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

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Abstract

The slow heating test is performed on ammunition and explosives (AE) 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 transport container. If the AE cooks off, the results can be severe because much of the energetic material is at an elevated temperature when the reaction occurs.

Historically, the slow heating test has been performed by heating the munition 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 testing. This was done by examining historical accidents and using the data to conservatively estimate the heating rates experienced by the AE involved. In the course of this analysis, no data was found 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. It is the recommendation of the author that the heating rate used for the slow heating test be increased to 15°C/hr.

Keywords

Slow heating, Hazard Classification Testing, Cook-off, Accident Investigation

Background

All ammunition and explosives (AE) must be hazard classified prior to being transported or stored. The procedure for determining the hazard classification of AE is outlined in TB 700-2 [1] and apply to all DoD and DoE AE in their storage and transportation configuration. These procedures subject the AE to a number of tests that are designed to determine if and how the AE will react when subjected to a number of different stimuli. The slow heating test is one of the tests that is used to characterize the hazards associated with the AE under test.

The slow heating test is performed on AE 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 not in direct contact with the AE but is instead separated from the munition by some barrier such as the walls of a magazine or shipping container. This is in contrast to the fast heating test where the munition is in direct contact with the fire. While it might seem that the worst case scenario would be to have the AE directly exposed to the fire, this is typically not true. In the slow heating scenario, the heat fluxes into the item are much smaller than in the fast heating case and the resulting temperature gradients are much lower. This means that at the time that the munition cooks-off, the average temperature of the energetic material is higher than it would have been if it had been heated more quickly. In many cases, this higher average temperature can cause the resulting reaction to be more severe because the elevated temperature of the energetic fill can cause normally stable materials to become more sensitive and detonate during slow heating. It is this phenomenon that is examined by the slow heating test.

The classification given to explosive items prior to shipment or storage consists of a hazard class followed by a hazard division (also referred to as a sub class number) and a compatibility group. Most AE fall under class 1 for explosives. For example, a common explosive designation is 1.4D. This classification defines the item as class 1 (explosive) division 4 (minor explosion hazard) compatibility group D (secondary explosive). This classification then defines how the material can be shipped, where it can be stored, and with what it can be shipped and stored.

Determination of the hazard division for Class 1 items relies on the results of a series of tests conducted according to the guidance within TB 700-2. Specifically, the hazard classification guidance is given as a flow chart, reproduced here in Figure 1. The slow heating test is outlined in red. Note that before the slow heating test is employed, the AE must first pass a number of tests including the liquid fuel/ external fire test (alternatively known as the fast heating test) and the sympathetic reaction test. The slow heating test is then only used for AE that could potentially be classified as 1.6.

The slow heating test procedure in TB 700-2 points to NATO STANAG 4382 [2] which defines the slow cook-off (SCO) test used for insensitive munitions (IM) testing under MIL-STD 2105 [3]. TB 700-2 specifies that procedure 1 in the STANAG be used. Currently, this procedure requires that the item under test 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. In addition to the ramp rate, other parameters such as item preconditioning and temperature gradients within the oven are specified in the test standard. TB 700-2 then duplicates these test parameters and defines how the test is to be performed. This could represent a problem because it is likely that the test parameters in the STANAG will change in the near future (discussed below) which will create a contradiction between the two documents.

The origin of the 3.3°C/hr heating rate is not known for certain. Some have pointed to ship fires during WWII that exploded up to 2 days after suffering below deck fires. By dividing the cook-off temperature by the fire duration a heating rate was obtained. Others have speculated that the test was meant to be performed at the slowest heating rate possible 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 (and the slow heating hazard classification test) has 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 STANAG so that the rate specified better represents realistic heating scenarios. The concern is that an item that has been designed to pass the 3.3°C/hr heating rate used in testing might react more violently at the higher rates that the item is more likely to encounter while in service. While these arguments have primarily been made with regard to insensitive munitions testing, they are equally valid for the slow heating test used for hazard classification.

In the spring of 2016, AC326 approved the formation of the Slow Heating Custodial Working Group (SHCWG) to revise STANAG 4382 and create a new Allied Ordnance Publication (AOP). A major part of the STANAG revision was to investigate whether the heating rate used in the test should be changed. 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. This made agreement on changing the heating rate impossible. This then led the AC326 subgroup B chairman to request that a study be performed to attempt to at least bracket possible heating rates. The results of this investigation were presented to the SHCWG at two subsequent meetings and contributed to the decision to increase the heating rate used for SCO testing. Although the new rate has not yet been ratified by AC326, there is currently agreement among the participants of the SHCWG to increase the rate from 3.3°C/hr to 15°C/hr.

The investigation that was undertaken consisted of both a modelling effort and a review of historical cook-off incidents. The modelling effort was summarized in a paper presented at the Insensitive Munitions and Energetic Materials Technology Symposium (IMEMTS) in April 2018 [2]. This paper focuses on the second part of the investigation which consists of a thorough study of cook-off incidents in an attempt to estimate possible real-world slow cook-off heating rates.

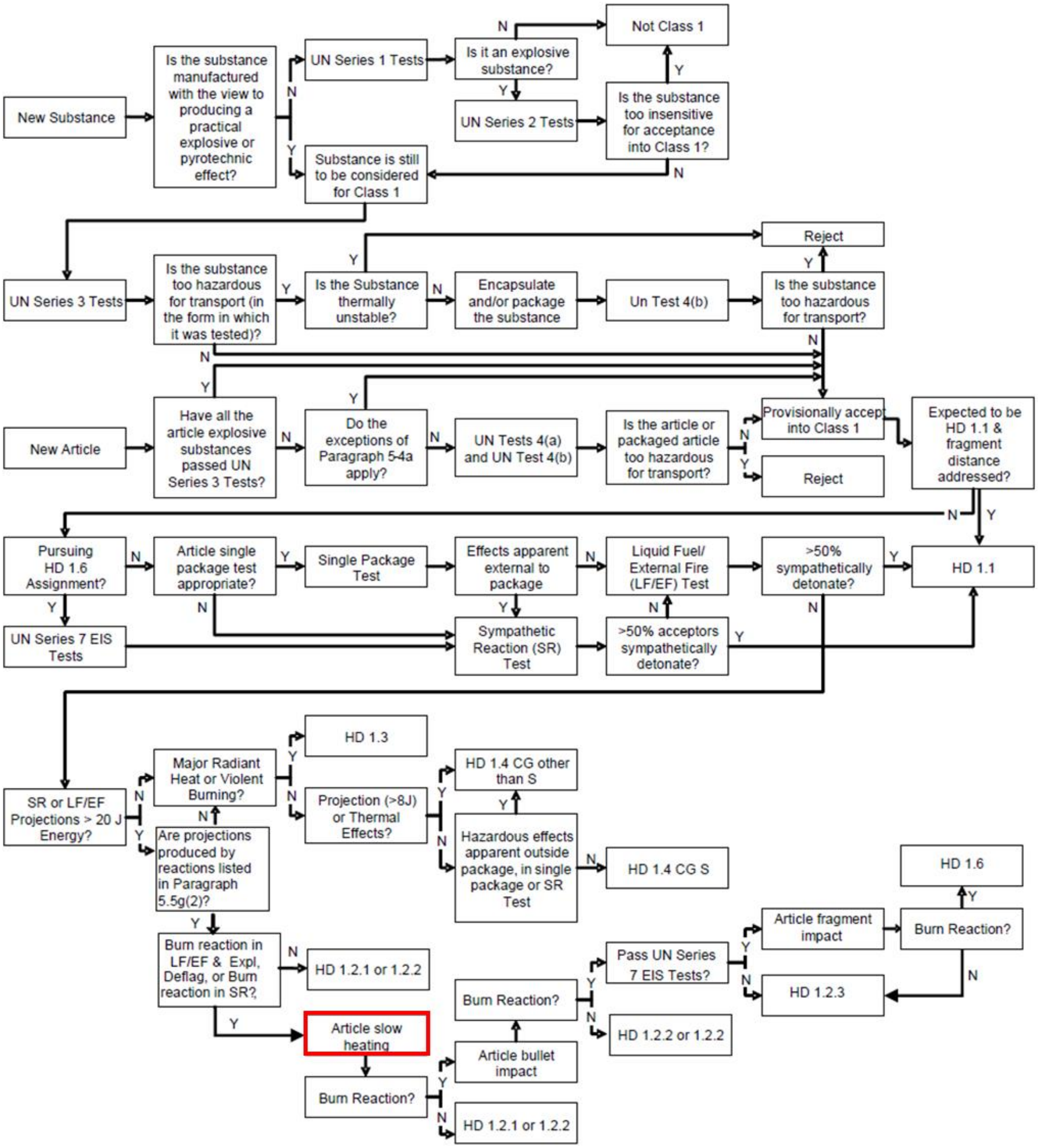

Figure 1:DoD and DOE AE hazard classification guidance for substance and articles. The Slow Heating test is outlined in Red. Reproduced from Figure 5-1 in TB 700-2 [1]

Accident/Incident Investigation

The goal of the incident investigation was to determine the slowest possible heating rate that AE could experience based on data from actual accidents and incidents involving AE. In order to estimate an average heating rate, the cook-off temperature and total heating duration are needed. The average heating rate is then simply the change in temperate of the reacting item divided by the total heating duration. Put another way, the average heating rate is the average slope of the temperature vs time curve of the AE from the time when the heating began up to the time when the item reacts. With these parameters in mind, a thorough review of incidents that occurred over the past 100 years was conducted.

In order for an item to experience a slow cook-off type reaction while in service, it must be heated for an extended duration prior to reacting. In an attempt to determine realistic heating durations, a review was conducted to identify incidents where AE were subjected to heating. Sources used to identify the accidents and incidents included the paper by Boggs et al [5] as well as the accident database within the MADx [6] site on the MSIAC web portal. Additional incidents were found using a variety of sources. In all, over 200 incidents were examined spanning from 1907 to 2015.

In many of the cases that were examined, multiple energetic items reacted during the duration of the incident. Due to the complex situation that arises after reactions begin, only the initial reaction that occurred in each incident was examined. For example, the train fire in Roseville, CA in 1973 resulted in dozens of explosions over a 32-hour period. However, for the analysis performed here, only the first explosion was studied. Subsequent reactions are ignored because it is unknown how previous reactions might have influenced these later reactions. Also, it is known that the early reactions spread the fire from one area to another. Examining only the initial reaction eliminates this potential confusion and eliminates the absurdly long heating durations found in some situations where reactions continued for many days. While it is still impossible to know if the first item that reacts was heated for the entire time from when the fire ignited until the item reacted, at least it is known that no earlier reactions contributed to it reacting. *For each incident studied, only the initial reaction was investigated and all subsequent reactions were ignored*.

It is never possible to know the true heating duration that an item experiences prior to it reacting. Even in cases where the fire ignition time is known and the time of initial reaction is known, it is still unknown if the fire was heating the AE from the very beginning. As the fire spreads, it could move closer to the AE and start heating it at some later time. However, by assuming that the AE starts getting heated at the same time that the fire starts, a conservatively slow calculated average heating rate is assured. *Therefore, it is assumed, for the sake of calculating the average heating rate for each incident, that the AE begins being heated the instant that the fire starts.*

In many cases the time that the initial reaction occurred is not reported. However, in many cases enough information can be found to conservatively estimate the amount of time that elapses prior to the initial reaction. For example, a news report might read: “The fire started at 0330 and explosions were heard during the morning.” Since the time of the first reaction is unknown but it is known that it occurred in the morning, the most conservative estimate is that the first reaction occurred at 1200 which gives a heating duration of 8.5 hours maximum. In this analysis, this time is referred to as t_{max} and represents the most important parameter needed to estimate a conservative average heating rate. *In this analysis, t_{max} represents the longest possible time that the AE could have been heated prior to reacting*.

Finally, to calculate an average heating rate, a temperature rise prior to reaction is needed. Since the type of item is rarely known, a cook-off temperature must be assumed. To ensure conservatism, the temperature rise should be as small as possible. Therefore, for each case, a cook-off temperature (T_{CO}) of 130°C was assumed and the initial temperature was assumed to be 30°C which yields a temperature rise (ΔT) of 100°C. This is considered conservative because 130°C is about the lowest cook-off temperature seen in any AE. *For this analysis, it is assume that the AE experiences a temperature rise of 100°C prior to cooking off.*

The preceding assumptions assure that any estimated heating rates that are calculated will be conservative. This can best be demonstrated by examining a mock temperature-time plot as shown in Figure 2. In all cases, the incident begins at $t=0$ with the munition at its initial temperature, T_i. Note that, based on the previous assumptions, the initial reaction can *only* occur in the green area at the top left. That is, it is known that the initial reaction occurred before t_{max} and the AE must have been at a temperature that is higher than T_{CO} when the reaction occurred.

In Figure 2, the black dots represent three possible points within this temperature-time space where reactions could occur. The slowest possible heating rate (most gentle slope) is demonstrated by the solid line that extends from the point ($t=0$, T_i) to (t_{max}, T_{CO}). In this case the slope is minimized because the temperature rise is minimized and the heating duration is maximized. Examining other possible scenarios demonstrates the conservativity of the preceding assumptions. Line A represents the case where the reaction actually occurred earlier than assumed (before t_{max}). Line B represents the case where the fire did not initially heat the item but then spread and began heating it at some later time. Line C is the case where the actual cook-off temperature of the item was higher than T_{CO}. Notice that all three of the dotted lines have a steeper slope (and therefore represent a higher average heating rate) than the solid line that was obtained using the selected assumptions. Put another way, it is impossible for the item to have actually experienced a slower heating rate than the rate that is calculated using the above assumptions. This is what is meant by assuring conservatism. *The conservative assumptions guarantee that the heating rates calculated are slower than the real-world heating rate for each incident.*

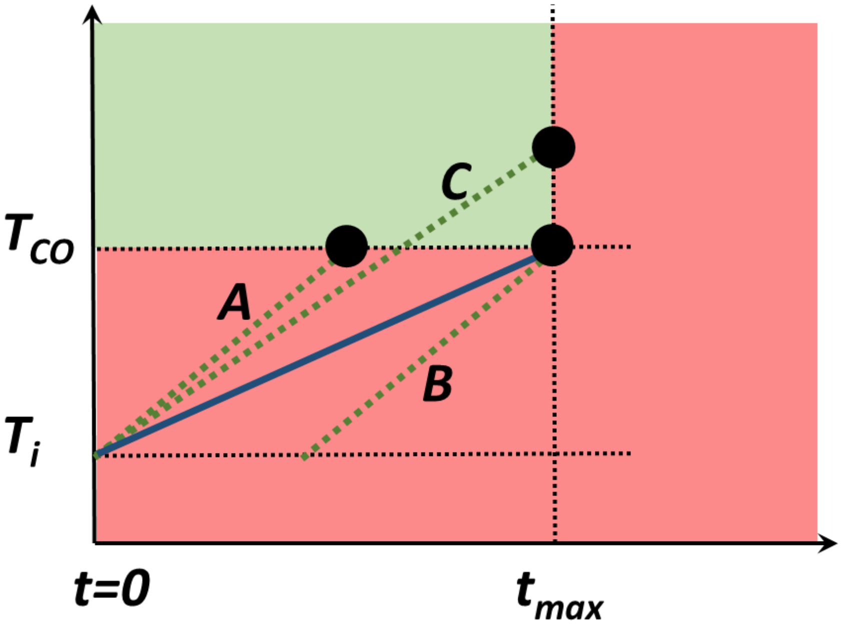

Figure 2: Demonstration of conservativity of assumptions used for average heating rate calculation. The first reaction could occur anywhere within the green region but not within the red region.

It is obvious from the preceding discussion that only incidents in which t_{max} can be determined are of any use for the purpose of calculating a conservative average heating rate. While the sources listed above were useful for identifying potential incidents to study, these sources rarely gave enough information to determine t_{max}. However, in most cases these sources did give both the location and date of the incident. This information was then used to search local news reports to obtain the information required to calculate t_{max}. Unfortunately, there were some cases in which t_{max} could still not be determined. However, of the other 200 incidents studied, there were 158 cases identified where AE was subjected to some form of heating and t_{max} could be calculated. These incidents were sorted by year and type as shown by the statistical breakdown in Figure 3. Here it can be seen that the majority of the incidents that were studied occurred after the year 2000 and the AE was predominantly located within depots, combat vehicles, and warships.

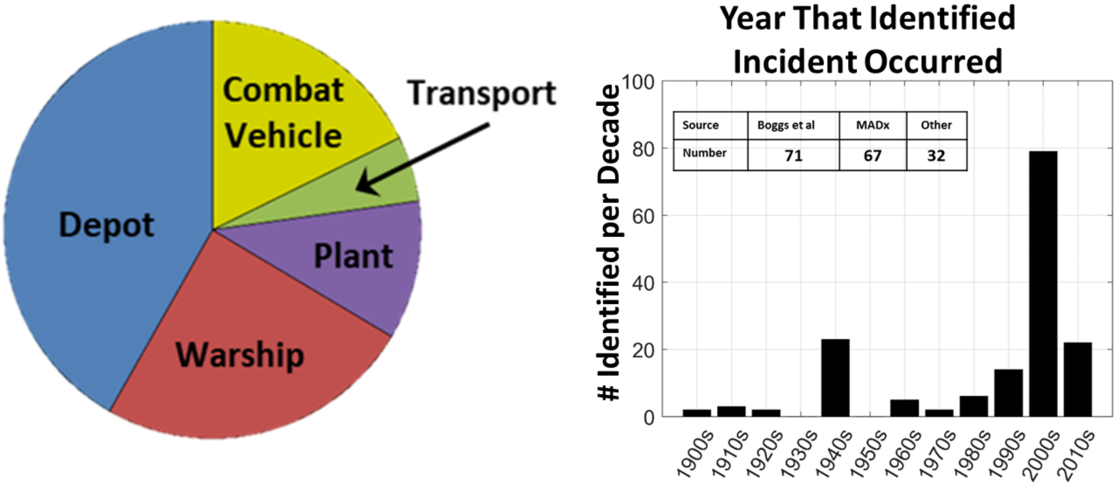

Figure 3: Category and year for the 158 incidents for which t_{max} could be identified

During the course of this investigation it was found that the heat source that caused the initial cook-off was always a fire of some kind. This is worth mentioning because, in the past, there has been speculation that a steam leak aboard a ship could result in a very slow heating rate which could lead to a cook-off. While this is theoretically possible, the author could not find any reports of this ever happening. There have been reports of steam leaks within magazines but in no cases did they result in a munition cooking-off. One reason for this is that it is very unlikely that a steam leak within a magazine would go undetected for long enough for it to heat the magazines contents to a temperature high enough to cause a cook-off. Also, most steam lines are not operated at high enough temperature and pressure to create cook-off temperatures after expanding to atmospheric pressure. For this reason, for the sake of this analysis, the incident start time is considered to be the time when the fire first started.

The data collected for the 158 incidents that were studied is presented in Figure 4. Here, each of the 158 incidents is shown on the y-axis while the estimated elapsed time from the time when the heating began is shown on the log scale on the x-axis. The incidents are shown in order of increasing t_{max} which is indicated by the thick red line and the color used for each incident represents its category. Although t_{max} is the only data needed for the estimation of the average heating rate, in many cases more data could be obtained from the sources. In the ideal case, the actual incident start time, the time of the first reaction, and fire extinguishment time (t_{end}) could all be determined. These cases are represented by the filled boxes in Figure 4. The left-hand side of the box represents the time of the first reaction and the right-hand side shows the total incident duration. In other cases, only t_{end} was known. Since reactions were known to have occurred, t_{max} is equal to t_{end} in these cases and they are shown as a left pointing arrow. These cases result in the most conservative heating rate calculation because it is known that AE reacted before the fire was extinguished but it is unknown when these reactions occurred relative to the fire ignition time. Finally, in relatively rare cases it was not possible to determine the total incident duration but it was possible to estimate the time to the first reaction. For example, there were many cases of combat vehicles that caught fire and it was reported that the stored munitions started exploding within the first half-hour but the total burn time was not reported. These cases are shown by the right-pointing arrows. Note that while in some cases the fire (and in many cases subsequent reactions) continue on for many days, in all cases the initial reaction occurs within the first 12 hours and in about half the cases it occurs within the first hour. Also, it is worth reiterating that in all the cases where the actual time to first reaction was not given, it was estimated as the longest possible time to first reaction.

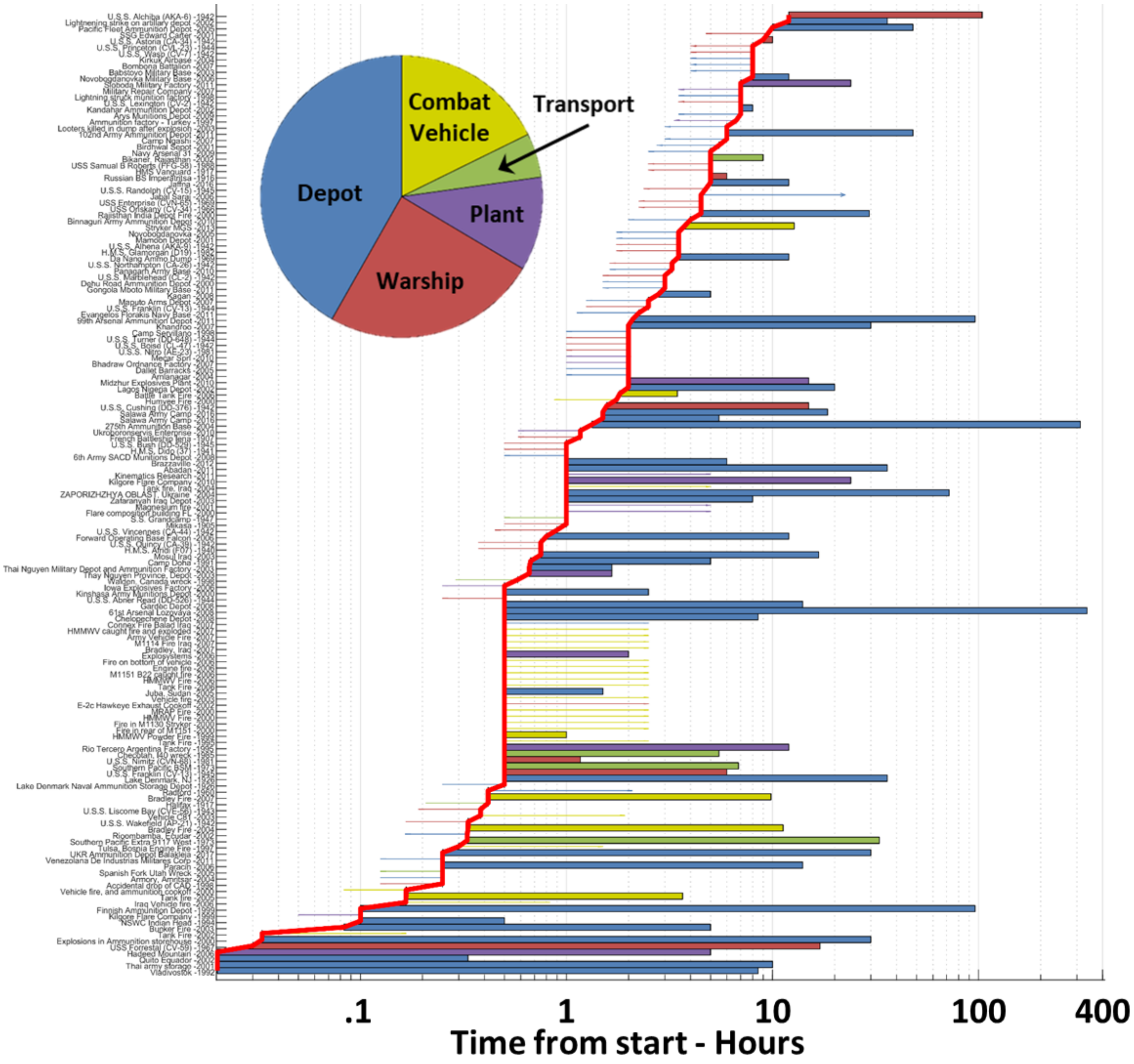

Figure 4: Plot of all incident durations from time that fire was initiated

With t_{max} known for the 158 incidents shown in Figure 4, the average heating rate can be conservatively estimated by simply dividing the assumed 100°C temperature rise (T_{CO}-T_i) by the maximum heating duration (t_{max}). These estimated heating rates are shown for each of the identified incidents by the filled circles in Figure 5. Note that the multiple levels of conservative assumptions used in the heating rate calculation effectively bracket the possible heating rate for the initial reaction that occurred in each incident. From Figure 2, it is known that the actual heating rate can be faster for each case but cannot be slower. This is depicted by the green (possible) and red (not possible) filled regions in Figure 5. That is, for each incident, the actual heating rate that the first item that reacted experienced could be any value faster within the green region but could not be any of the slower values in the red region. Note that even with these extremely conservative assumptions, in all cases the calculated average heating rate is far above the 3.3°C/hr that is currently used for the slow heating test.

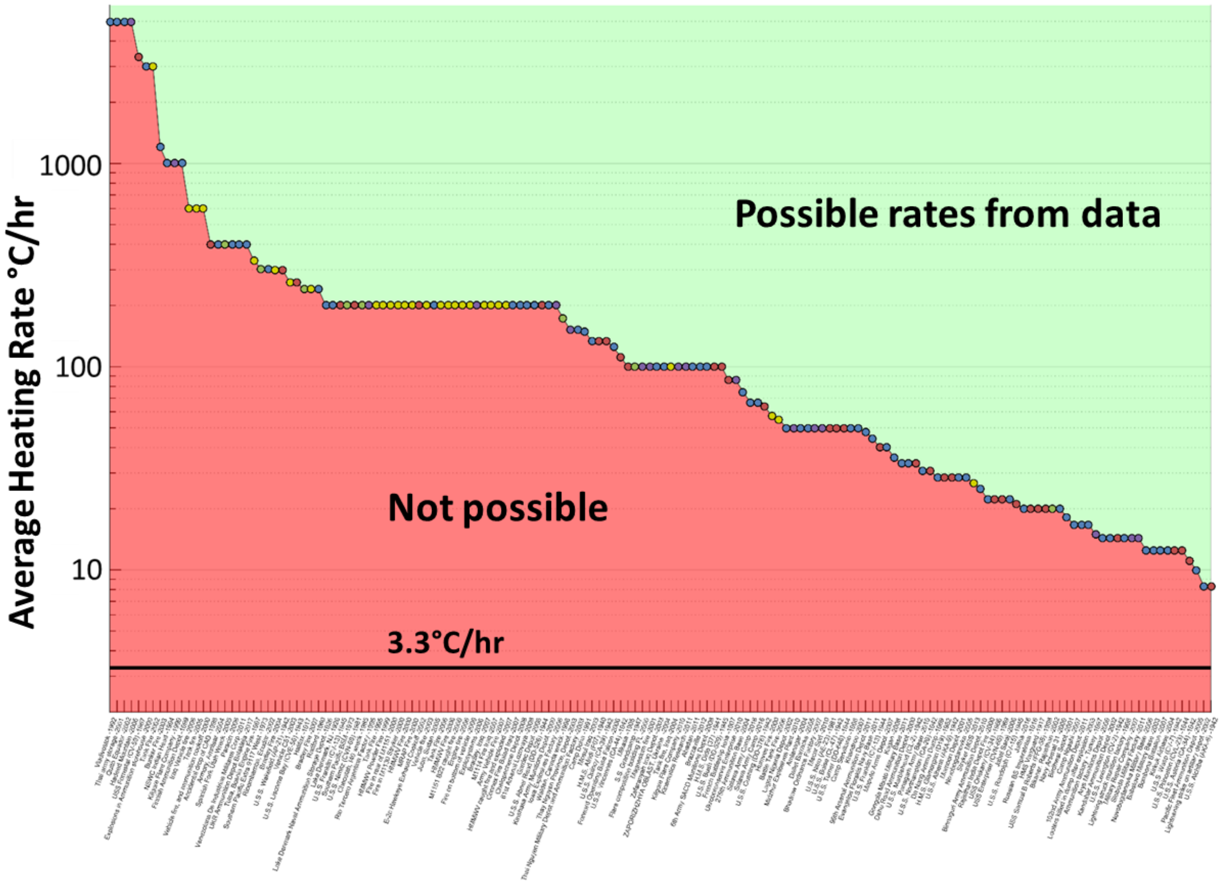

Figure 5: Possible heating rates that led to initial reaction for each incident

When the SHCWG was in the process of selecting a new heating rate for the SCO test, it was determined that it would be desirable to know the percentage of incidents covered by any given heating rate. To answer this question, the data shown in Figure 5 was re-plotted as shown in Figure 6. Here, for each heating rate shown on the x-axis, the y-axis shows the percentage of calculated heating rates that were faster than the selected rate. This curve allows a more systematic approach to the selection of an appropriate heating rate. For example, after the last SHCWG meeting, a heating rate of 15°C/hr was selected to be specified as procedure 1 for SCO testing when STANAG 4382 is updated. As shown, a rate of 15°C/hr is slower than *at least* 92% of incidents studied. So, increasing the SCO test heating rate to 15°C/hr would still test at least 92% of munitions slower than they would be heated in actual incidents. Again, as in Figure 5, this curve is based on extremely conservative estimations so the actual curve would most likely be above the curve shown. Also, it can be seen that the current rate of 3.3°C/hr is slower than 100% of the incidents studied.

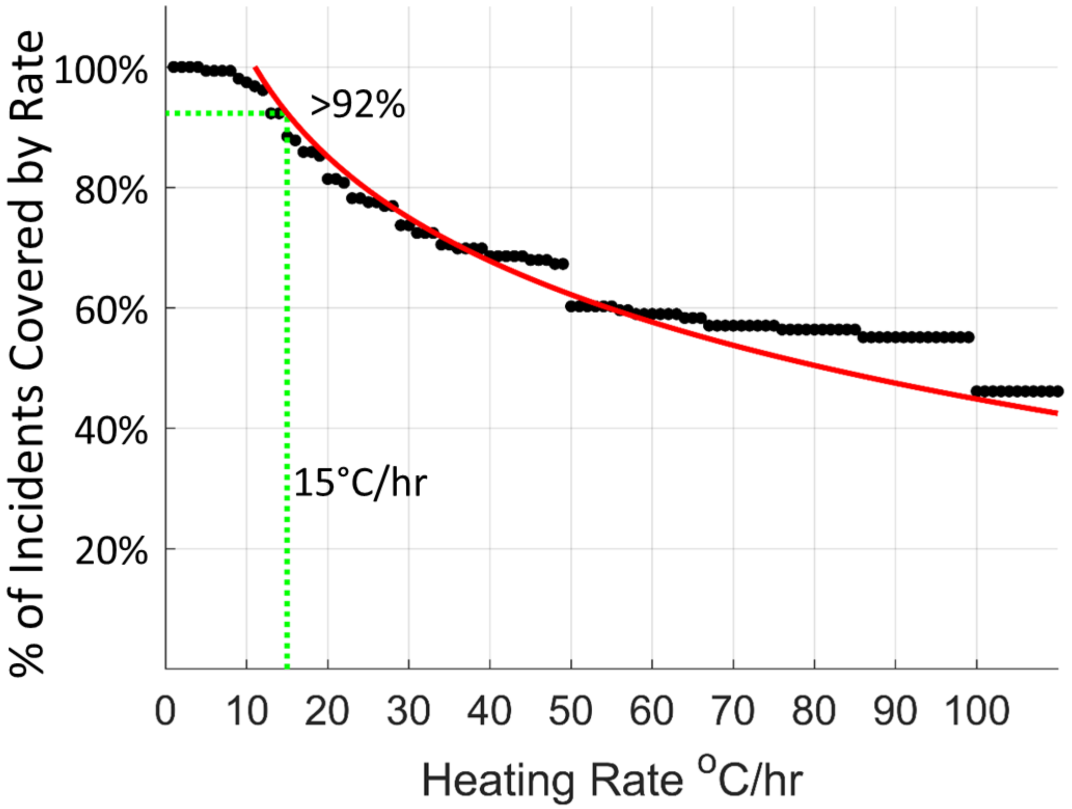

Figure 6: Plot showing percentage of incidents that are faster than given heating rates

Discussion

The purpose of this work was to use documented incidents involving explosive materials to conservatively estimate the heating rates that explosive materials have experienced in real-world scenarios. While this work was performed specifically to help the SHCWG select a heating rate for the SCO test used in IM testing, the results are equally valid to the slow heating test used for hazard classification. These results demonstrate that the current heating rate of 3.3°C/hr is much slower than anything that items experience in actual incidents. While not presented in this paper, it has also been shown through a thorough modelling effort that it is impossible to heat a munition to a temperature high enough to cause a cook-off at a rate any slower than 10°C/hr. These studies have, in part, led the SHCWG to recommend that the heating rate used for SCO testing be increased to 15°C/hr. It is recommended that the Slow Heating test used for hazard classification also change and specify a heating rate of 15°C/hr to ensure that the IM and HC tests remained harmonized.

Acknowledgments

This work was funded by the Insensitive Munitions Advanced Development (IMAD) program.

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