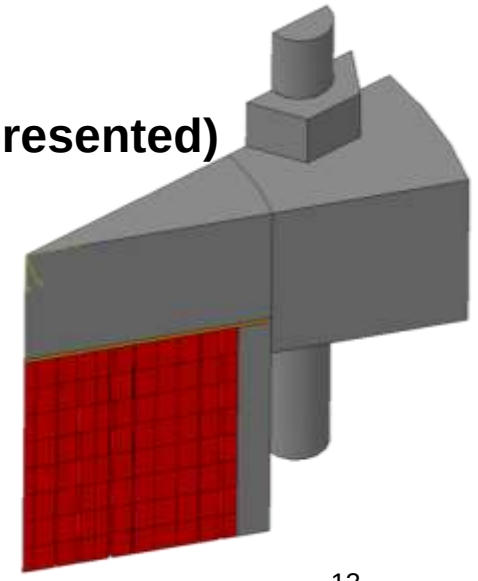
# Heat Transfer Finite Element Model Efforts

- **Goal: Leverage previously developed Navy granular propellant models/simulations that mimic results of a SCO to aid in research and design**
- **Simulation details**
  - **Software: ABAQUS CAE v.14**
  - **Free convection (3.5E-6 Btu/in$^2$-sec-F) will be used**
  - **Self Heating of the energetic material created by Arrhenius Equation**
  - **Thermal Runaway is defined as Δ1000°F < 5 minutes**
  - **Simulate compression of cylindrical grains by providing flat spots on the cylindrical sections**
  - **Alignment of granules in various arrays**
- **Preliminary Model Graphics (steel, copper, propellant represented)**

Horizontal Alignment

Vertical Alignment

Alternating Array



# FEM SCO Model for ALPI Propellant

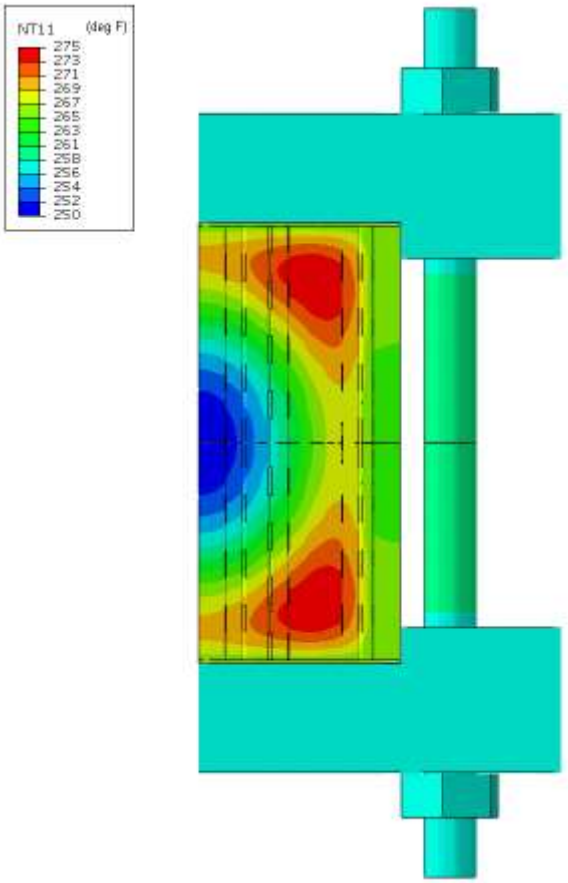
- **ALPI propellant material properties used as input for FEM model**

| Kinetic Parameters | ALPI |
|---|---|
| Density - ρ (kg/m3) | 1570.0 |
| Specific Heat - Cp (J/kg°K) | 209.32 |
| Thermal Conductivity - K (W/m°K) | 0.0005 |
| Heat of Reaction - Q (cal/g) | 389.14 |
| Frequency Factor - Z (1/sec) | 2.3810E+14 |
| Activation Energy - Ea (cal/mol) | 34000 |
| Thermal Diffusivity - α (m2/sec) | 1.4815E-09 |
| Grain Dimensions (inches) | 0.2812 D x 0.6215L |

- **Estimates for propellant material properties for selected propellants have been determined from TC data and will be used for future SCO simulations**

# FEM Simulation for ALPI Propellant Results

- **Simulations predict reaction location is near the case/end plate joint and in the off center–axis position**
- **Future simulations being conducted to examine effects of ethafoam insulation (between end-plates and propellant) on reaction location**




| Thermocouple / Nodal Temperature Comparison | | |
|---|---|---|
| | Temperature (Deg F) | |
| | ALPI GPSC Test | FEM Simulation |
| Center | 266 | 250-269 |
| Off Center | 274 | 259-273 |
| Top Case | 273 | 265 |
| Bottom Case | 275 | 265 |
| Oven Air | 268 | 267 |
| Time to Rxn | 32.5 hrs | 32.5 hrs |

# Technical Conclusions and Path Forward

- **Trial GPSC shots on ALPI, AHPI, BLII, BHII propellants complete**
  - **Thermocouple data captures Tco, time to cook-off, and illustrates differences in propellant material properties (conductivity and diffusivity)**
  - **Trends in Tco and time to cook-off observed between GPSC and full-scale tests**
  - **Differences in violence of reaction were observed**
    - Oven debris, GPSC apparatus debris (condition of cartridge case, bolts, end-plates)
    - Level of damage observed shows there are some correlations with full-scale data
  - **Self Heating Zone as observed by the Australians observed in some cases**
    - Examine correlations with reaction violence
- **Additional testing of suite of granular propellants is necessary to further examine extent of correlation between sub-scale and full-scale IM response**
  - **Conduct GPSC run on Army propellant that has full scale SCO data**
  - **Continue ARC testing (pressurization rate and reaction violence)**
- **Establish acceptable criteria for evaluating level of violence**
  - **Incorporate additional instrumentation (pressure transducers, strain gages or force probes) to more accurately quantify or compare violence**
  - **Use models as guidance (i.e. location of reaction, insulation, effects of varying heating rate) – continued validation with HPSB and GPSC experimental results**

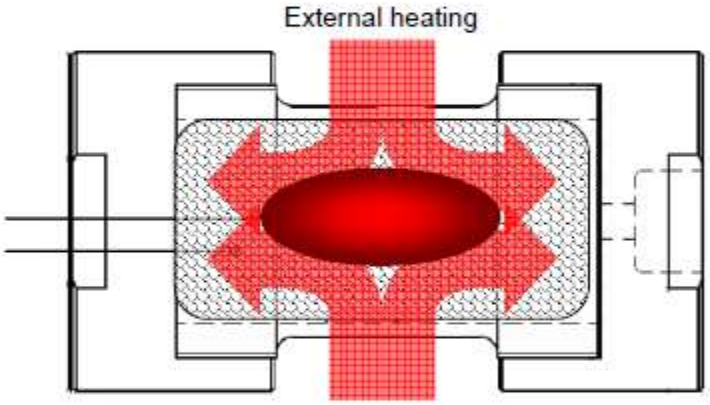
# *Backups*

# Australian Efforts
# Small-Scale Slow Cook-off Trials

Australian Government
Department of Defence
Defence Science and Technology Organisation

## Accelerated self heating zone

Accelerated self heating zone (ASHZ) is the part of the energetic material in a slow cook-off tube where the heat release from its own thermal decomposition has outpaced the external heating source.




After thermal decomposition outpaces the heat transfer, a cook-off event is inevitable, even it takes some time. When the tube is cooked off, there is certainly an ASHZ inside

Weapons Propulsion Group, TTCP SCO Workshop, Unclassified - For Official Use Only