NATO STANDARD

AOP-4382

SLOW HEATING
TEST PROCEDURES FOR MUNITIONS

Edition A Version 1
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NORTH ATLANTIC TREATY ORGANIZATION
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NORTH ATLANTIC TREATY ORGANIZATION (NATO)

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NATO LETTER OF PROMULGATION

9 March 2020

1. The enclosed Allied Ordnance Publication, AOP-4382, Edition A, Version 1, SLOW HEATING TEST PROCEDURES FOR MUNITIONS, which has been approved by the nations in the CNAD Ammunition Safety Group (CASG – AC/326), is promulgated herewith. The agreement of nations to use this publication is recorded in STANAG 4382.

2. AOP-4382, Edition A, Version 1, is effective upon receipt.

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4. This publication shall be handled in accordance with C-M(2002)60.

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Zoltán GULYÁS
Brigadier General, HUNAF
Director, NATO Standardization Office

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RECORD OF RESERVATIONS

CHAPTER	RECORD OF RESERVATION BY NATIONS
Note: The reservations listed on this page include only those that were recorded at time of promulgation and may not be complete. Refer to the NATO Standardization Document Database for the complete list of existing reservations.	

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RECORD OF SPECIFIC RESERVATIONS

[nation]	[detail of reservation]

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CHAPTER 1: INTRODUCTION

When reviewing requirements for this test, SRD AOP-39.1 should first be read for guidance in the organization, conduct and reporting of full-scale tests.

1.1 ANNEXES

A. Methods to Determine Temperature Preconditioning Time

B. Historical Overview: History of the Slow Heating Test Requirements

1.2 RELATED DOCUMENTS

AOP-39	Policy for Introduction and Assessment of Insensitive Munitions.
SRD AOP-39.1	Guidance on the Organization, Conduct and Reporting of the Full Scale Tests
STANAG 4439	Policy for Introduction and Assessment of Insensitive Munitions
STANAG 4382	Slow Heating Test Procedures for Munitions
AASTP-03	Manual of NATO Safety Principles for the Hazard Classification of Military Ammunition and Explosives

1.3 AIM

The aim of this Agreement is to provide a standard test procedure for assessing the response of a munition when subjected to a heat source that slowly heats a nearby or adjacent storage hold (magazine), such as on a ship, in a depot or on a railcar.

1.4 AGREEMENT

Participating nations agree that the requirements and procedures incorporated in this Standard will be used for assessing the response, if any, of munitions and weapon systems to a gradually increasing thermal environment.

Participating nations further agree that national standards, orders, manuals, and instructions implementing this AOP will include a reference to STANAG 4382 for purpose of identification.

No departure may be made from this agreement without consultation with the NATO Tasking Authorities/Delegated Tasking Authorities (TA/DTAs). Nations may propose changes at any time to the TA/DTAs where they will be processed in the same manner as the original agreement.

This Standard is supported by the guidance in SRD AOP-39.1 which makes recommendations on the organization, conduct and reporting of the test methods in both this and in other full-scale test Standards.

1.5 DEFINITIONS

For the purpose of this document, definitions of terms to be used to describe test details and events are given in the NATO Terminology Management System that is available by reference for all Allied Publications.

1.6 GENERAL

Effort to minimize the violence of the response of munitions to slow heating conditions is a continuing requirement of weapons designers so that the safety of personnel and material will not be unduly jeopardized.

This Standard addresses the situation where munitions and weapon systems may be exposed to a nearby prolonged heating source. This can occur in peacetime as the result of accident, dissident/saboteur activity, or on operations as a consequence of enemy action.

The purpose of the selected slow heating test is to determine the response and the time to reaction, of the munitions when subjected to an adjacent heat source for a prolonged timeframe.

1.7 DETAILS OF THE AGREEMENT

This Standard provides guidance and procedures for Slow Heating testing. Testing should be conducted by the participating nations as a part of the Insensitive Munition (IM) assessment where required by STANAG 4439, Policy for Introduction and Assessment of Insensitive Munitions.

This Standard may also be used for Hazard Classification (HC) as required by STANAG 4123 and UN Document ST/SG/AC.10/11/Rev 6 (rev 7 is expected by July 2019) and any amendments thereto, and other applications not covered by these documents where the response of a munition to slow heating is required to be known or assessed.

If testing is to be used for Hazard Classification, an agreement must be reached between Hazard Classification and Safety Authorities on the testing details.

This Standard specifies 3 test methods:

a. Test Method #1 is the Standard Test that requires the item to be heated at a rate of 15°C/hour until a reaction occurs.

b. Test Method #2 is the Alternative Test for which the heating rate is identified in a Threat Hazard Analysis. A heating rate determined by national authorities should be used if a THA is unavailable.

c. Test Method #3 is the Hazard Classification Test that is the UN 7(h) test for HD 1.6 assignment.

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CHAPTER 2: TEST SPECIFICATIONS

2.1 TEST ITEM CONFIGURATION

1. The test item configuration shall be the final production standard and in accordance with the condition as appropriate to the life cycle phase represented by the test, or representative as approved by the national authority. As slow heating testing is often performed on munitions in their logistical/storage configuration, in these cases such configurations are synonymous with the term "test item" within this Standard.

2. Guidance on variations to the production standard and condition (logistical shipping and/or storage), as given in SRD AOP-39.1 Annex B shall be considered.

2.2 TEST METHODS

There are three methods for performing the Slow Heating Test for Munitions: the "Standard Test", an "Alternative Test" and the "HC Test". A minimum of two tests will both be performed in a logistical/storage configuration, unless otherwise determined by national authorities, regardless of which method is followed. If testing is conducted in a logistical/storage configuration and, therefore, the munition under test is not visible to a video camera recording the reaction through an oven window, then it is strongly recommended that a supplementary (third) test be performed on the munition without the container present. Such supplemental test results can contribute to the whole body of evidence for a final evaluation and assessment.

a. Method 1 (Standard Test). Precondition the test item in the oven at 50°C (± 3°C) until the test item has reached thermal equilibrium. Annex A provides three methods to determine when a test item is considered to have reached equilibrium: direct measurement, modeling or a calculation based on size. The preconditioning period is not required to exceed 24 hours but can be extended if desired. After the preconditioning period is complete, subject the test item to gradually increasing temperatures, at a rate of 15°C/hour, until a reaction occurs. Record the reaction as a function of time and temperature. Temperature reporting shall be the average of the functioning thermocouples at the times of recorded reaction events.

   [**NOTE**: Some gradient in oven air temperature measurements around the test item is to be expected but no two concurrent measurements should exceed a gradient greater than 15°C. Also, at no point throughout the test should any of the surrounding oven air temperature measurements deviate from the prescribed constantly-increasing oven set point temperature by more than 15°C.]

b. Method 2 (Alternative Test). Temperature preconditioning may be used but is not required with this test method where the heating rate is based on a THA. Real scenarios for slow heating can lead to many heating rates. If a THA analysis suggests that a particular heating rate is appropriate for the test item, the heating rate identified by the analysis may be used in this test, provided national authorities agree. Details of the relevant THA should be provided with the test data in the test report.

c. Method 3. (Hazard Classification Test). Using the facility, test set up, and instrumentation specified herein and in the Test Plan, subject the test item to gradually increasing temperatures, at a rate of 3.3°C/hour, until a reaction occurs. Record the reaction as a function of time and temperature. Temperature preconditioning may be used but is not required with this method. If used prior to starting to ramp up the oven temperature, preconditioning at 55°C below the predicted reaction temperature until the test item reaches thermal equilibrium is allowed.

2.3 TEST CONDITIONS

1. The test item state and condition shall be applied in coherence with the life cycle phase represented by the test, or representative as approved by the national authority.

2. Guidance on variation to the test conditions (including munition positioning / orientation, restraint, conditioning, marking) as given in SRD AOP-39.1 shall be considered.

2.4 TEST LIMITATION

1. The slow heating test is designed to simulate a consistent thermal condition that a munition might experience when exposed to an adjacent heating source over a prolonged period. The slow heating tests do not simulate a particular in-service or accident scenario. Should it be desired to represent specific in-service or accident situation, Method 2 may be modified to reflect the actual requirements, for example, heating rate, and test configuration. It should be noted that the heating rate identified for the Standard Test (Method 1) may not represent the most hazardous condition for all energetic materials.

2. Explosive-filled test items involved in a slow heating real-life accident scenario will experience non-linear heating rates. Non-linear heating rates could cause heating of the items at a much faster rate than the rate seen in one of the test methods listed.

3. Data obtained from these tests should not be extrapolated with respect to either temperature or time to derive forecasts of performance in other situations that involve heating rates not tested or non-linear heating rates. Rates of heat flow and thermal gradients within complex assemblies can become non-linear when changes of state and / or the loss of integrity of internal structures and components occur.

2.5 TEST REQUIREMENTS

1. The test consists of placing the test item in a disposable oven and increasing the air temperature inside the oven at a constant rate and recording the reaction(s) as a function of time. The test is terminated upon completion of the reaction(s) of the test item.

2. The test is performed by placing the test item in a disposable oven and heating the test item with heated circulating air. The test facility shall be capable of increasing the air temperature at the prescribed rate throughout the anticipated temperature range and maintaining a uniform temperature in the air around the test item. It is anticipated that there will be a temperature gradient between the test item's outer surface, which approximates the oven's air temperature, and the internal temperature inside the test item. Larger temperature gradients should be expected for larger or more thermally protected test items. The oven should be constructed to avoid influencing the test items reaction violence or the measurement thereof, provide the least possible confinement for any reactions that occur, and it should have a window through which videoing the test item reaction.

3. Materials used in the construction of the oven should be able to withstand the predicted reaction temperature of the test item but should allow test item debris to be ejected with minimal interference. Some gradient in air temperature around the test item is to be expected, but this should not be greater than 15°C. As an aid to achieving a uniform temperature throughout the test item, there should be an air space of at least 200 mm wide on all sides of the test item to allow for air circulation. The oven should be insulated., A minimum of 6 thermocouples is required to measure a more consistent, remote indication of the air temperature within the oven. These thermocouples shall be mounted 40-60 mm from the surface of the test item at positions fore, aft, starboard, port, above and below along planes through the centerline of the test item, i.e., one in the air space near the oven's air inlet (fore) and another near the exit (aft), plus one in the air space on four sides of the test item (starboard, port, above and below) (see Figure 1). Data must be recorded at a sample rate greater than or equal to 2 samples per minute. Additionally, where it is possible to get access to the interior of the test item without altering the test item, interior temperatures should also be measured with additional thermocouples.

   [**NOTE**: In addition to the minimum number and placement of thermocouples described above and in Figure 1, at least two more thermocouples can be mounted on opposite surfaces of the test item if deemed necessary and prescribed by national authorities.]

2.6 DOCUMENTATION AND COMPLIANCE

1. A test directive, test plan and test report shall be produced and shall be agreed by the national authority. Guidance on completion of documentation, responsibilities for completion and review are discussed in detail in SRD AOP-39.1

2. It is essential that the test is conducted in accordance with the Test Directive. One of the responsibilities of the Project Team is to confirm compliance.

3. Where deviation from the agreed Test Directive and Test Plan or the procedure agreed at the Trial Readiness Review prove necessary, these must be approved on behalf of the review body by the appropriate Project Team representatives, taking advice as necessary from the safety advisor and technical specialists.

2.7 OBSERVATIONS AND RECORDS

Guidance on specific aspects of the conduct of full-scale testing, observations and data recording is discussed in more detail in SRD AOP-39.1. Unless notes are identified as “optional” for IM purposes, the following minimum data must be obtained and records kept. Test requirement, records, and observations for HC testing and assessment are mandated in the UN Manual of Tests & Criteria are not optional, however, test plans and such specifics shall be reviewed for approval by national hazard classification authorities prior to testing.

a. Test item identification and configuration (model, serial number, etc.); Type of energetic material and weight, listing of environmental preconditioning tests performed; the spatial orientation of the test item

b. Test setup/configuration: type of procedure; specific construction of the oven used; thermocouple identification and locations; method of suspension or mounting and/or restraint; distances of test item to any protective wall or enclosure; identification and location of any other instrumentation if used

c. A record of temperature and events, including reactions, versus time through the end of the test (time zero = when ramping up the oven temperature begins).

d. The nature and distribution of test item remains/residue and debris, including range, position, photographs, identification (as possible), and mass of each piece.

e. Overpressure, sound levels, and imagery

f. Thermal data: thermocouple readout (versus time) for all sensors.

g. Photographs of the test setup;

h. Thermocouple identification and locations;

i. Photographs of witness plates (if used);

j. Number and depth of penetrations in fragment recovery panels (if used);

k. Video and sound track

l. A complete data record shall be compiled to include pressure, sound, imagery, fragmentation, debris and propulsion information

2.8 EVALUATION OF TEST RESULTS

Policy and procedures for evaluation of tests are given in:

a. STANAG 4439, Policy for Introduction and Assessment of Insensitive Munitions
b. AOP-39, Policy for Introduction and Assessment of Insensitive Munitions
c. AASTP-03, Manual of NATO Safety Principles for the Hazard Classification of Military Ammunition and Explosives

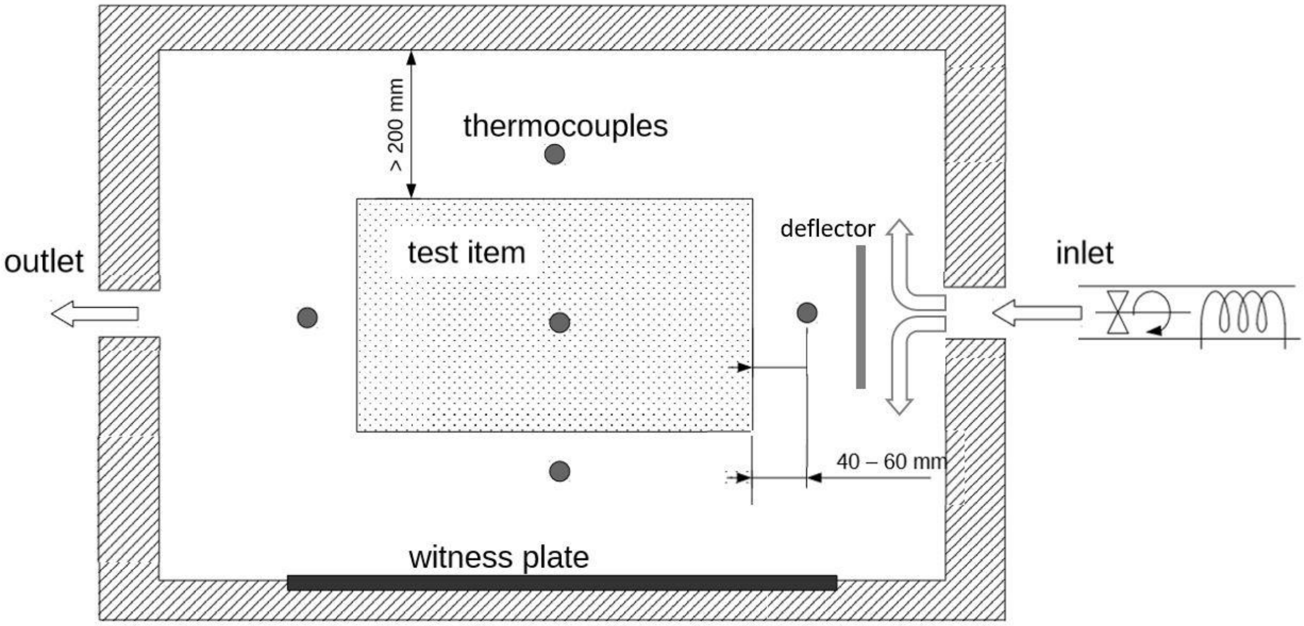

Figure 1 – Side view of a “typical” slow heating test setup with a generic test item in a forced air flow oven.

Note: Figure 1 shown above represents a typical but not the only acceptable oven configuration. A closed system with internal heating elements and an internal method for air circulation could also be used as an acceptable oven configuration

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ANNEX A: METHODS TO DETERMINE TEMPERATURE PRECONDITIONING TIME

A.1 INTRODUCTION

1. There is a temperature preconditioning requirement listed for Test Method 1. The test item shall be soaked at 50°C ± 3°C until it reaches thermal equilibrium. In this case, thermal equilibrium is defined as 50°C +3°C / -5°C. The test item preconditioning period is not required to extend beyond 24 hours, especially when testing larger diameter or thermally insulated test items. However, the preconditioning time period may be extended at the discretion of the test facility (e.g. plan for the expected reaction to occur during daylight hours).

2. It is highly recommended that prior to conducting this test the method of choice used to determine when thermal equilibrium has occurred be included in the test plan, which is reviewed and approved by national authorities prior to testing.

A.2 SUGGESTED METHODS

1. Direct Measurement: Thermocouples placed in or near the center of mass of the test item may be used to determine when thermal equilibrium is reached. It is important that the placement of such thermocouples does not influence the test item's reaction violence. For example, any holes drilled into the container or munition must be sealed closed to withstand the temperature and pressures prior to or during the reaction and will not contribute to test item venting.

2. Modeling: If a thermal model is used to determine the duration of the temperature preconditioning period required for the test item to reach thermal equilibrium, the model must be of sufficient fidelity to capture the various paths that heat can transfer from the surrounding air to the energetic material. For simple geometries, a 1-D transient finite difference solver in cylindrical coordinates might be adequate. More complex test items will likely require a more complex finite-element model of the item. No matter what model is used, the goal is to determine how long the test item must be held within a 50°C oven before all of the energetic material within the item reaches a temperature of at least 45°C. This will require knowledge of the thermal properties (i.e. density, thermal conductivity, and specific heat) of each major component of the test item. It will also require knowledge of the boundary conditions between the oven air and the test item. While the convective heat transfer coefficients for the oven and test item are location-specific, values will likely fall in the range of 10-25 W/m^2K for most oven configurations. The initial temperature of the test item in the model should

be the temperature at which the actual test item will be stored prior to starting the test.

3. Size versus temperature preconditioning period calculation: The duration of the temperature preconditioning period, measured in hours, can be determined by inserting the dimension S [mm] of the test item in the formula below. Note how this dimension applies to test item shapes.

$$\textbf{Preconditioning period (hrs.)} = 0.000148\ S^2 + 0.0785\ S$$

- For cylindrical test items, the dimension S (mm) is the diameter.
- For rectangular prism-shaped test items, e.g., a typical munition or multiple munitions packaged in a typical cuboid-shaped container, the dimension S (mm) is the length of the diagonal between the two shortest sides.

ANNEX B: HISTORICAL OVERVIEW: History of the Slow Heating Test Requirements

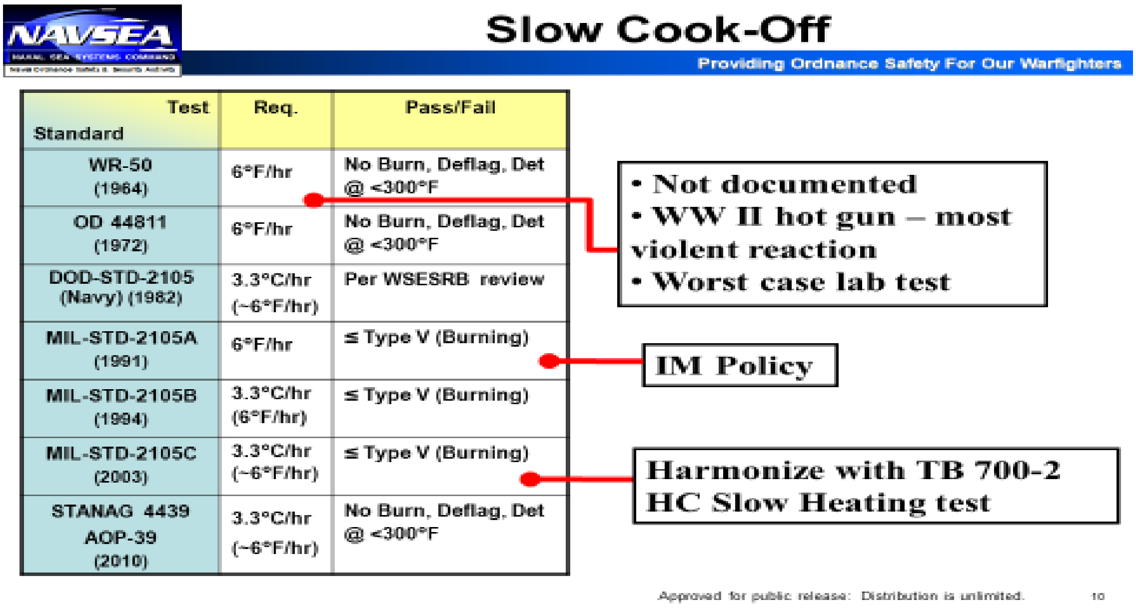
B.1 FORWARD

The objective of this historical report is to provide background information that established the Slow Heating Test and a summary of the research / work determining realistic heating rates potentially seen during the life-cycle of a munition. It is not meant to be a comprehensive review. All information referenced in this report was used as the basis of the final heating rate selected in procedure #1. The current SCO test procedure, as outlined in AOP 4382, Version 1, Edition 1, specifies that the munition be heated in an oven wherein the air temperature is increased at a constant rate of 15.0°C/hr. (22°F/hr.) until the item reacts. There is also a provision that allows a different heating rate to be selected (procedure 2) in an effort to Harmonize testing with the Hazard Classification requirement of 3.3°C/hr. (6.0°F/hr.). A third procedure is listed such that allows a rate to be selected based on the requirements identified in a Threat Hazard Assessment. The passing criterion for all procedures is a reaction violence no more severe than burning (Type V).

B.2 IN THE BEGINNING…

The Navy established a very robust weapons safety program in response to the Accident on the USS Forrestal on 29 July 1967. A Zuni rocket misfired flying across the deck striking the fuel tank of an A-4 Skyhawk jet. It ruptured a fuel tank, caught fire and caused a massive amount of damage. The results of the accident killed 134 Sailors, injured another 161 and destroying 21 aircraft. The ship lost its operational capacity for a long time.

The Navy's highest priority within their safety program was to fully characterize the thermal properties and to transition technologies that would help minimize the reaction level of the munition during an accident. Thermal tests included testing new materials and weapons at several different heating rates to establish a thermal profile. At one extreme of the heating rate an energetic material was placed in a fuel fire, later to be call the Fast Cook Test and then the Fast Heating Test. And at the other extreme, the material was placed in an oven and heated at 3.3°C/hr. These tests were analyzed but not scored. Thermal tests were conducted for several years but were first listed in the Navy's WR-50 as policy. Interim documentation and testing demonstrated the need for a safety program. It was speculated that the slowest possible heating that the oven controllers could reliably function at the time was 3.3°C/hr (6°F/hr or one degree increase for every 10 minutes). Later, that rate was justified by the scenario of a large steam leak in an adjacent room filled with munitions. This 3.3°C/hr was conservative, based upon the knowledge at the time, but the specific scenario used to justify this rate has been proved to not be valid. Regardless of the origins, the SCO test was usually performed at a rate of 3.3°C/hr for more than 50 years. Other rates had been used, the US Army Insensitive Munitions Board used a rate of 27.8 °C/hr (50 °F/hr until US harmonization). In 1991, it was listed in MIL-STD 2105A as an IM test with a pass/fail criterion. Figure 1 shows a US Navy historical progression on documentation involving slow heating characterization.



Standard / Test	Req.	Pass/Fail
WR-50 (1964)	6°F/hr	No Burn, Deflag, Det @ <300°F
OD 44811 (1972)	6°F/hr	No Burn, Deflag, Det @ <300°F
DOD-STD-2105 (Navy) (1982)	3.3°C/hr (~6°F/hr)	Per WSESRB review
MIL-STD-2105A (1991)	6°F/hr	≤ Type V (Burning)
MIL-STD-2105B (1994)	3.3°C/hr (6°F/hr)	≤ Type V (Burning)
MIL-STD-2105C (2003)	3.3°C/hr (~6°F/hr)	≤ Type V (Burning)
STANAG 4439 AOP-39 (2010)	3.3°C/hr (~6°F/hr)	No Burn, Deflag, Det @ <300°F

Figure 1: 2010 IMEM Technology Symposium, Oct 2010, Dr. Kerry Clark

Historically the heating rates have been periodically reviewed, using the best available data at the time. Joint Army, Navy, NASA, and Air Force (JANNAF) workshops where held in 2011, 2012, and 2015 on the subject as well as a MSIAC Workshop on the Science of Cook-off in 2016. Internal reviews by Porada (2006), Frey (2000), Fontenot et al (1988) and Gokee (1996) were conducted determining the best heating rate, with varying results. Conclusions of these reviews is best summed by Frey "Fires come in an infinite variety, and I do not think any analysis will ever lead to a single appropriate rate."

B.3 AC/326 CUSTODIAN WORKING GROUP

There has been increasing pressure to change the test requirement 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, or costs are being increased for an unrealistic rate.

In the spring of 2016, AC/326 approved the formation of the Slow Heating Custodian Working Group (SH CWG) to investigate the SCO heating rate and to revise STANAG 4382, creating a new Allied Ordnance Publication (AOP). At the first SH CWG 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 AC/326 Subgroup B chairman to request that a study be performed which would summarize any slow heating related accidents and previously performed slow heating analysis to be presented at subsequent SH CWG meetings. Additional modeling was also performed to specifically examine slow heating rates. This material was meant to present facts to the group and help guide the discussion towards realistic threat scenarios. This new analysis was funded by the US Navy.

B.4 INVESTIGATION OVERVIEW

The investigation that was performed was done in three stages:

1. A review of historical incidents
2. A review of existing slow heating related analysis
3. Additional modelling of slow heating 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.

B.5 HISTORICAL INCIDENTS

The goal of the incident review was to attempt to predict a lower bound for potential slow 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 slow heating event 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 included.

These accidents were sorted by type (location):

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 transporting energetics by truck, train, or ship.
4. Plant - incident occurred at a production facility where energetic materials are manufactured.

The bar chart in Figure 2 shows the total duration of the 73 incidents while the pie chart shows the distribution by type.

Figure 2 demonstrates that the vast majority of the incidents occurred either at depots or on warships and only a few involved transportation and plant incidents. 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 fires are fought ferociously.

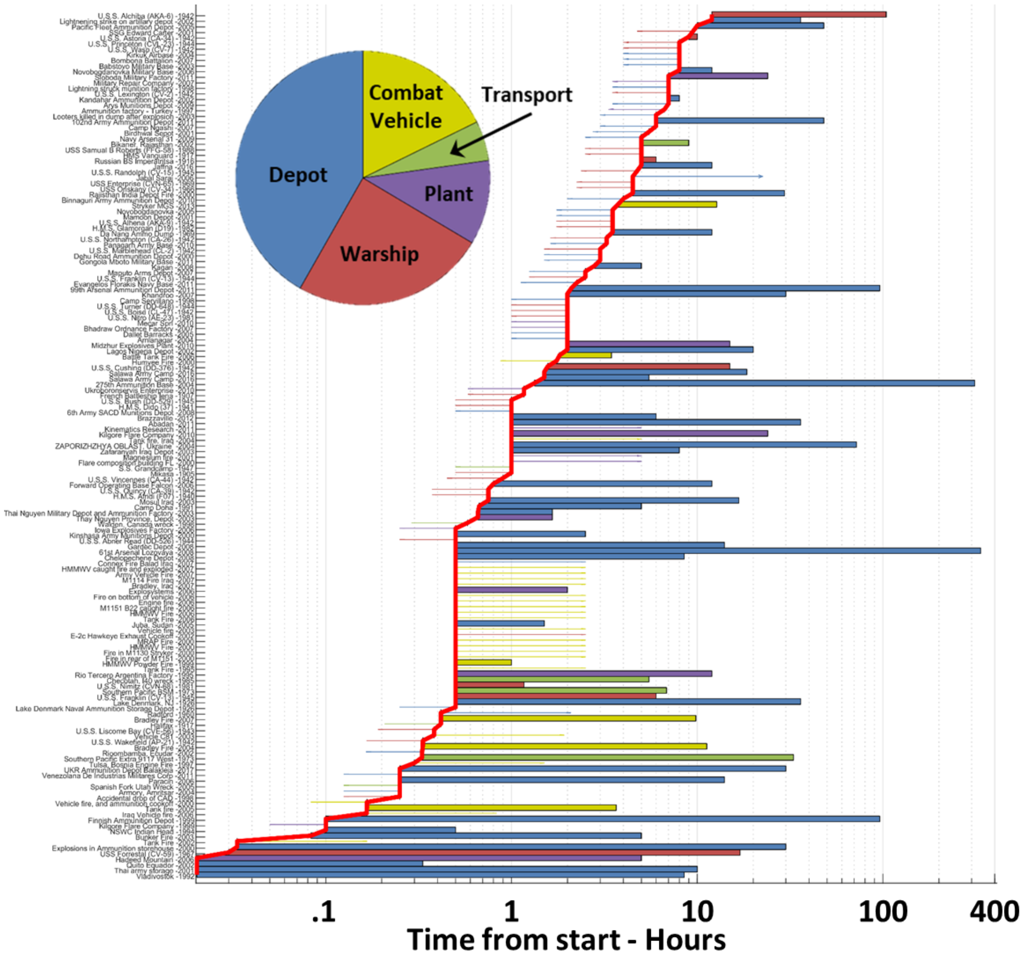


Figure 2: Plot showing the distribution of incident type and duration. The red line indicates t_{max}.

With t_{max} known for the incidents shown in 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 3. 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. Based on the assumptions used, 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 3. 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.

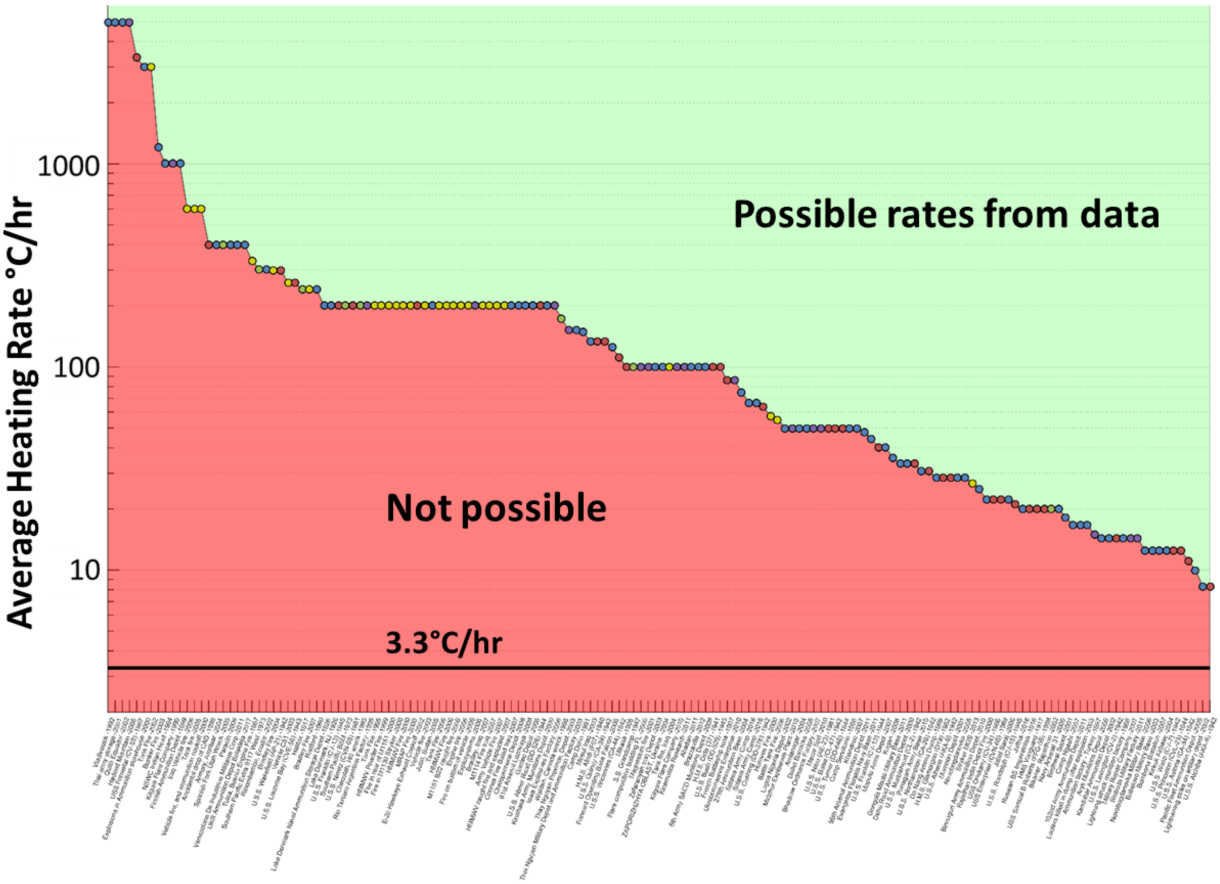


Figure 3: Possible heating rates that led to initial reaction for each incident

B.6 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 slow heating 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:

- ➔ Transportation accident – truck or train fire
- ➔ Dump storage accident – a fire moving past an ammunition storage area
- ➔ Debris pile from a deck fire – aftermath of a fast heating event
- ➔ Below deck fire – fire heats the bulkhead of a storage magazine in a ship
- ➔ Steam leak – steam leaks into a magazine on a ship and heats ordnance

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 slower 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 slow heating 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 slow heating event 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.

B.7 ADDITIONAL MODELING

The goal of this modeling investigation was to determine the slowest possible heating rate that an ordnance item could experience in service that could result in a cook-off. Before a model can be used to attempt to answer this question, an underlying assumption is required. Specifically, what is the lowest possible temperature at which a cook-off could occur? It will then be assumed that once the magazine air reaches this temperature, then it will be possible for a cook-off to occur. In this work, a threshold temperature of 130°C was chosen as the lowest possible temperature that could result in a cook-off. This value was chosen based on a number of conversations with various subject matter experts and is considered a conservatively low number. This value is considered conservative because any increase in this threshold value will result in an increase in the calculated heating rate. While this might appear counter intuitive, the reason behind this become clear once a simple thermal model was developed that simulates the magazine/fire system. 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. For more details, please see Hubble, D.O., “*An Investigation into a Proper Heating Rate for Slow Cook-off Testing*” 2018 IMEMTS.

The model allowed a number of parameters to be varied throughout the study and one that had a large impact on the results was the size of the fire. For example, the left figure in Figure 4 demonstrates this effect by showing ten different magazine gas temperature curves 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 increases the calculated rate drastically 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. This fire size, which must be determined for each set of parameters, is therefore the one that produces the slowest rate that could produce a cook-off at a shorter period of time. In the graph on the right in Figure 4, the final magazine temperature is plotted along with the time to 90% temperature rise. For each case, an average heating rate can be 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 model results are presented.

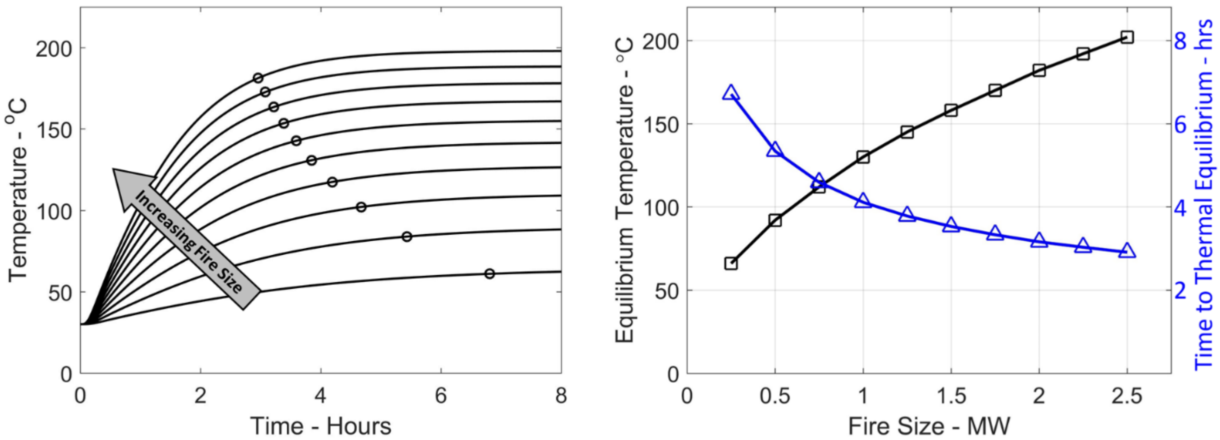


Figure 4: At left, increasing fire size causes magazine gas to reach a higher temperature in a shorter amount of time as shown by the equilibrium temperatures and time to equilibrium temperatures shown at right.

The effects of changing the size and aspect ratio (width/length) of the magazine was investigated. The results for an empty magazine with 12.7mm thick walls are shown in Figure 5. For each set of magazine parameters (wall thickness, area, and aspect ratio) the model was run a number of times to determine the fire size required that resulted in a final magazine temperature of 130°C. These results are shown in the figure at left. The final magazine temperature and time to reach equilibrium were used to determine the average heating rate for each case as shown at right.

As expected, as the size of the magazine and its surface area increase, 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 defined by the width times 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 decreases. To obtain a higher bulkhead temperature, a larger fire is required.

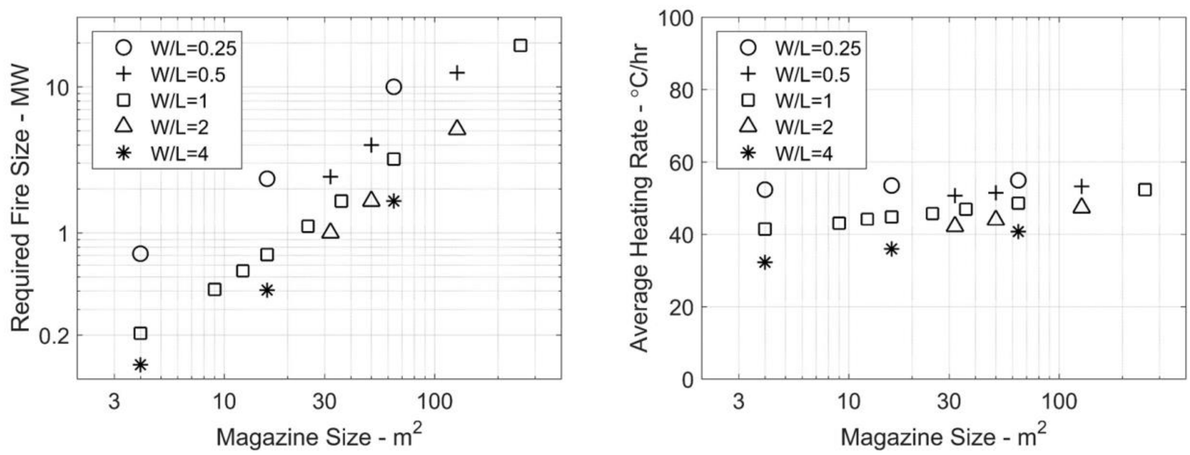


Figure 5: The size and aspect ratio of the magazine compartment has a large influence on the size of fire required to reach 130°C (left) but has a modest impact on the average magazine heating rate (right)More important is the effect on average heating rate. As the size of the magazine increases, its thermal mass increases but the size of fire required to reach 130°C also increases. The end result is that the two affects essentially offset and the effect of magazine size on average heating rate is minimal. The aspect ratio actually has a larger influence on average heating rate then the size of the magazine.

The results shown in Figure 5 were for an empty magazine with 12.7mm thick walls. The addition of ordnance to the magazine significantly affects the heating rate as shown in Figure 6. Here, the average heating rates for full magazines are shown for two different wall thicknesses: 12.7mm thick walls in the left figure and 25mm walls in the right figure. For smaller magazines, both the bulkhead thickness and aspect ratio have a larger impact on the heating rate then for larger magazines. This has to do with the ratio of wall mass to ordnance mass. For small magazines, even when fully loaded the mass of the magazine walls is significant compared to the mass of the ordnance that it contains. As the size of the magazine increases, the mass of the ordnance within the magazine increases more rapidly than the mass of the magazine walls and dominates. That is why the average heating rate for the largest magazine with 12.7mm thick walls is 12°C/hr and increasing the wall thickness of the same magazine to 25mm only reduces the average heating rate to 10.5°C/hr.

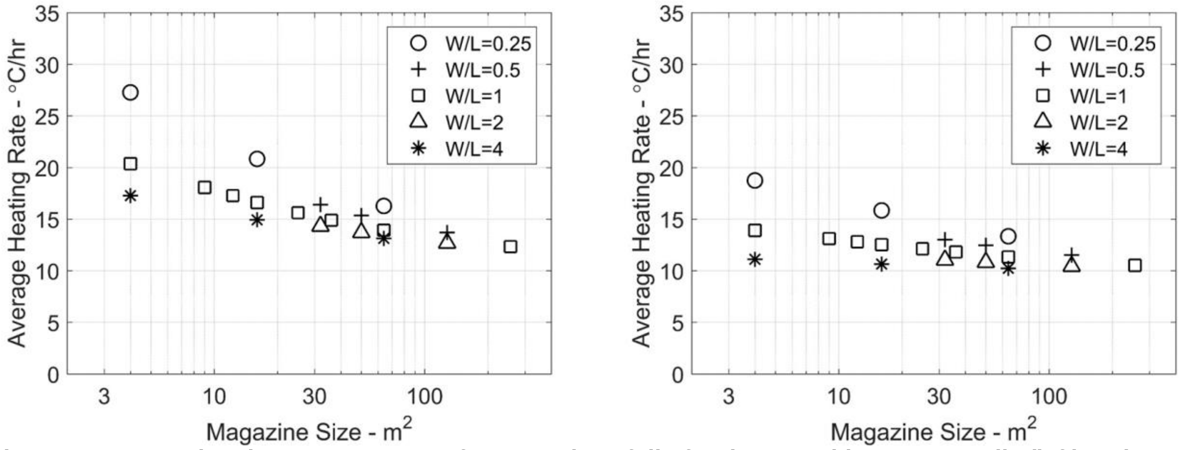


Figure 6: Average heating rates to 130°C for magazines full of ordnance with 12.7mm walls (left) and 25mm walls (right)

B.8 THE WAY FORWARD

The historical information and model analysis data were presented to the SH CWG which concluded that it did not make sense to continue to develop technologies to "fix" the munition shortfalls at the slower heating rate. Each consensus of the SH CWG was that the heating rate should be somewhere between the slowest legitimate rate of 10°C/hr (which is slower than the conservative estimate for 98% of all incidents investigated) and 25°C/hr (still slower than 80% of incidents) and after further discussions that was narrowed to between 15°C/hr and 20°C/hr. The final decision was to establish the new rate at 15°C/hr (covering 92% of incidents) based on two ideas; the first was that it was closer to the original rate in an effort to be able to still compare to the existing baseline test data and the second while it still represented the legitimate rate found in "real-life" accident scenario.

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