An Investigation into a Proper Heating Rate for Slow Cook-off Testing

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Overview

• The Slow Cook-off (SCO) test, as specified by STANAG 4382, specifies a constant heating rate of 3.3°C/hr

• The validity of this 3.3°C/hr heating rate has been questioned
  – Concern that it is too slow to represent accidents
  – Mitigations designed to work at 3.3°C/hr might not work at the higher rates that occur in accidents

• The Slow Heating Custodial Working Group (SHCWG) was formed to review the test standards and create a new Allied Ordnance Publication (AOP)

• A key topic for the SHCWG, what should the SCO heating rate be?
Overview

- The first SHCWG meeting was held in April 2017
  - There was disagreement within the group as to what accidents had occurred and what analysis had been performed
  - Agreement on an appropriate heating rate could not be reached
- The group chairman requested that an investigation be performed to be presented to the group at the second meeting
  - The investigation was meant to present facts and guide the discussion towards realistic threat scenarios
- A significant portion of this investigation was a modelling effort to identify realistic worst case SCO heating scenarios
- This paper presents the results of the modelling effort
Modelling Overview

- The goal of the modelling effort was to attempt to determine the slowest heating rates that could result in a cook-off.
- A review of existing analysis indicated that the slowest heating rates would result from a fire adjacent to a magazine.
- A model was developed to study the fire/magazine system.
- The magazine air temperature curves were then used to determine average heating rates.
Model Overview

- A model was developed to calculate magazine temperatures during fires
  - Allows varying parameters that would influence the magazine temperature curve
    - Magazine dimensions, ordnance quantity, wall thickness, and fire size
  - Lumped mass model, includes convection and radiation but no conduction
  - Uses correlations given in Wikström 2016 – “Temperature Calculation in Fire Safety Engineering”
  - Solved using coupled, explicit finite difference equations
Model Validation

- Data from an instrumented fire aboard EX Shadwell was used to validate model
  - Compartments and fire size modeled based on data given in the report
  - The measured temperatures were compared to model results
- Model agreement with test data is sufficient to allow it to be used to simulate SCO scenarios
How Model is Used

• Determine the slowest heating rate that still produces cook-off temperatures within magazine
  – Increasing fire size increases final temperature
  – Assume that the lowest temperature that result in a cook-off is 130°C
  • Conservative assumption, higher value results in higher average heating rates
  – For each set of model parameters, there is only 1 fire size that results in a final temperature of 130°C—Worst case fire size
Average Heating Rate Calculation

• Want to calculate an average heating rate (average slope) from the worst case magazine temperature curve

\[
\bar{dT}\over dt = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \overline{dT}\over dt \cdot dt = \frac{T(t_2) - T(t_1)}{t_2 - t_1} = \Delta T \over \Delta t
\]

• Must assume an equilibrium temperature, \(T(t_2)\)
  – Equilibrium temperature selected as 90% of total temperature rise
    • Selection ensures conservatism, the higher the value the slower the calculated rate
    • Also, 90% has been used in prior analysis
  – Time to 90%, \(t_2\), is then determined and average heating rate (\(\Delta T/\Delta t\)) is calculated

➤ All results are based on a 130°C cook-off temperature and a 90% temperature rise
How Model is Used

- Example for one particular set of model parameters
  1. Determine the fire size that results in 130°C final magazine temperature, 1 MW in this example
  2. Calculate time to equilibrium, \( t_2 = 4.1 \text{ hrs} \)
  3. Use \( t_2 \) to calculate average heating rate, 24.3°C/hr
     - Note that higher cook-off temperatures result in higher heating rates
Model Results – Bulkhead Thickness

- Increasing the thickness of the bulkhead increases the total thermal mass and consequently increases the time to equilibrium
  - Does not affect equilibrium temperature within the magazine
  - Increasing bulkhead thickness decreases average heating rates

**Magazine Air Temperature**

- \( t_2 \) increases as bulkhead thickness increases

**Average Heating Rate**

- Thicker walls = slower heating rates
• Examined empty magazines of various sizes and aspect ratios
  – As magazines get larger, a larger fire is required to reach 130°C
    • More wall area to lose heat
  – Fire size and thermal mass both increase with increasing magazine size
  – Effects offset; magazine size has a minimal effect on average heating rate

**Model Results – Magazine Size**

**Magazine Size vs Required Fire Size**

- Required Fire Size - MW
- Magazine Size - m²
- W/L=0.25
- W/L=0.5
- W/L=1
- W/L=2
- W/L=4

**Magazine Size vs Average Heating Rate**

- Average Heating Rate - °C/hr
- Magazine Size - m²
- W/L=0.25
- W/L=0.5
- W/L=1
- W/L=2
- W/L=4
Model Results – Full Magazine

- Model was run with the magazines full of ordnance
  - Ordnance increases thermal mass which decreases the average heating rate
  - Ordnance partially blocks radiation exchange within the magazine which further decreases the average heating rate
  - Results shown are for magazines with 12mm and 25mm thick bulkheads
  - Slowest average heating rate found was $12^\circ\text{C}/\text{hr}$ for 12mm walls and $10^\circ\text{C}/\text{hr}$ for 25mm walls
Model Results – Full Magazine

- Slowest heating rates will occur in full magazines with thick walls
- It is **not possible** for a constant sized fire to heat ordnance to cook off temperature any slower than 10°C/hr
  - Only way to get a slower rate would be a fire that gradually increased in size over many hours
  - Below deck fire size dependent on vent area, fire size usually remains essentially constant until it starts dying out
  - **Slowest rate calculated is 3 times faster than the currently specified heating rate**
Forward Operating Base

- MILVAN containers in the configuration in which they are used at forward operating bases (FOBs) were also analyzed
  - Size and maximum allowable ordnance quantity are specified
  - Assume a truck fire while loading/unloading ammunition
  - Worst case is one full container surrounded by empty containers and a fire that causes the final temperature to reach 130°C
    - Empty containers insulate magazine
  - Slowest average heating rate possible is 18°C/hr
Summary

• Modelling was performed to determine the slowest heating rate that could be achieved within a magazine that could result in a cook-off
  – Assumed that heating was caused by an adjacent fire
  – Determined fire size that would result in a magazine temperature of 130°C
  – Calculated the average heating rate based on time to 90% temperature rise
  – Slowest heating rate found was **12°C/hr** for magazines with 12mm thick walls and **10°C/hr** for 25mm thick walls
  – A FOB MILVAN was analyzed and the slowest rate found was **18°C/hr**

• Based on these results, the current heating rate of 3.3°C/hr used in slow cook-off testing is too slow to represent a credible scenario and should be increased
Acknowledgements

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Determining the Average Heating Rate

- Temperature history, $T(t)$, is a curve with a changing heating rate, $dT(t)/dt$

- The average heating rate is the average of this changing rate:

$$\overline{dT} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{dT}{dt} \cdot dt = \frac{T(t_2) - T(t_1)}{t_2 - t_1}$$

  - $T(t_1)$ is the initial temperature, $t_1$ is 0, and $t_2$ is the time to thermal equilibrium
  - Curve is asymptotic, never reaches equilibrium
  - Equilibrium temperature is therefore defined as point where the temperature reaches an arbitrary percentage of the total temperature rise
  - Increasing percentage decreases average rate

- 90% was chosen for this work
Heat released by fire is a function of the available air to support combustion.

For typical hydrocarbons:

\[ q \sim 1.35 \times 10^6 \cdot A \sqrt{h} \]

Assuming a circular hole:

\[ q \sim 1.06 \times 10^6 \cdot D^{2.5} \]

Wikström 2016 – “Temperature Calculation in Fire Safety Engineering”
1. Transportation accident
   - Railroad boxcar fires at Corning, Tobar, Benson, and Roseville
   - Slow heating rates reported in the past have included long initial duration before ordnance is actually heated
   - Analyzed test date where boxcars containing simulated bombs were burned
   - Slowest rate recorded during testing was a Mk 81 bomb at $83°C/hr$

2. Dump storage accident
   - Lowest heating rate results from a large, slow moving fire near the storage area
   - Slowest heating rate from simulations, that still reaches cook-off temperatures, is $52°C/hr$

3. Debris pile from deck fire
   - Ordnance is buried within debris pile during and after a fire/FCO event
   - Slowest heating rate from simulations is $52°C/hr$
4. Below deck fire
   - Fire in a compartment adjacent to a magazine which contains ordnance
   - Fire heats common bulkhead which then heats ordnance by radiation
   - Analysis **does not** calculate temperature of air within magazine, only the average ordnance temperature for four different sized munitions
   - Average rate to 150°C for four sizes of munitions was calculated
     - 250 lb – 51°C/hr
     - 500 lb – 29°C/hr
     - 1,000 lb – 17°C/hr
     - 2,000 lb – 7°C/hr
5. Steam leak within magazine

- Intermediate pressure steam saturated at 3100 kPa and 236°C leaks into a magazine, expansion results in superheated steam at 165°C (328°F)
- Condensing steam heats magazine and everything in it to 100°C within 2 hours
- The ordnance (Mk83 1,000 lb bomb in Fontenot’s analysis) then asymptotically approaches 165°C (328°F) steam temperature
- By selecting ordnance temperature arbitrarily close to final temperature (e.g. 327°F), a heating rate of 3.3°C/hr was obtained
- If time to 150°C is used for rate calculation (as in scenario 4) a rate of 8°C/hr is obtained
- Rate is based on ordnance temperature, not surrounding air temperature
- Only 1 steam leak in the literature, no reaction occurred

<table>
<thead>
<tr>
<th>Duration</th>
<th>Temp. (°F)</th>
<th>Rate (°F/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 hrs.</td>
<td>273</td>
<td>20</td>
</tr>
<tr>
<td>15 hrs.</td>
<td>297</td>
<td>15</td>
</tr>
<tr>
<td>25 hrs.</td>
<td>317</td>
<td>10</td>
</tr>
<tr>
<td>35 hrs.</td>
<td>325</td>
<td>7</td>
</tr>
<tr>
<td>45 hrs.</td>
<td>327</td>
<td>6</td>
</tr>
</tbody>
</table>

Temperature table copied from Fontenot report