Investigating a Proper Heating Rate for the Slow Heating Test Using Documented Incidents
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Background

- Hazard classification testing is performed to assess the potential reaction of Ammunition and Explosives (AE) to specified phenomenon
- One phenomenon studied is exposure to an external thermal stimulus
  - Heating an energetic item can cause it to react, or “cook-off”
  - The rate that the item is heated influences the violence of the reaction

➢ Slow heating often results in a severe reaction because the energetic fill is at a high average temperature when the cook-off occurs
Background

• The Slow Heating Test is performed to simulate accident scenarios in which AE are slowly heated

• Typically, the test is performed by heating the AE in a disposable oven at a rate of 3.3°C/hr until it reacts

• Recently, the validity of the 3.3°C/hr rate has been questioned
  – Is it too slow to represent a realistic threat?
  – Concern that mitigations that are designed to work at 3.3°C/hr might not work at higher, more realistic rates
The SHCWG

• The Slow Heating Custodial Working Group (SHCWG) was formed to review the test standards that govern the slow cook-off test used for Insensitive Munitions testing
  – A key topic for the SHCWG – What should the heating rate be?

• At the first SHCWG meeting there was a general consensus that 3.3°C/hr was too slow but a new rate was not selected
  – This led the chairman of the group to request a thorough investigation be performed to guide the discussion towards realistic threat scenarios
Investigation Overview

• The goal of the investigation was to determine the slowest heating rate that could occur that could lead to a cook-off

• The investigation consisted of both a thermal modelling effort and a review of historical incidents
  – The results of the modelling effort were presented at IMEMTS 2018 in Portland, Oregon

• This presentation will focus on the portion of the investigation that attempted to determine realistic heating rates from actual incidents and accidents

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1 D. O. Hubble, "An Investigation into a Proper Heating Rate for Slow Cook-off Testing," in IMEMTS, Portland, OR, 2018
• Can the heating rate that AE experienced be conservatively estimated from real-world incidents?
  – If the heating duration and the cook-off temperature are known, then the average heating rate can be estimated \((\Delta T/\Delta t)\)
  – Conservative means slowest possible, minimize \(\Delta T\) and maximize \(\Delta t\)
• Unfortunately, in most incidents there are multiple items that react
  – In some cases there are hundreds of reactions over several days
• To simplify the analysis, only the initial reaction was investigated
  – All subsequent reactions were ignored
  – Eliminates the confusion of fire spreading from early reactions
Identifying Incidents

• A major focus of this investigation was to find as many incidents as possible in which heating durations could be estimated
  – Used MSIAC’s MADx database of ~13,000 accidents
  – Analyzed each of the 173 incidents contained in the Boggs et al.² report
  – Additional independent incident review

• These sources rarely contained the information needed to estimate durations but were crucial in identifying cook-off incidents (when and where)
  – Heating details were then obtained from other sources
  – Relied heavily on old news reports to determine heating durations

Maximum Time to 1st Reaction

• While the actual time to initial reaction is rarely documented, there is often enough information to conservatively estimate the amount of time that elapses prior to the first reaction
  – Example: “fire started at 0330, explosions heard during the morning”
  – Know when the fire started and that explosions started before noon so: 
    1200 - 0330 = 8.5 hrs max

• This estimate is the “Maximum Time to First Reaction” \( (t_{\text{max}}) \)
  – This can then be used to conservatively estimate the average heating rate \( (\Delta T/t_{\text{max}}) \) experienced by the first item that reacted
  – Ensuring the duration estimation is high \( (t_{\text{max}}) \) is conservative because it ensures the slowest possible calculated heating rates
Incident Review

- In total, 158 incidents were found where a heat source existed, ordnance was present, and $t_{\text{max}}$ could be obtained.
- Incidents sorted into 5 categories:
  - Depot, ship, plant, transport, and vehicle.
- Incidents span over 100 years:
  - Primarily after 1980 with the exception of documented WWII incidents.

![Incident Distribution Graph]

Year That Identified Incident Occurred

- # Identified per Decade
Incident Duration Data

- Durations shown on a log time scale on bar chart
  - Heating begins at $t=0$
  - Sorted by increasing $t_{\text{max}}$
    - Left arrow means only time to end is known
    - Right arrow means only $t_{\text{max}}$ is known
    - Filled region means $t_{\text{max}}$ and time to end are both known
- Data allows conservative estimation of heating duration prior to initial reaction for 158 incidents

Can only estimate time to end
Sorted by $t_{\text{max}}$
Can only estimate time to 1st
Estimate both start and end time

.1 1 10 100 400
Time from start - Hours
Cook-off Temperature

• In most cases the type of energetic item is not reported
• Since the cook-off temperature is unknown, it must be assumed
• To ensure a conservatively low heating rate estimation, the cook-off temperature should be as low as possible
  – $\Delta T/\Delta t$, already maximized $\Delta t$, now minimize $\Delta T$
• For this investigation, a cook-off temperature of 130°C was used with an initial temperature of 30°C
  – 130°C is lower than any cook-off temperature ever measured during testing at Dahlgren

➢ In each case, $\Delta T$ is assumed to equal 100°C
Estimating Heating Rates

- Use $t_{\text{max}}$ and $\Delta T$ to estimate average heating rates
- Implied assumptions (blue line)
  - Heating begins when fire starts
  - Cook-off after 100°C rise
  - Cook-off occurs at $t_{\text{max}}$
- Most conservative estimate
  - For each case, actual heating rate could be faster **but not slower**
    A. Reaction before $t_{\text{max}}$
    B. Delayed initial heating
    C. Higher cook-off temperature

➢ Any possible green line will be steeper than the blue line
Estimated Heating Rates

Each point represents the slope of the “blue line” for that incident.

Possible rates from data “green lines”

Not possible

3.3°C/hr
Heating Rate Probabilities

- Determine, for any given heating rate, the minimum percentage of incidents that are faster than that rate
  - From curve fit to data, **at least** 92% of the initial reactions were heated faster than 15°C/hr
  - A test performed at 15°C/hr would subject a **minimum of 92%** of these items to a **slower heating rate** than they actually experienced
Incident Review Conclusions

• A review of historical incidents was performed and 158 cases were identified in which the time to 1st reaction could be conservatively estimated

• These durations were used to calculate average heating rates based upon a conservative temperature rise of 100°C

• The results show that in over 92% of these cases the initial reaction occurred after the ordnance item was heated faster than 15°C/hr

• The current rate of 3.3°C/hr is far slower than any of the heating rates indicated by the incident investigation

• Based partially on these results, the test standard that defines the Slow Cook-off Test is currently being revised to specify a heating rate of 15°C/hr
Acknowledgments

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