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GUN & ELECTRIC WEAPON SYSTEMS DEPARTMENT (E)

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

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Overview

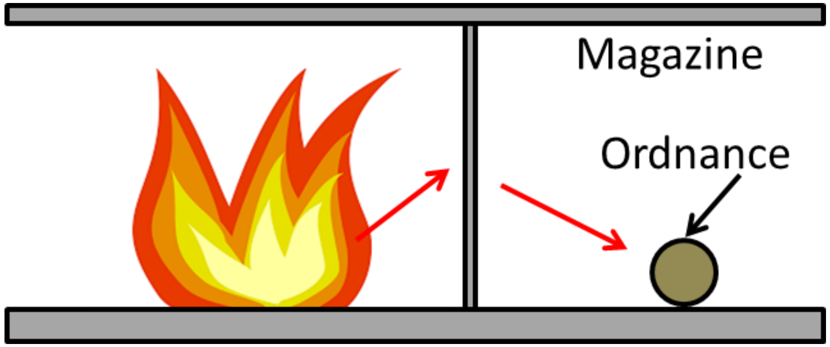
- The Slow Cook-off (SCO) test, as specified by STANAG 4382, specifies a constant heating rate of 3.3°C/hr
- The validity of this 3.3°C/hr heating rate has been questioned
  - Concern that it is too slow to represent accidents
  - Mitigations designed to work at 3.3°C/hr might not work at the higher 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?

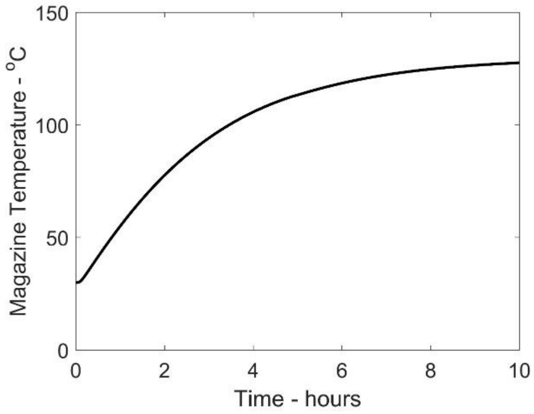
Overview

- 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

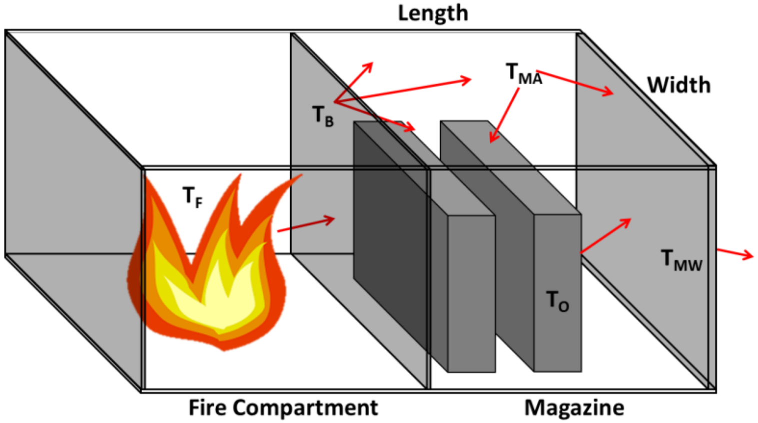
- The goal of the modelling effort was to attempt to determine the slowest heating rates that could result in a cook-off
- A review of existing analysis indicated that the slowest heating rates would result from a fire adjacent to a magazine
- A model was developed to study the fire/magazine system
-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

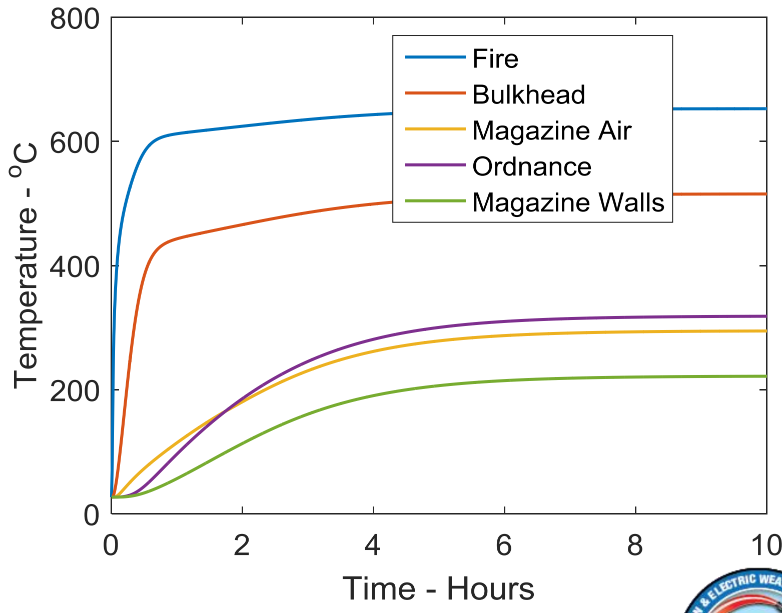




Model Overview

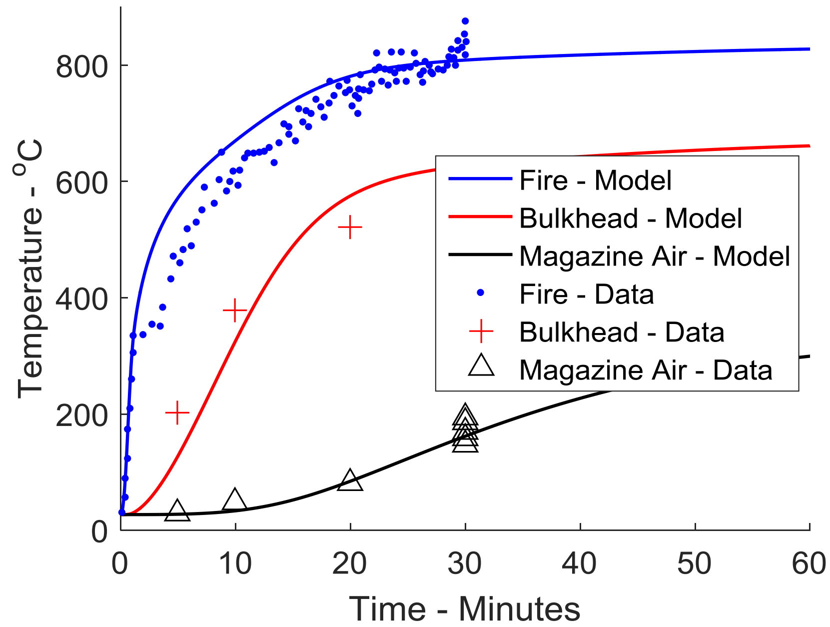
- A model was developed to calculate magazine temperatures during fires
  - Allows varying parameters that would influence the magazine temperature curve
    - Magazine dimensions, ordnance quantity, wall thickness, and fire size
  - Lumped mass model, includes convection and radiation but no conduction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





Model Validation

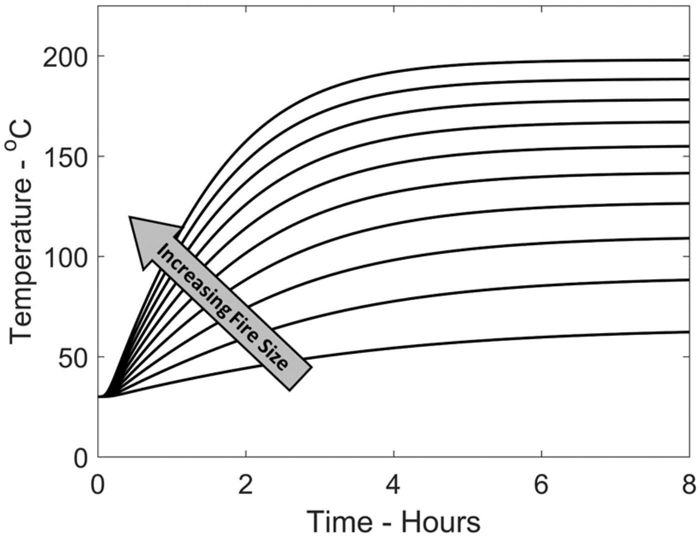
- Data from an instrumented fire aboard EX Shadwell was used to validate model
  - Compartments and fire size modeled based on data given in the report
  - The measured temperatures were compared to model results
- Model agreement with test data is sufficient to allow it to be used to simulate SCO scenarios



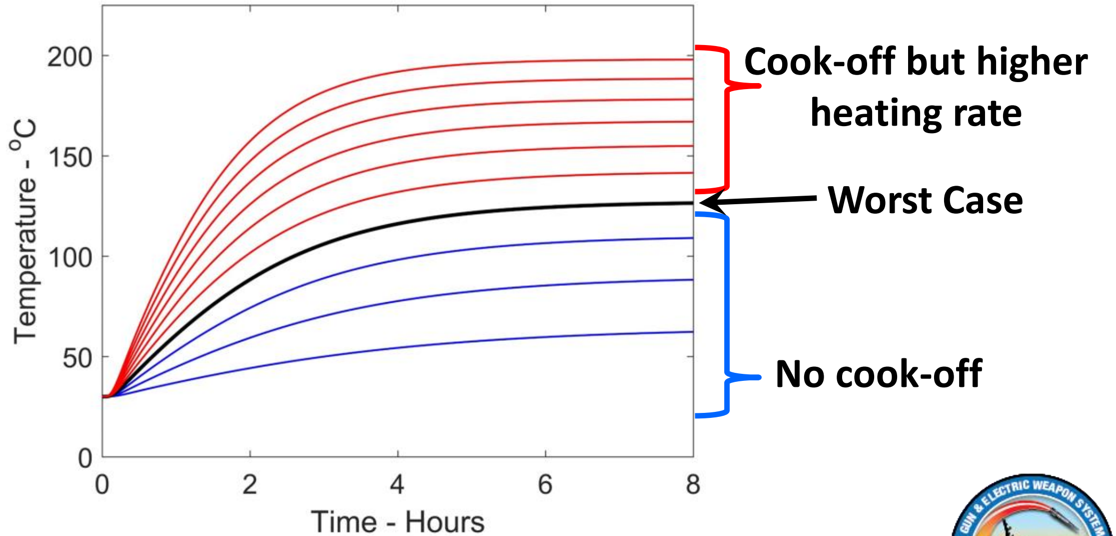
How Model is Used

- 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**

Magazine Gas Temperature History



Worst Case Fire Size

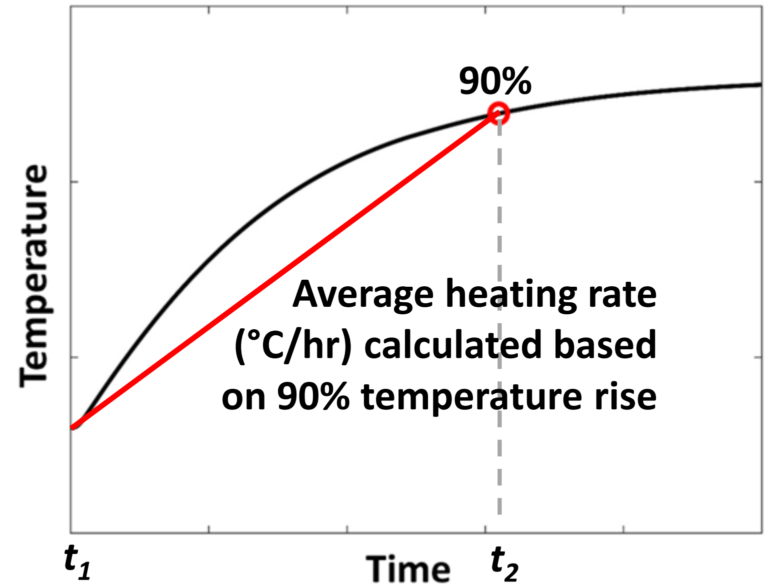


Average Heating Rate Calculation

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

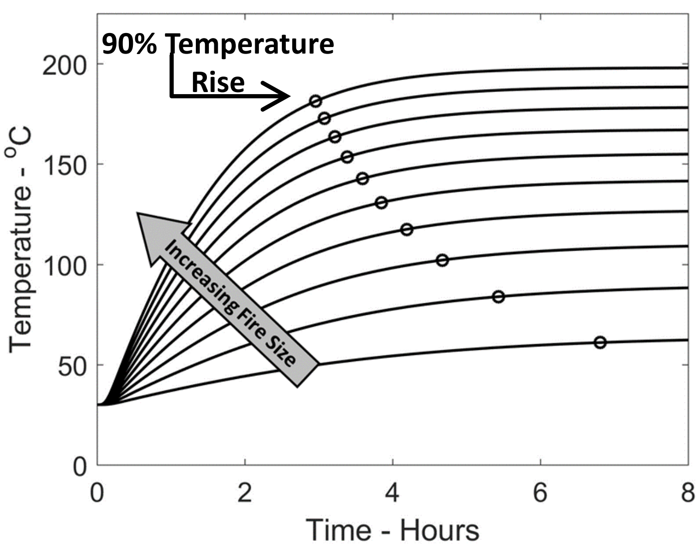
$$\overline{\frac{dT}{dt}} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \frac{dT}{dt} \cdot dt = \frac{T(t_2) - T(t_1)}{t_2 - t_1} = \frac{\Delta T}{\Delta t}$$

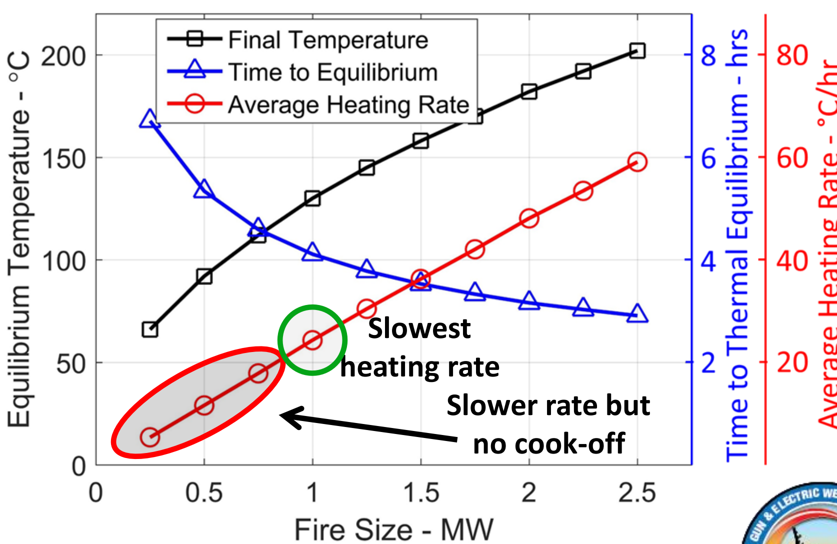
- Must assume an equilibrium temperature, *$T(t_2)$*
  - Equilibrium temperature selected as 90% of total temperature rise
    - Selection ensures conservatism, the higher the value the slower the calculated rate
    - Also, 90% has been used in prior analysis
  - Time to 90%, *t_2*, is then determined and average heating rate (ΔT/Δt) is calculated
  - ➢ **All results are based on a 130°C cook-off temperature and a 90% temperature rise**



How Model is Used

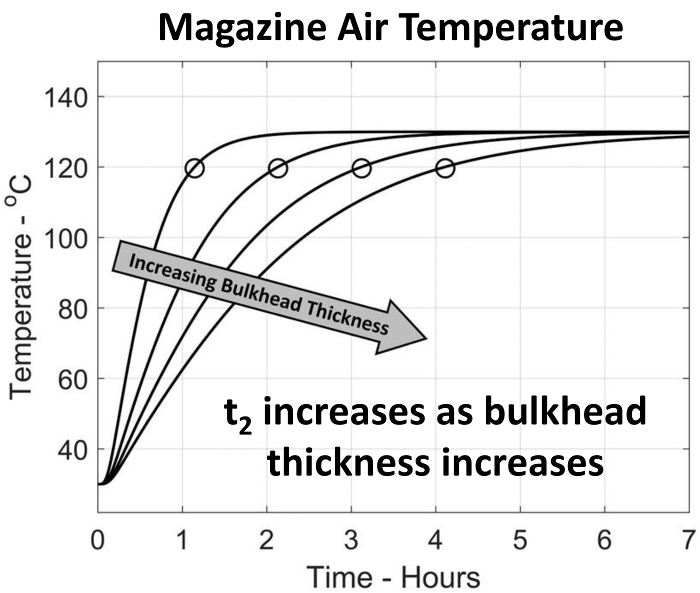
- Example for one particular set of model parameters
  1. Determine the fire size that results in 130°C final magazine temperature, 1 MW in this example
  2. Calculate time to equilibrium, $t_2 = 4.1$ *hrs*
  3. Use t_2 to calculate average heating rate, 24.3°C/hr
  – Note that higher cook-off temperatures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

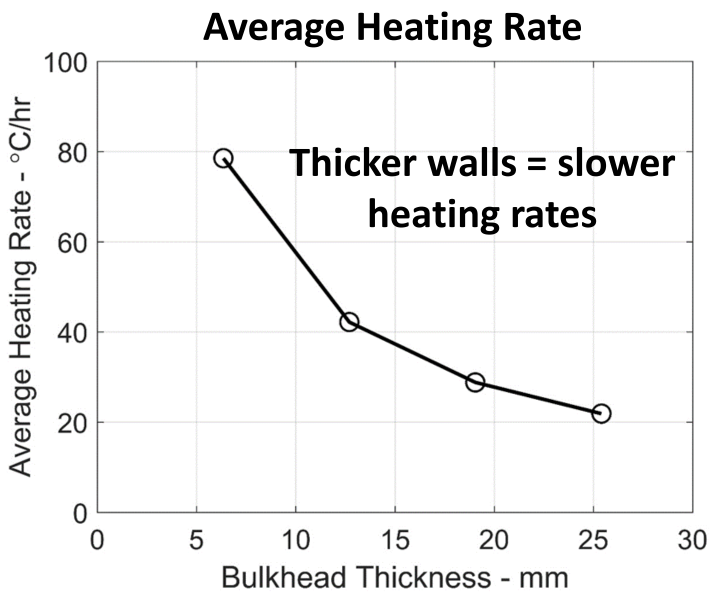




Model Results – Bulkhead Thickness

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

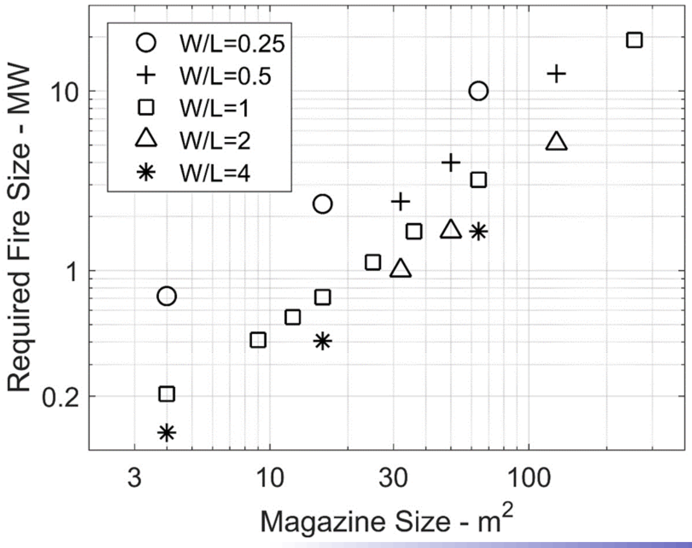




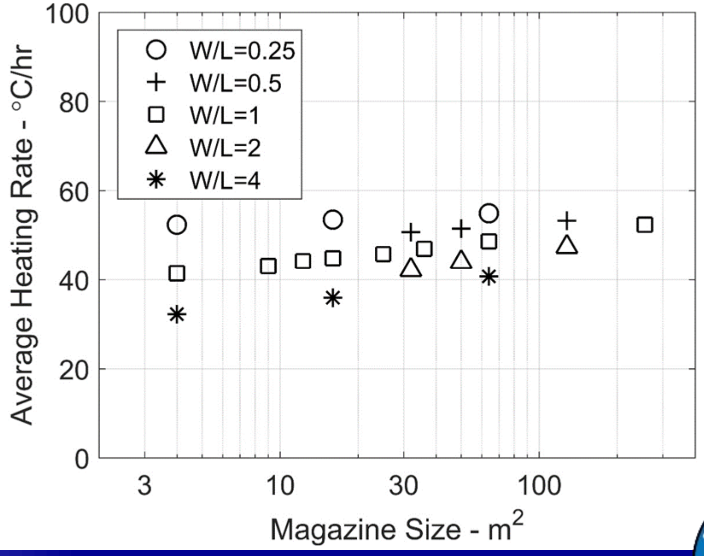
Model Results – Magazine Size

- 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

Magazine Size vs Required Fire Size



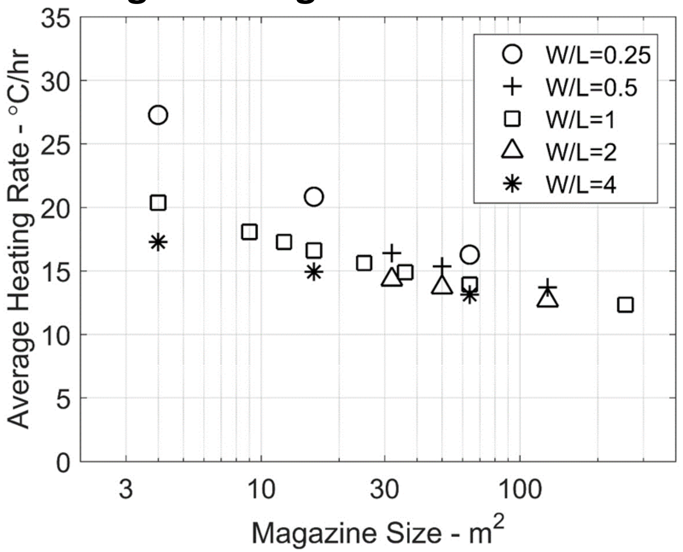
Magazine Size vs Average Heating Rate



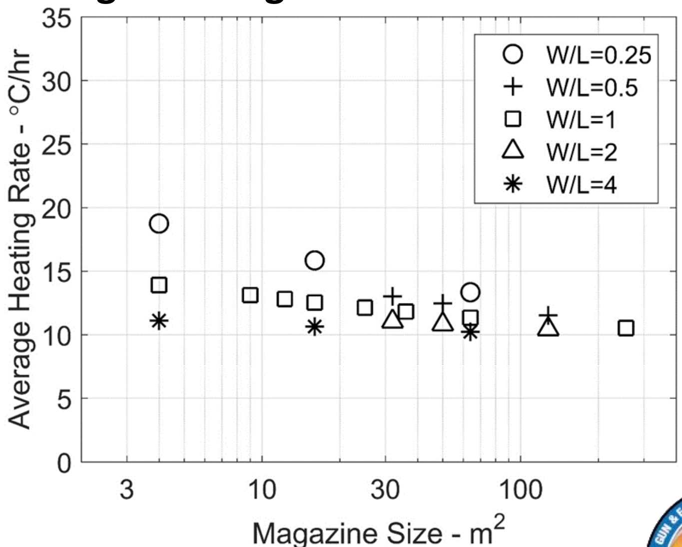
Model Results – Full Magazine

- 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°C/hr** for 12mm walls and **10°C/hr** for 25mm walls

Average Heating Rate – 12mm Bulkhead

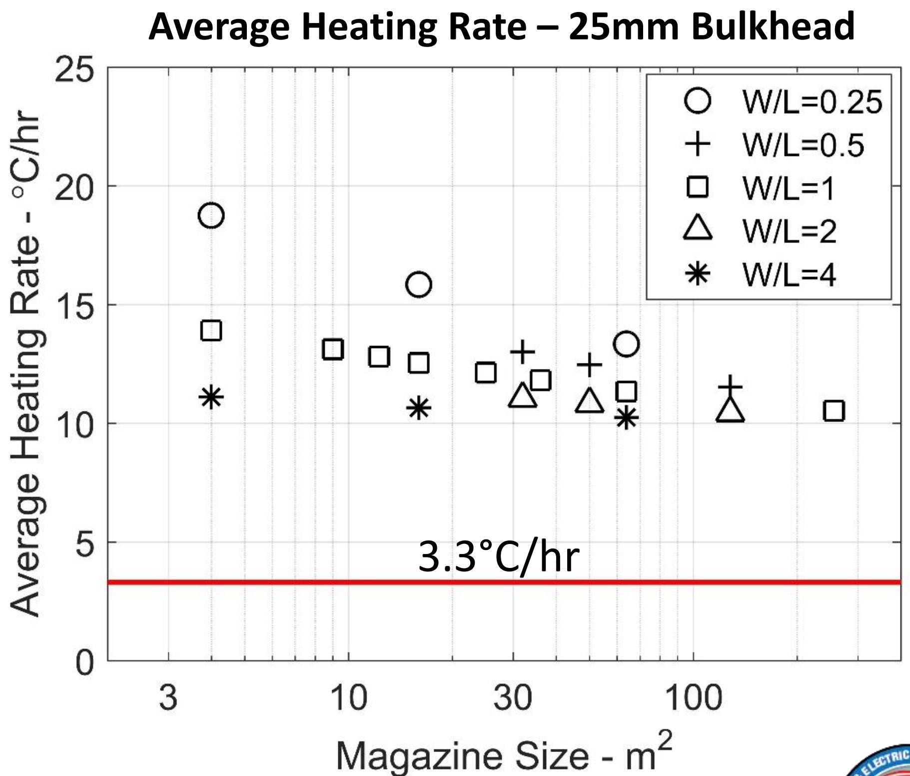


Average Heating Rate – 25mm Bulkhead



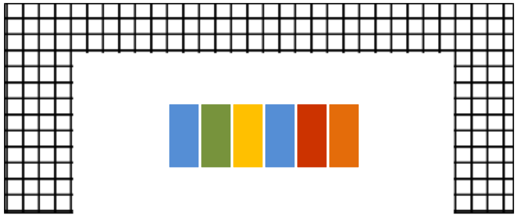
Model Results – Full Magazine

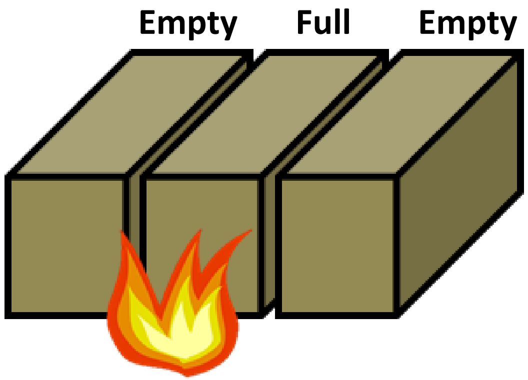
- Slowest heating rates will occur in full magazines with thick walls
- It is **not possible** for a constant sized fire to heat ordnance to cook off temperature any slower than 10°C/hr
  - Only way to get a slower rate would be a fire that gradually increased in size over many hours
  - Below deck fire 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

Funding provided by:

- The Insensitive Munitions Advanced Development (IMAD) Program

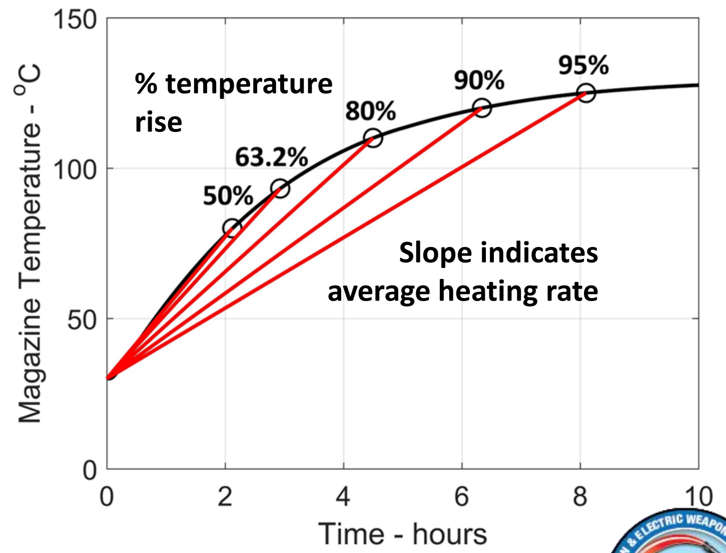
Extra Material

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:

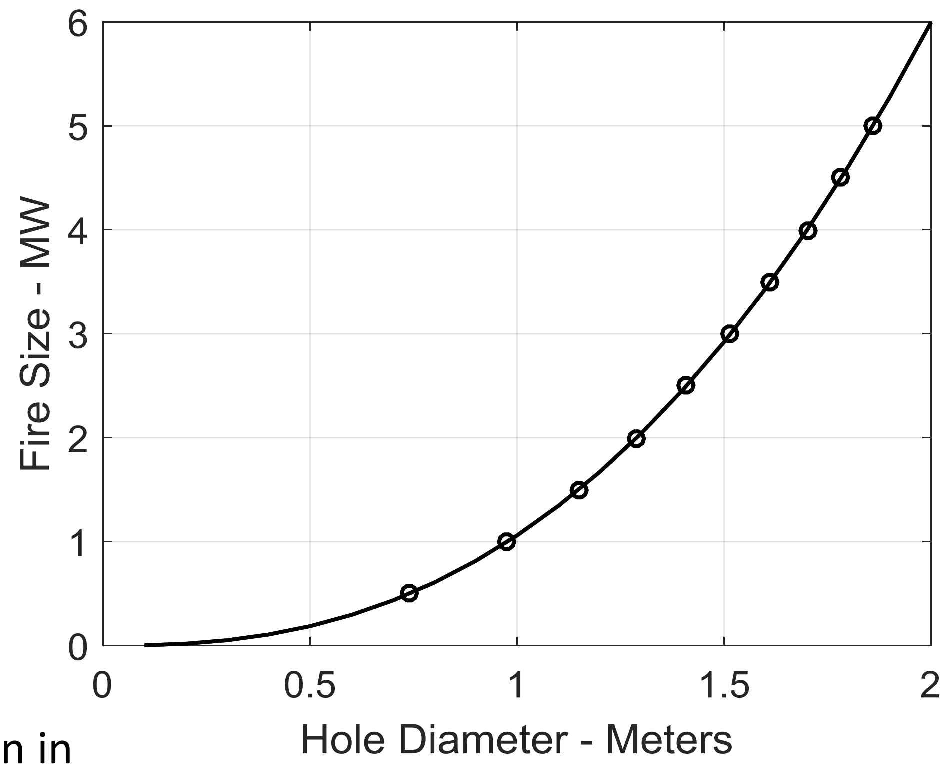
$$\overline{\frac{dT}{dt}} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \frac{dT}{dt}\cdot dt = \frac{T(t_2) - T(t_1)}{t_2 - t_1}$$

  - $T(t_1)$ 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



Fire Size vs Vent Size

- Heat released by fire is a function of the available air to support combustion
- For typical hydrocarbons:
- $q \sim 1.35E6 \cdot A\sqrt{h}$
- Assuming a circular hole:
- $q \sim 1.06E6 \cdot D^{2.5}$



Wikström 2016 – "Temperature Calculation in Fire Safety Engineering"

Fontenot Report

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**

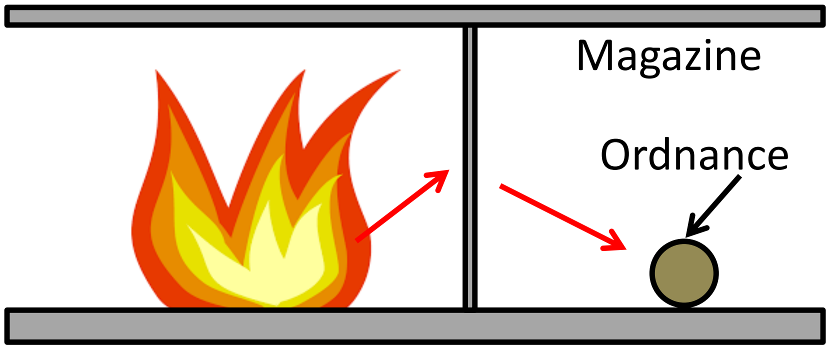
3. Debris pile from deck fire

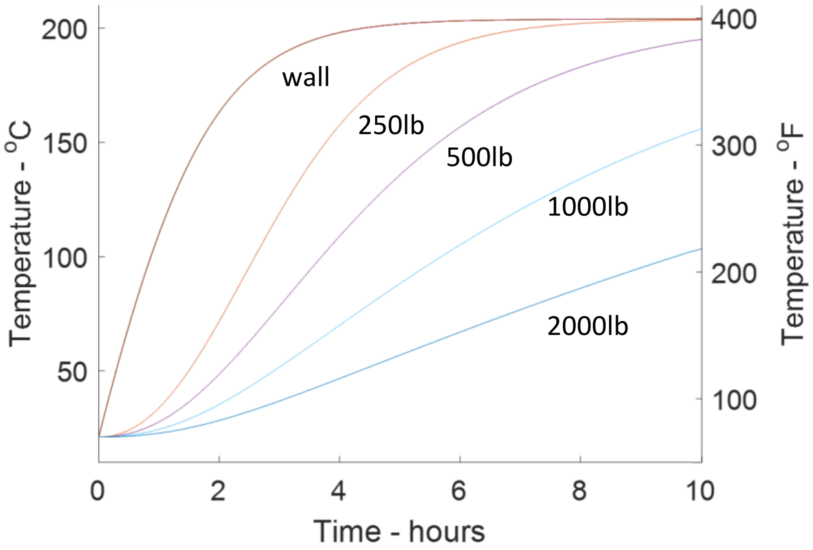
- Ordnance is buried within debris pile during and after a fire/FCO event
- Slowest heating rate from simulations is **52°C/hr**

Fontenot Report cont.

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**

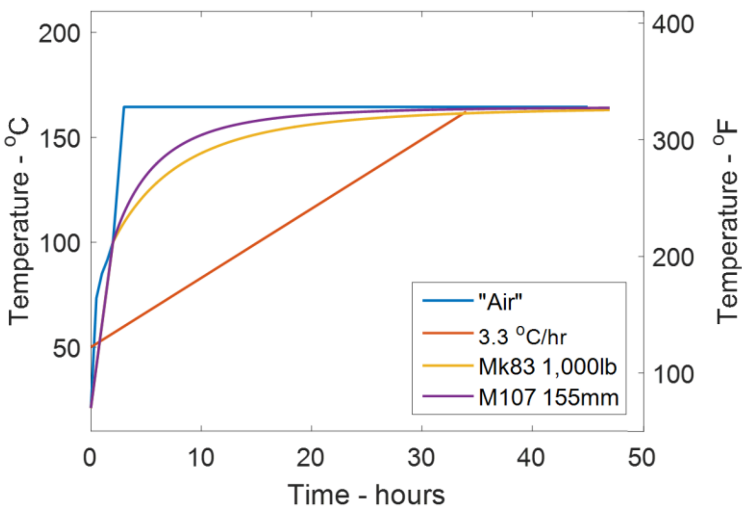




Fontenot Report cont.

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



Duration	Temp. (°F)	Rate (°F/hr)
10 hrs.	273	20
15 hrs.	297	15
25 hrs.	317	10
35 hrs.	325	7
45 hrs.	327	6

Temperature table copied from Fontenot report