Modeling Methodology for Predicting SCO Performance of the Excalibur Warhead

May 2009 – Approved for Public Release
Introduction

• The objective of this presentation is to describe a thermal modeling methodology used to analyze Slow Cook-Off in the Excalibur Warhead

• Modeling Goals are as follows:
  • To gain understanding of heat transfer in the Excalibur warhead when exposed to slow heating environment
  • Use this understanding to design mitigation methods that ensure the Excalibur warhead burns (Type V Reaction) during slow heating environment
Excalibur SCO Test Article

Base (Mass Mock)
Billet [PBXN-9]
Nose (Mass Mock)

Body
Liner
Vent Plug
Upper Liner
Nose Mount

Booster Cup
Booster
Fuzewell Assy
Lower Liner

Fuzewell Liner [HDPE]
Fuze Simulant (Mass Mock)
Polyurethane Foam

Front Retainer
Fuze Retainer
Forward Spacer
Aft Spacer

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.
Methodology

• Steps used for thermal modeling and analysis
  – De-Feature Model
  – Apply Contact Resistances
  – Define Material Properties
  – Define Thermal Loads and Constraints
  – Run Thermal Model
  – Compare Model to test results
“De-featuring” a solid model means parts are simplified or combined in an effort to reduce computational size of the model.

- Assemblies made from the same material can be combined
- Features such as fillets and chamfers are eliminated
- Symmetry used where possible
  - Use “wedges” on axisymmetric parts or assemblies
Apply Contact Resistances

- Presence of gaps caused by tolerances can change how heat transfers across material interfaces
- Contact resistances can be applied between surfaces
  - Interfaces must be line to line
  - Resistance value calculated based on gap thickness and thermal conductivity of filler material (air, RTV, etc.)
    - Gap Thickness = t [m]
    - Thermal Conductivity = k [W/m·K]
    - Contact Resistance = t/k [K·m²/W]
    - Resistance increases as gap thickness increases
    - Resistance increases as thermal conductivity decreases
The three cases below illustrate how interface conditions can change thermal transfer:

- One hour calculation with convection applied to upper surface

A perfect, line-to-line interface between two parts allows for ideal heat transfer:

Accidentally putting in a gap can change the heat transfer across the interface:

Contact Resistance representing 0.01” air gap (0.010 m²•K/W):
Define Material Properties

• Material properties required for thermal model:
  – Density
  – Thermal Conductivity
  – Specific Heat
  – Kinetic Constants
    • Activation Energy
    • Pre-Exponential Factor
    • Heat of Reaction
Basic Material Properties

- Basic Material Properties are input as constants or as a function of temperature
  - Density
  - Thermal Conductivity
  - Specific Heat
- Material properties for explosive formulations are not always published so the Rule of Mixtures can be applied based on the component materials

\[ k = \sum (f_i \cdot k_i) = f_1 k_1 + f_2 k_2 + \ldots + f_i k_i \]

\[
\begin{align*}
  f_1 &= \frac{\text{wt\%}_1 / \rho_1}{\text{wt\%}_1 / \rho_1 + \text{wt\%}_2 / \rho_2 + \ldots + \text{wt\%}_i / \rho_i}, \\
  f_2 &= \frac{\text{wt\%}_2 / \rho_2}{\text{wt\%}_1 / \rho_1 + \text{wt\%}_2 / \rho_2 + \ldots + \text{wt\%}_i / \rho_i}, \\
  \text{etc...}
\end{align*}
\]

- \( k \) = thermal conductivity of each component
- \( f \) = volume fraction of each component
- \( \text{wt\%} \) = weight percentage of each component
- \( \rho \) = density of each component
Self Heating Properties

- An Arrhenius rate equation is used to calculate the self-heating properties of the explosive as a function of temperature.
- Activation Energy, Heat of Reaction and Pre-Exponential Factor are the kinetic constants.
- Activation Energy and Pre-Exponential factor must be calculated by ASTM-E 698-05, if not published.

\[ \text{Heat Rate} = \rho \ Q \ Z \ e^{-E/RT} \]

\[ \begin{align*}
\rho &= \text{Density} \\
Q &= \text{Heat of Reaction} \\
Z &= \text{Pre-Exponential Factor} \\
E &= \text{Activation Energy} \\
R &= \text{Universal Gas Constant} \\
T &= \text{Absolute Temperature}
\end{align*} \]
Thermal Loads and Constraints

• The initial temperature of all components is the start temperature to be used during SCO tests
  – 122°F most common

• Convection is applied to all surfaces that will be exposed to moving air within the oven.
  – Convection Coefficient: 12 W/m² K
  – Bulk Temperature of convective medium heated at 50°/hour or 6°/hour, depending on test conditions intended for study

• Self heating properties of explosive applied as heat power generated as a function of temperature
Thermal Plot at 6°F/hr Heating

Thermal Plot

Material Plot

Thermocouple Location
Test Data Comparison at 6°F/hr

Temperature Comparison - 6°F/hour

- Model Air
- Test (RT08-023) Air
- Model Skin
- Test (RT08-023) Skin

Δ6.3%
Thermal Plot at 50°F/hr Heating

Thermal Plot

Thermocouple Location

Material Plot

Temp (Fahrenheit)
Test Data Comparison at 50°F/hr

Temperature Comparison - 50°F/hour

- Model Air
- Test Air (RT07-123)
- Model Skin
- Test Skin (RT07-123)

Δ3.4%
• Conclusions
  – A standard methodology has been developed for predicting
    SCO reaction times and temperatures
  • Accurate within 7% at 6°F/hour heat rate on Excalibur
  • Accurate within 4% at 50°F/hour heat rate on Excalibur
  – Method can be applied to other systems

• Future Work
  – Continue to gather test data and compare to models
  – Develop burn models to calculate what happens after
    reaction takes place
    • Models only predict reaction time and temperature, not Type
Acknowledgements

• Ernest Baker – ARDEC
• Nausheen Al-Shehab – ARDEC
• Joe Morris – General Dynamics – OTS
• Mike Steinberg – General Dynamics - OTS
• Mike Gunger – Gunger Engineering