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

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Abstract

Historically, slow cook-off (SCO) testing has been performed by heating the munition under test in an oven at a constant rate of 3.3°C/hr until a reaction occurs. Recently, however, the validity of this heating rate has been disputed and it has been argued that it is too slow to represent a realistic threat scenario. While many agree that the heating rate should be increased, there has been no real consensus on what the new rate should be. This investigation was performed to help determine what heating rates are possible for munitions and to help select a more appropriate heating rate for future SCO testing. This was done by examining historical accidents, reviewing existing analysis, and modelling possible threat scenarios. In the course of this analysis, no data was found or generated which supports a rate as slow as 3.3°C/hr and it is concluded that a heating rate faster than 10°C/hr is more appropriate and better represents real-world threats to munitions.

Background

SCO testing is performed to simulate accident scenarios in which a munition is slowly heated over an extended period of time. This can result when a fire occurs but is separated from the munition by some barrier such as the walls of a magazine. This is in contrast to a fast cook-off (FCO) where the munition is directly exposed to the fire. In a SCO scenario, the heat fluxes into the item are much smaller than in the FCO and the resulting temperature gradients are much lower. Therefore, if the munition cooks off, the reaction can be severe because much of the energetic material is at an elevated temperature when the cook-off occurs. This elevated temperature can cause normally stable energetics to detonate during slow heating. SCO testing is therefore necessary to help developers improve the response of munitions to this type of thermal threat and ensure that any reaction that occurs is as mild as possible.

The current SCO test procedure, as outlined in STANAG 4382, specifies that the munition be heated in an oven wherein the air temperature is increased at a constant rate of 3.3°C/hr (6°F/hr) until the item reacts. There is also a provision that allows a different heating rate to be selected (procedure 2) based on a threat hazard assessment (THA), but the test generally defaults to the 3.3°C/hr rate specified in procedure 1. In addition to the ramp rate, other parameters such as item preconditioning and temperature gradients within the oven are also specified in the test standard. A passing criteria is a reaction violence no more severe than burning (type V).

The origin of the 3.3°C/hr heating rate is not known for certain. Some point to ship fires during WWII that exploded up to 2 days after suffering below deck fires. By dividing the predicted cook-off temperature by the fire duration a heating rate of approximately 3°C/hr can be obtained. Others have speculated that the slowest possible heating was desired and 3.3°C/hr was simply as slow as oven controllers could reliably function at the time. Regardless of the origins, the SCO test has primarily been performed at a rate of 3.3°C/hr for more than 50 years. Recently, however, there has been increasing pressure to change the document so that the rate specified in procedure 1 better represents realistic heating scenarios. The concern is that an item that has been designed to pass the 3.3°C/hr heating rate of the SCO test could react more violently at the higher rates that the item is more likely to encounter while in service.

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In the spring of 2016, AC326 approved the formation of the Slow Heating Custodial Working Group (SHCWG) to investigate the SCO heating rate and to revise STANAG 4382, creating a new Allied Ordnance Publication (AOP). At the first SHCWG meeting in Utrecht, Netherlands in April 2017, the topic of changing the heating rate was debated. Unfortunately, there was much disagreement among the participants as to what analysis had previously been done and what relevant accidents had occurred which made agreement on an appropriate heating rate impossible. This then led the AC326 subgroup B chairman to request that a study be performed which would summarize any SCO related accidents and previously performed SCO analysis to be presented at the subsequent SHCWG meeting. Additional modelling was also to be performed to specifically examine SCO heating rates. This material was meant to present facts to the group and help guide the discussion towards realistic threat scenarios. This paper presents the results of the requested study. These results were, in part, presented at the 2nd SHCWG meeting which was held in Brussels, Belgium in September 2017. This paper also includes work that was completed after the September meeting.

Investigation Overview

The investigation that was performed was done in three stages.

1. A review of historical incidents
2. A review of existing SCO related analysis
3. Additional modelling of SCO scenarios

The goal of this investigation was to determine the slowest possible heating rate that an ordnance item could experience in service that could result in a cook-off.

Incident Review

The goal of the incident review was to attempt to predict a lower bound for potential SCO heating rates from historical accounts of incidents involving explosives. By estimating cook-off temperatures and the total heating duration, the average heating rate could be calculated by dividing the temperature rise by the total heating time ($\Delta T/\Delta t$). Therefore, the primary goal of the incident review focuses on determining total heating duration prior to reaction.

In order for an item to experience a SCO while in service, it must be heated for an extended duration. In an attempt to determine realistic heating durations, a review was conducted to identify as many incidents as possible where explosives were subjected to heating. These were then sorted based on incident type and heating duration. A large number of the incidents examined were found in the paper by Boggs et al. (Thomas L. Boggs, 2013). Additional incidents were found using a variety of sources including the accident tool on MSIAC's web portal (MSIAC, 2017). In all, over 200 incidents were examined spanning from 1907 to 2015.

Since cook-off is the primary focus of this work, only incidents that involved some type of thermal threat were desired. Of the incidents that were identified there were 138 in which a fire was the initial reaction or a fire was created by the initial reaction or attack. In other words, 138 incidents were found where either a cook-off occurred or the potential for a cook-off existed for at least some period of time. Of these 138 incidents, 83 were documented in sufficient detail to determine the total heating duration. Typically, this means that both the time that the heating started and the time that the event concluded were both reported. Note that the event can conclude in a variety of ways. Examples include: the fire was extinguished, the factory exploded, or the ship sunk. By defining the heating duration in this way, a very conservative (long) heating duration is obtained because it assumes that the munition is heated for the entirety of the heating event.

Of the 83 incidents identified, 10 involved bulk explosive material such as ammonium nitrate or ammonium perchlorate. Since the focus of the SHCWG is the testing of military explosives, it was decided to remove these from consideration. These refinements resulted in 73 incidents that involved military explosives where a cook-off was possible and where it was possible to at least put an upper bound on the heating duration. Finally, these 73 incidents were sorted by type:

1. Depot – incident occurred at a military facility where munitions are stored
2. Warship - incident occurred on a military ship other than a transport ship
3. Transportation - incident occurred while transporting energetics by truck, train, or ship
4. Plant - incident occurred at a production facility where energetics are manufactured

The bar chart in Figure 1 shows the total duration of the 73 incidents while the pie chart shows the distribution by type. Figure 1 demonstrates that the vast majority of the incidents occurred either at depots (34) or on warships (31) and only 5 transportation and 3 plant incidents were found. It is also apparent that incidents on warships are more likely to have a shorter duration as compared to depots. This is due to the way these fires are fought. When a fire occurs at a depot, firefighting efforts are typically abandoned very early on and the fire is left to burn out on its own which, in some cases, can take up to a week or more. On a ship, however, this is not an option and the fire is fought ferociously.

As can be seen, the incident durations span from 15 minutes all the way to 312 hours. In nearly all of these cases, the type of ordnance present is not identified and in many cases a variety of munitions are present. Therefore, to obtain a conservatively slow heating rate, a low cook-off temperature of 130°C is assumed for each case. A temperature of 130°C is based on the lowest cook-off temperatures seen in SCO testing for double base propellants. High explosives typically have higher cook-off temperatures and would result in faster calculated heating rates. If an initial temperature of 30°C is assumed (giving a $\Delta T=100°C$) then the heating durations in Figure 1 result in heating rates ranging from 400°C/hr to 0.3°C/hr with an average value of 59°C/hr and a median value of 22°C/hr.

The preceding analysis assumes that the ordnance was heated for the entire incident duration. In actuality this is almost certainly not the case. In practice, it is impossible to determine how long any particular munition was heated prior to reacting. For example, consider the Roseville, California train accident in 1973. Here, a train that contained 21 boxcars loaded with 7,056 Mk81 250 lb bombs caught fire. The total incident duration, from fire ignition to last explosion, was 33 hours. If this heating duration is used to obtain an average heating rate a value of approximately 3°C/hr is obtained. But, was the last bomb that exploded actually heated for 33 hours? Of course not, the fire moved from one car to the next causing explosions along the way. In fact, the only information that can be known with certainty is that no munition was heated for *longer* than 33 hours. This example demonstrates the difficulty in determining a heating rate from accident data.

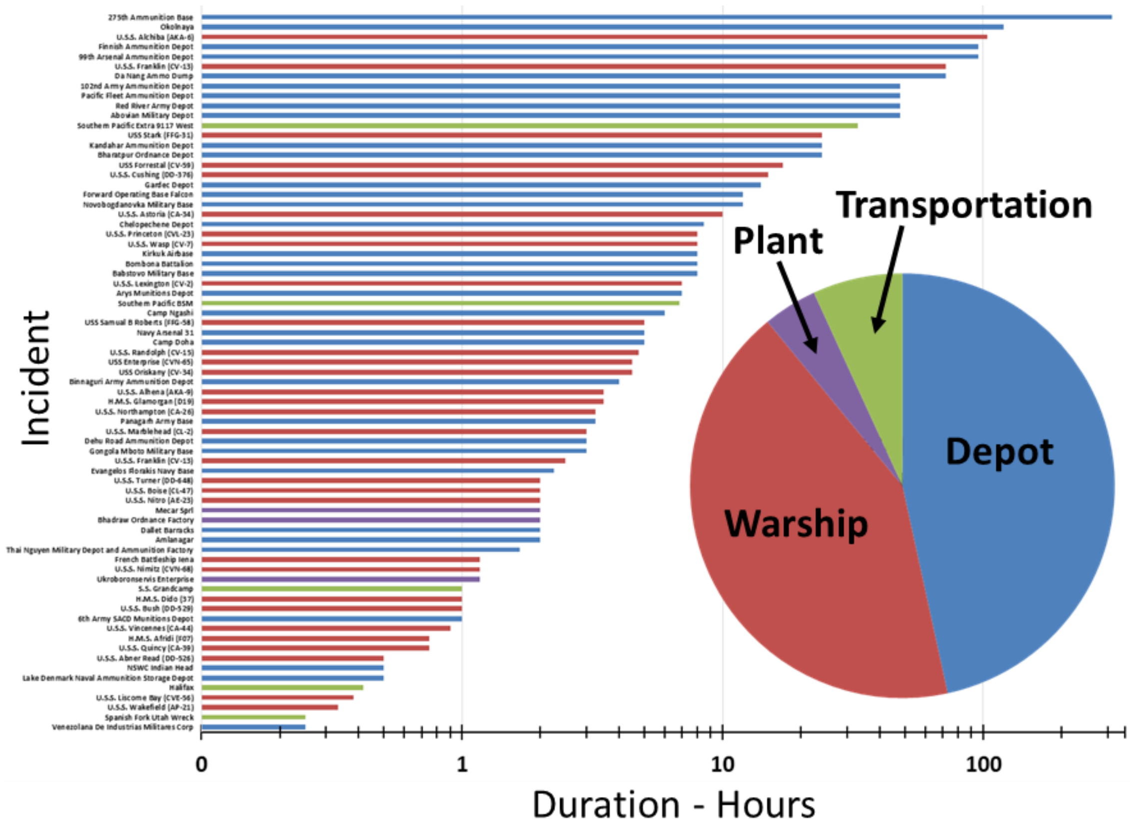

Figure 1: Plot showing the distribution of incident type and duration

In many of the incidents studied, there were multiple explosions throughout the total incident duration. These initial explosions make it difficult to draw any conclusions about the heating rate that led to later reactions because it is known that the initial reactions spread the fire from one area to another. One way to avoid this confusion is to look at the time from the fire ignition to the *initial* reaction. While it is still impossible to know if the first item that reacts was heated for this entire time, at least it is known that no earlier reactions contributed to it reacting. Unfortunately, the time from fire ignition to initial reaction is rarely known as shown in Figure 2. The information needed to determine the time to initial reaction was only available in 14 of the 73 incidents under review. However, it is worth noting that the longest duration found to initial reaction was just over 2 hours. If this value is used, along with the conservative cook-off temperature of 130°C used above along with the assumed initial temperature of 30°C, a heating rate of 44°C/hr is obtained which is a full order of magnitude faster than the currently specified rate. While this sample size is much too small to draw any real conclusions, it points to the possibility that the appropriate heating rate might be much faster than the 3.3°C/hr that is currently used for SCO testing.

Regrettably, most of the incidents that were examined were not documented in enough detail to accurately predict the heating rate that the munitions experienced prior to reacting. For this reason, the data available from actual incidents is sorely lacking. Instead, we must rely on models and analysis to determine what realistic SCO heating scenarios exist. These models can then be used to help determine the slowest possible heating rates that could result in a cook-off.

Review of Existing Analysis

One of the first attempts to analyze potential slow heating scenarios was done by Fontenot and Jacobson in 1988 (Jacobson, 1988). At this time the SCO test was an existing standard safety test and they were specifically trying to identify scenarios that could create the 3.3°C/hr heating rate that was already being used in the test. Through the course of their analysis, they identified and examined 5 scenarios that could result in the slow heating of munitions:

1. Transportation accident – truck or train fire
2. Dump storage accident – a fire moving past an ammunition storage area
3. Debris pile from a deck fire – aftermath of a FCO event
4. Below deck fire – fire heats the bulkhead of a storage magazine in a ship
5. Steam leak – steam leaks into a magazine on a ship and heats ordnance

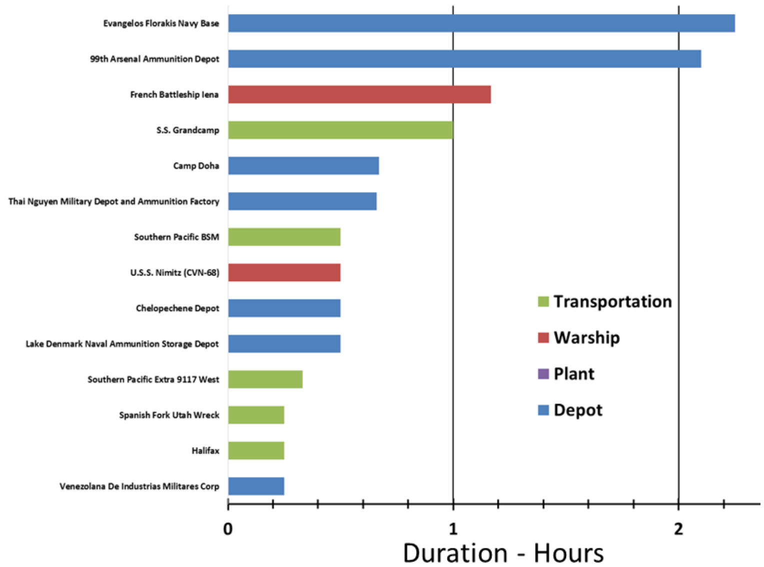

Figure 2: Time from fire ignition to initial reaction

For each of the five scenarios, mathematical models were constructed and the slowest possible heating rates that would result in ordnance temperatures of at least 150°C were identified. It was found that scenarios 1-3 all resulted in the slowest heating rates being on the order of 50-80°C/hr. For scenarios 4, the below deck fire, the ordnance item was allowed to exchange radiation with a bulkhead which was being heated on the backside by a fire. The heating rate was calculated for four different sized munitions ranging from 250lb to 2,000lb. As one would expect, the larger munitions heated more slowly and the slowest heating rate obtained was 7°C/hr. It is worth noting that in this analysis the ordnance temperature was examined but not the temperature of the air surrounding the ordnance.

The final scenario examined an intermediate pressure (saturated at 3100kPa and 236°C) steam leak into a magazine. The steam would expand to superheated steam at 165°C which would condense within the magazine and heat everything within it to 100°C within the first 2 hours. The ordnance would then experience convective heating and asymptotically approach 165°C. After 45 hours a 1,000lb bomb would reach 164°C and by dividing the temperature change by this duration a heating rate of 3.3°C/hr was obtained. Here it is worth noting that the selection of 164°C as the final temperature was somewhat arbitrary and if 150°C had been selected, as was done for the previous scenarios, then a heating rate of 8°C/hr would have been obtained. Also, as in scenario 4, again the ordnance temperature was examined and not the temperature of the surroundings. Since a SCO test controls the surrounding air temperature perhaps that is a more important parameter to examine in real-world scenarios.

In a later report, Mansfield (Mansfield, 1996) identified the below deck fire as the most likely scenario that would result in a SCO and created a computer model that allowed it to be examined in detail. Specifically, the model allowed parameters such as fire size, bulkhead thickness, fire compartment size, magazine size, and soot concentration to be varied. For each set of parameters, the model was run and the temperatures of the fire compartment, the common bulkhead, and the magazine gas were calculated as a function of time. In this way, the effect of each parameter on the magazine gas temperature could be determined.

Mansfield's analysis allowed several interesting trends to be observed. First, in general, larger fires create higher heating rates and higher final temperatures compared to smaller fires. Another way of looking at this is all else being equal, a larger fire gets the magazine hotter quicker. Second, thicker bulkheads result in slower heating rates. Third, the size of the magazine did not significantly affect the response time of the magazine gas. Therefore, the slowest magazine gas heating rates will occur when a small fire exists and is separated from the magazine by thick walls. However, if the fire is too small, it will not create temperatures high enough within the magazine to create a cook-off. When a minimum final gas temperature of 150°C is considered, the longest time found to reach equilibrium was 8 hours. If an initial temperature of 30°C is assumed, this analysis results in an average heating rate of 15°C/hr ([150°C-30°C]/8hrs) which is significantly faster than the 3.3°C/hr currently being used.

Additional Modeling

Mansfield's analysis did a good job of studying the fire-magazine system but that analysis wasn't specifically trying to determine worst case heating rates. The current work expands upon this existing analysis in an attempt to help the SHCWG determine realistic worst case (slowest heating rate) scenarios that could result in a cook-off.

The Model

A simple thermal model was developed that is loosely based on Mansfield's work. Figure 3 shows an overview of the system that was modeled and the heat paths used. There are five temperatures histories calculated by the model: the fire compartment temperature T_F, the bulkhead temperature T_B, the ordnance temperature T_O, the magazine air temperature T_{MA}, and the magazine wall temperature T_{MW}. Each of these is modeled using the lumped capacitance assumption that each item is at a uniform (not constant) temperature. This was done to greatly simplify the approach instead of performing a full finite element model for each of the items modeled. This simplification also allowed each run of the model to be completed on the order of seconds. A number of simplifying assumptions were used in order to create a model that would be useful. First, it is assumed that all the walls of the fire compartment are at the same temperature as the bulkhead. That is, the energy from the fire is evenly distributed to the entire fire compartment area and all the walls have identical backside heat loss. Second, the magazine walls (with the exception of the common bulkhead) loose heat by convection and radiation to an infinite sink that is at the initial temperature. This implies that there isn't an additional compartment beyond the magazine. This may or may not be true depending on the ship layout. Third, the maximum ordnance loading density in the magazine is 700 kg/m^2. This was based on estimates for stack height and minimum clearances around stacks. In the model, the quantity of ordnance (loading ratio) was then varied from 0 to 100% of this loading density. Estimates had to also be made concerning the surface area of the ordnance. Here it was assumed that when fully loaded, for each m^2 of floor area, the ordnance surface area was 8 m^2.

Again, this was based on rough estimates after analyzing several different classes of munitions from bare rounds and bombs to munitions in boxes. The specific heat of the ordnance was also required in order to determine its thermal mass. For this analysis, a value of 300 J/kgK was used as it lies between the values for steel (434 J/kgK) and most explosives (~230J/kgK). Also, it was assumed that the fire size was constant with time and continued to output the same amount of heat. A real fire could grow or shrink over time in any number of different ways which would greatly increase the complexity of an already difficult problem. Finally, estimates had to be made to determine the view factor from the common bulkhead to the ordnance. Since the ordnance is likely to be stacked near the bulkhead, the view factor was assumed to be 0.75 times the loading ratio That is, when fully loaded, 75% of the radiant energy leaving the bulkhead impacts the ordnance and the remaining 25% reaches the magazine walls. As the loading ratio decreases, the stacks become shorter and more of the radiant energy is allowed to reach the magazine walls. Once this view factor was assumed, all of the remaining view factors could be calculated using standard procedures based on the defined geometry of the compartments.

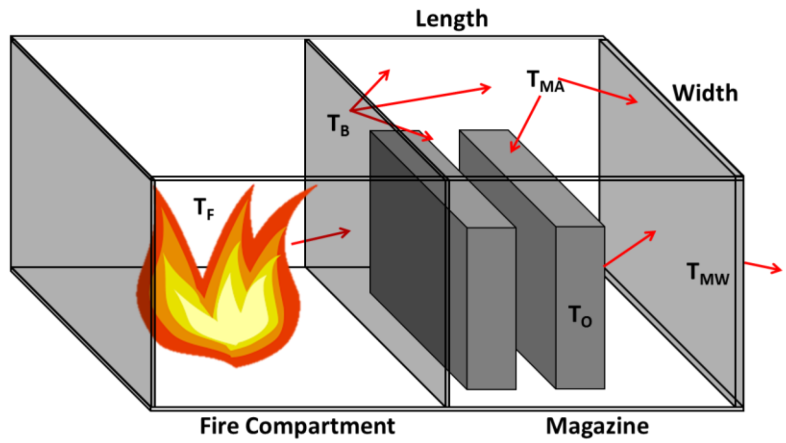

Figure 3: Overview of thermal model. Heat flows from the fire to the common bulkhead and then to the ordnance, magazine gas, and magazine walls.

For each of the five lumped masses that were analyzed, an energy balance was performed. The fire compartment temperature was modeled based on the correlations given by (Wickstrom, 2016). For any given fire size (q_{in} - Watts) the mass flow rate of air that is required to support combustion ($\dot{m}$) can be calculated. This air must be supplied to the compartment, heated to the current fire compartment temperature, and then exhausted, carrying heat with it. Heat is also lost to the common bulkhead by convection and radiation from the compartment gas. For the radiation component, Wickstrom recommends assuming that the fire have an emissivity of 1 and the calculation is therefore straight forward. The convection heat transfer coefficient between the fire and the wall is also based on correlations found in Wikstrom's book and is calculated as:

$$\bar{h} = 76 \cdot [(T_F + T_B)/2]^{-0.66} \cdot |T_B - T_F|^{0.66}$$

Here, *h* is in W/m^2K and the temperatures are in Kelvin. The convection coefficient between the magazine gas and the bulkhead, ordnance, and magazine walls were all calculated using this same correlation. The convection between the fire compartment and the bulkhead as well as the convection on the outside of the magazine walls were also calculated using this correlation.

The mass of gas (m_{gas}) in each compartment was based on the volume of the compartment and the density of air calculated at the previous time step's temperature. The specific heat (C_p) of the gas was also allowed to vary based on the temperature, again based on the previous time step temperature for that region. The lumped heat capacity equation for the fire compartment is then:

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_{stored}$$

$$\dot{q}_{in} - \dot{m} \cdot C_p \cdot (T_F - T_\infty) - h \cdot A \cdot (T_F - T_B) - \sigma \cdot A \cdot \left({T_F}^4 - {T_B}^4\right) = m_{gas} \cdot C_p \cdot \frac{dT}{dt}$$

Once an energy balance was created for each of the five lumped masses, a set of explicit finite difference equations were created. Care must be exercised when solving explicit finite difference equations that stability is maintained. In this work, it was found that a time step of 1 second was sufficiently small to ensure stability for all the cases analyzed.

Model Validation

As a qualitative validation of the model's performance, it was used to simulate an instrumented ship fire. In the work of Bailey and Tatum (Bailey, 1995), a fire that was set aboard the Ex-USS Shadwell was described in sufficient detail to be duplicated using the simple lumped mass model. Here, a 9MW diesel fire was allowed to burn in a compartment for 30 minutes while the temperatures of the fire compartment gas, common bulkhead, and adjacent compartment gas were measured. The results of the model and the data obtained during the test fire are shown in Figure 4. While the agreement is not perfect it is good considering the simplicity of the model.

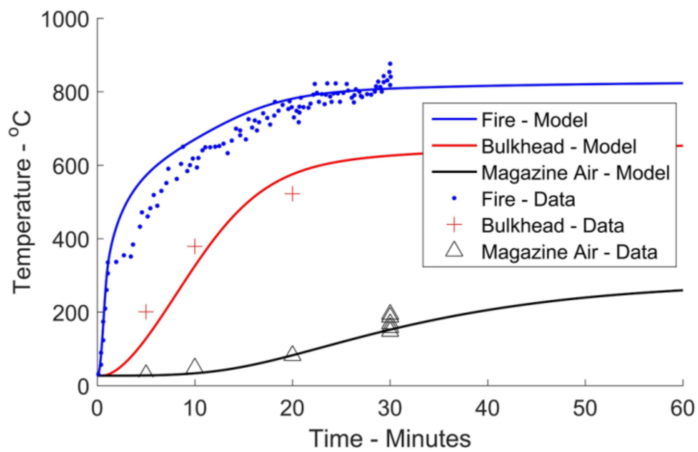

Figure 4: Comparison of model results to data obtained during a 9MW fire aboard the Ex-USS Shadwell

Model Results

The independent variables that were varied during the investigation were the fire size (q_{in}), the physical size of the fire compartment and magazine, the thickness of the walls, and the load ratio. For each combination of these parameters the model was run resulting in 5 temperature-time curves. Since the SCO test mimics the magazine gas temperature, the magazine gas temperature curve is of most interest and it will be used to calculate average heating rates. As shown in Figure 5, the magazine gas temperature curve is asymptotic and has a slope (dT/dt) that is continuously changing. Therefore, to determine the average rate of change, a threshold final temperature value must be selected. This is done as a percentage of the total temperature rise. In the right plot in Figure 5, five different selections from 50% to 95% temperature rise are shown. As can be seen, the selection has a significant effect on the value of the average heating rate as indicated by the different slopes of the red lines. For this particular case, selecting 50% temperature rise gives an average heating rate of nearly 24°C/hr while selecting

95% yields 12°C/hr. This is quite a large variation and demonstrates the difficulty in simulating a continuous curve with a straight line. For this work, a value of 90% was selected and all average heating results are calculated using the 90% temperature threshold. A value of 90% was selected for two reasons. First, the higher the value selected the more conservative (slower average heating rate) the results will be. Second, 90% was the value selected by Mansfield and this consistency allows the results to be directly compared.

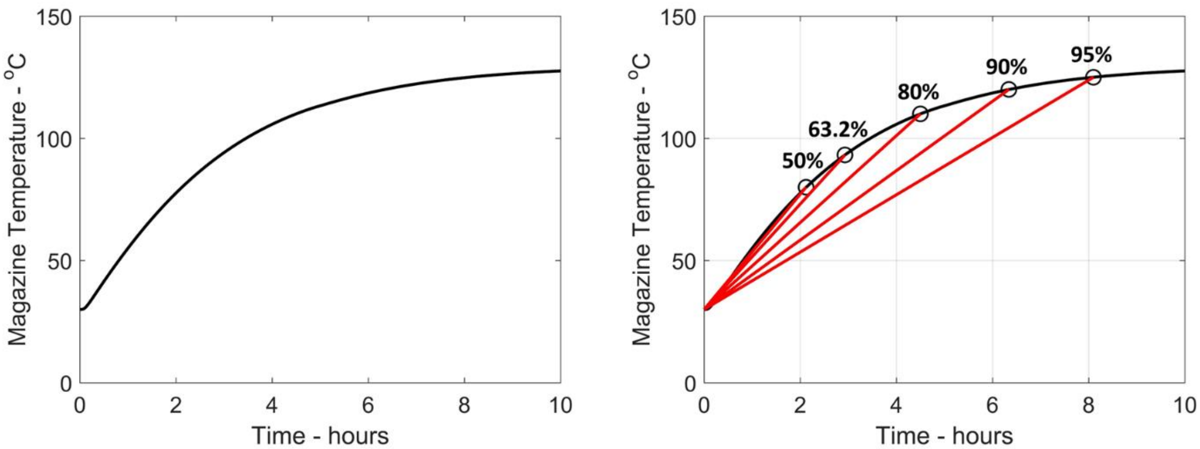

Figure 5: Example of magazine gas temperature curve (left) and effect of choice of equilibrium temperature (right) on calculation of average heating rate

The model allowed a number of parameters to be varied throughout the study. The first parameter that was investigated was the impact of the fire size as shown by the results in Figure 6. In the left plot, ten different magazine gas temperature curves are shown where the fire sized was varied from 0.25MW to 2.5MW. The circle on each curve represent the point where the magazine gas has reached 90% of its final temperature rise. As can be seen, as the fire size increases, the magazine gas reaches a higher final temperature and reaches its 90% equilibrium temperature in a shorter period of time. In the right hand plot in Figure 6, the final magazine temperature is plotted along with the time to 90% temperature rise and the average heating rate. The average heating rate is obtained by subtracting the initial temperature from the final temperature (to obtain the temperature rise or ΔT) and then dividing by the time to equilibrium (Δt). Note that as the fire size increases the calculated heating rate increases because ΔT is increasing *and* Δt is decreasing. Also, for the case shown here, the slowest rate of concern occurs for a fire size of 1MW because the final magazine temperature for that fire size is 130°C. The smaller fires result in a slower rate but would not achieve a cook-off (final temperature below 130°C) so they are not of concern. The larger fires would result in a cook-off but they would not result in the slowest heating rate. So, for every combination of bulkhead thickness, magazine size, and ordnance quantity, there is only one fire size that results in a final magazine temperature of exactly 130°C. Moving forward, as other parameters are varied, the first step is to determine the fire size that results in a final magazine temperature of 130°C. The heating rates that are then calculated are known to be the slowest possible that will still result in the possibility of a cook-off.

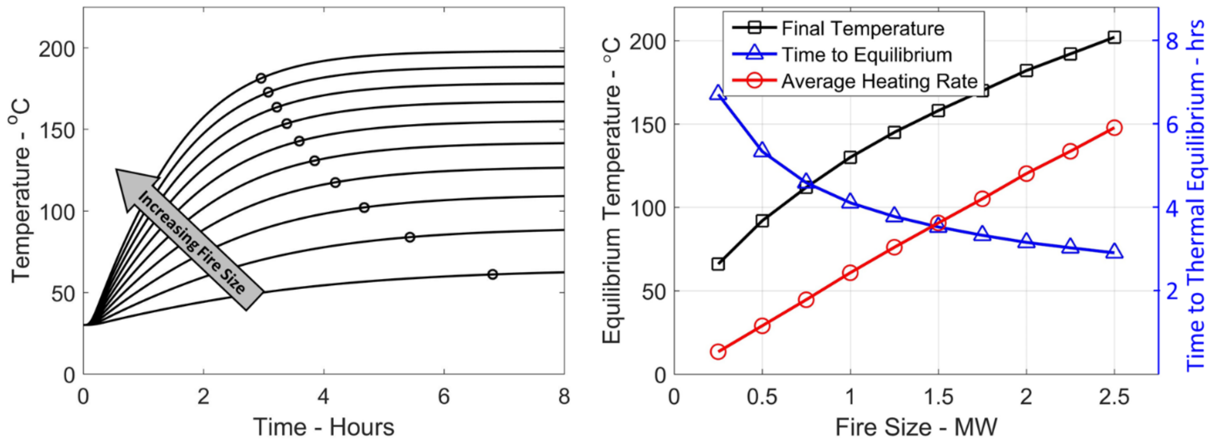

Figure 6: At left, increasing fire size causes the magazine gas to reach a higher temperature in a shorter time. End result is an increase in final temperature and average heating rate as shown at right.

The effect of the thickness of the bulkhead on magazine heating rate is shown in Figure 7. Here the bulkhead thickness was increased from ¼ inch to 1 inch (6 mm to 25 mm). Increasing the bulkhead thickness does not affect the size of the fire required to reach a final magazine temperature of 130°C because the area for the fire to loose heat to the surroundings is not affected. However, the time required for the magazine gas to reach equilibrium does increase as the bulkhead thickness increases. This is because increasing the wall thickness increases the thermal mass of the material that must be heated and more time is required for the magazine to reach the 90% threshold temperature. This increase in time has a direct influence on the average heating rate as shown at right.

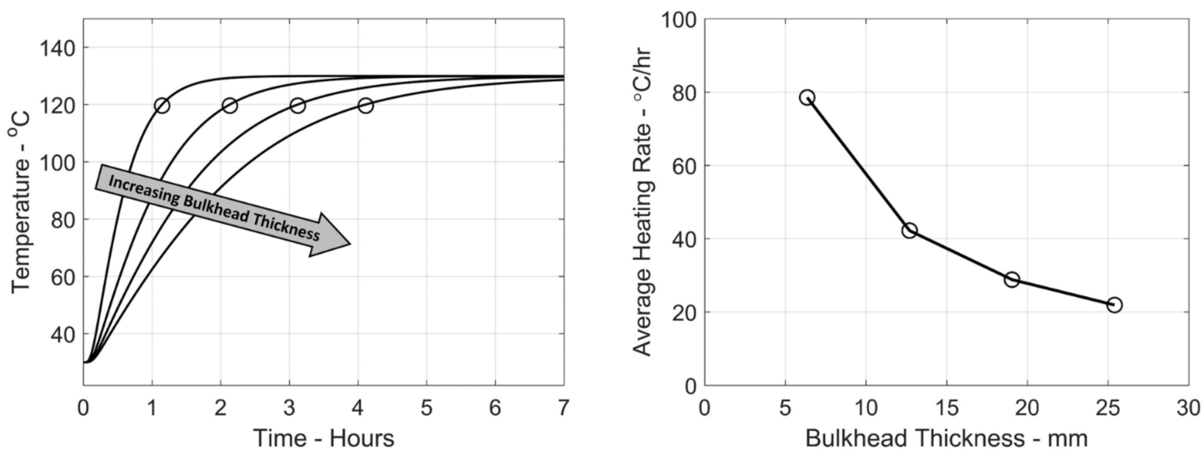

Figure 7: Effect of bulkhead thickness on magazine gas temperature (left), and average heating rate (right) for one particular magazine and fire size.

The effects of changing the size and aspect ratio (width/length) of the magazine was investigated. The results for empty magazines with 12.7 mm thick walls are shown in Figure 8. At left, the size of fire required to reach 130°C is shown as a function of magazine area. For each case, the time required to reach the 90% temperature rise was also calculated and was used to determine the average heating rate for each case as shown in the plot at right.

As would be expected, as the size of the magazine increases and its surface area increases, the size of the fire required to reach any given temperature (130°C in all cases here) also increases. Less obvious is the effect of the aspect ratio. The magazine has six surfaces, only one of which is heated by the fire. The area of the heated bulkhead is the product of the width and height. As the ratio of W/L decreases, the ratio of heated area to cooled area increases. Therefore, to reach any given final temperature, the common bulkhead must be hotter as W/L

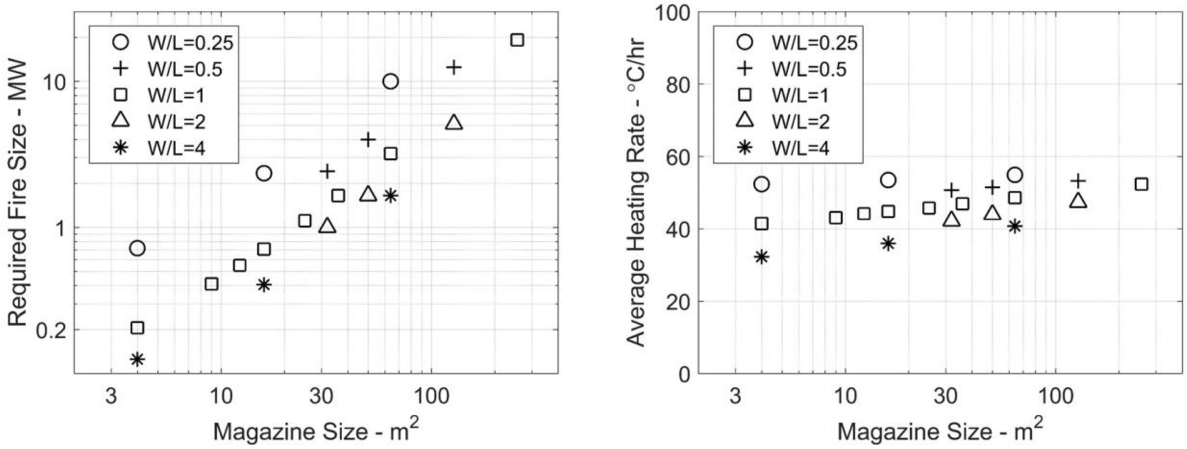

Figure 8: The size and aspect ratio of the magazine compartment has a large influence on the size of fire required to reach 130°C (left) but has a modest impact on the average magazine heating rate (right)

decreases. To obtain a higher bulkhead temperature, a larger fire is required.

More important is the effect on average heating rate. As the size of the magazine increases, its thermal mass increases but the size of fire required to reach 130°C also increases. The end result is that the two affects essentially cancel out and the effect of magazine size on the average heating rate is minimal. The aspect ratio actually has a larger influence on average heating rate then the size of the magazine. Results for magazines with thicker walls follow the same general trend and are therefore not shown. The slowest heating rate for empty magazines was 32°C/hr for 12.7 mm thick walls and 16°C/hr for 25 mm thick walls. These results compare well with the work of Mansfield.

The most important case to examine is magazines which are full of ordnance. The addition of ordnance to the magazine significantly affects the average heating rates as shown in Figure 9. Here, the average heating rates for full magazines are shown for two different wall thicknesses: 12.7 mm thick walls at left and 25 mm walls at right. As compared to empty magazines, the addition of ordnance significantly slows the average heating rates. There is also a stronger influence of magazine size on average heating rates. This is because as the magazines get larger, the mass of ordnance that they contain increases faster than the magazine’s surface area increases which causes the average heating rate to decrease. Put a different way, the magazine’s total thermal mass is increasing faster than its surface area. There is also an insulating effect that the ordnance has which reduces the radiation transfer from the hot bulkhead to the cold walls. This allows a smaller fire to reach the 130°C temperature threshold for a full magazine than would be require for an empty magazine. This also causes the average heating rate to decrease. The overall effect is that for full magazines the slowest average heating rates that were calculated are 12°C/hr for magazines with 12.7 mm walls and 10.5°C/hr

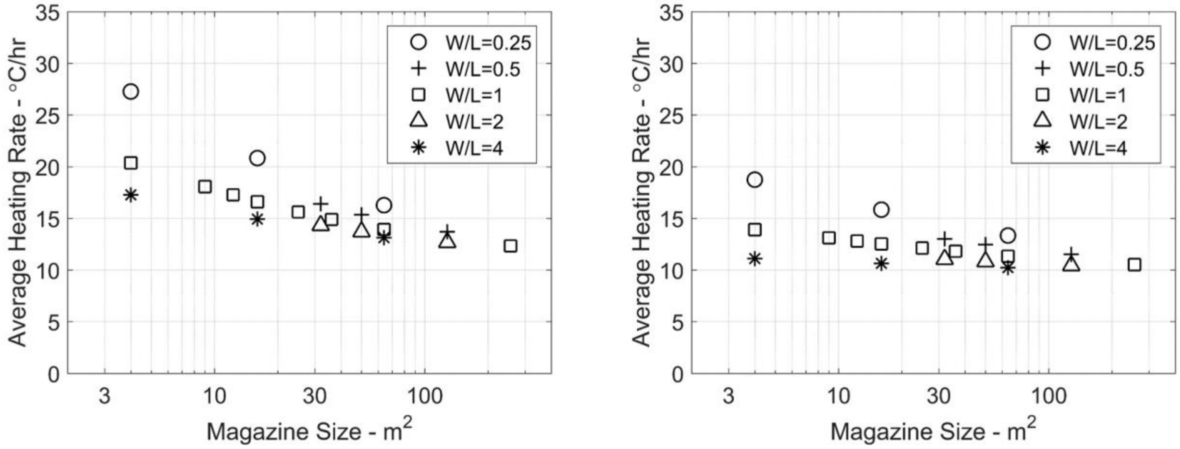

Figure 9: Average heating rates to 130°C for magazines full of ordnance with 12.7mm thick walls (left) and 25mm thick walls (right)

for magazines with 25 mm walls.

Discussion

The slowest heating rate that was identified was 10.5°C/hr for a large, fully loaded magazine with 25 mm thick walls. This means that a constant sized fire would heat the magazine air to 120°C (90% temperature rise to 130°C final temperature) in just over 9 hours. A smaller fire would result in a slower heating rate but would not result in a final temperature of 130°C. The only way to produce a slower average heating rate would be to allow the fire size to slowly grow with time over the course of many hours. In this way, it would be possible to achieve any heating rate and still eventually reach cook-off temperatures. This scenarios seems exceedingly unlikely and should not be the basis for a standard safety test.

The slow cook-off test is performed with a constant temperature ramp rate. As the results of the preceding analysis show, the magazine temperature does not increase at a constant rate but instead will follow a curve that asymptotically approaches its steady-state temperature. Simulating this behavior with a straight line is difficult but greatly simplifies the test. Specifically, if one wanted to perform a test with an asymptotic profile, a very difficult question would arise; what should the final temperature be? In this work 130°C was chosen because it was on the low end for a double base propellant and would result in the slowest possible heating rates. But, if a SCO test was designed where the temperature would only approach 130°C, most items would never react at all. By specifying a constant temperature ramp whose temperature continues to increase, an eventual reaction is assured.

The lumped thermal mass assumption greatly simplified the analysis but also ensured conservatism when calculating heating rates. The analysis performed assumed that both the magazine air and the ordnance were at two different uniform temperatures. In reality, the air and ordnance that are near the heated bulkhead will be heated more quickly than those near the cooled walls. Ordnance near the heated wall would therefore reach cook-off temperature and react before any of the ordnance that was being heated more slowly would. This initial reaction is the only reaction of concern because once an item reacts within the magazine, even a type V reaction will lead to subsequent reactions or at the very least a rapid rise in magazine gas temperature.

Conclusions

The purpose of this work was to help identify possible slow cook-off heating rates and determine the most appropriate heating rate for SCO testing. Unfortunately, the review of historical accidents was of little help and only demonstrated the tragedy of these types of accidents and the importance of continued improvement through testing. The existing analysis review was helpful in identifying the most likely SCO scenarios but was incomplete insofar as calculating potential SCO heating rates. The analysis that was performed examined the effect of fire size, magazine size and arrangement, wall thickness, and ordnance quantity on magazine gas temperature histories. In each case, the fire size that resulted in a final magazine gas temperature of 130°C was first determined and then the time to 90% temperature rise was calculated. By dividing the change in temperature by this time ($\Delta T/\Delta t$) the average heating rate for each case was calculated. The slowest average heating rate that was found was 10.5°C/hr which is a little over 3 times faster than what is currently specified in STANAG 4382.

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