

**NATO STANDARD**

**AOP-4382**

**SLOW HEATING  
TEST PROCEDURES FOR MUNITIONS**

**Edition A, Version 2**

**MARCH 2022**



**NORTH ATLANTIC TREATY ORGANIZATION**

**ALLIED ORDNANCE PUBLICATION**

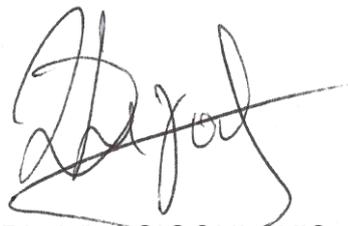
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4 March 2022

1. The enclosed Allied Ordnance Publication AOP-4382, Edition A, Version 2, 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.
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<b>CHAPTER 1      INTRODUCTION</b>
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When reviewing requirements for this test, **SRD AOP-39.1** should first be read for guidance in the organization, responsibilities and conduct of full-scale testing.

**1.1 ANNEXES**

- A. Best Practices
- B. Historical Overview

**1.2 RELATED DOCUMENTS**

STANAG 4439	Policy for Introduction and Assessment of Insensitive Munitions (IM)
AOP-39	Policy for Introduction and Assessment of Insensitive Munitions (IM)
SRD AOP-39.1	Guidance on the Organization, Conduct and Reporting of Full-scale Tests
STANAG 4382	Slow Heating Test Procedures for Munitions
AASTP-03	Manual of NATO Safety Principles for the Hazard Classification of Military Ammunition and Explosives
United Nations	Manual of Tests and Criteria (ST/SG/AC.10/11)

**1.3 AIM**

The aim of this AOP is to specify the test requirements and procedures to provide evidence of the response of munitions and weapon systems to the threat represented by 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**

1. Participating nations agree that the requirements and methods incorporated in this AOP will be used for determining the response of munitions and weapon systems to a gradually increasing thermal environment.
2. 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.

3. No departure may be made from this agreement without consultation with the NATO Tasking Authority. Nations may propose changes at any time to the NATO Tasking Authority where they will be processed in the same manner as the original agreement.

## **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 Database (NATOTerm) that is available by reference for all Allied Publications.<sup>1</sup>

## **1.6 GENERAL**

1. Efforts to minimize the violence of the reaction of munitions to slow heating conditions is a continuing commitment of weapons designers in order that the safety of personnel and materiel will not be unduly jeopardized.

2. This AOP addresses the situation where munitions and weapon systems are exposed to a nearby prolonged heating source. This can occur in peacetime as the result of an accident, dissident/saboteur activity, or on operations as a consequence of enemy action, which can result in a significant compromise of safety.

3. The objective of the Slow Heating Test is to determine the response of the munition(s) when subjected to an adjacent heat source for a prolonged timeframe.

4. This test may also be used for Hazard Classification (HC) as required by AASTP-03 and UN Document ST/SG/AC.10/11 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 a test is to be used for Hazard Classification, an agreement must be reached between Hazard Classification and Safety Authorities on the required test, number of test items, their configuration (e.g. packaged or unpackaged), and the number of tests to be performed.

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<sup>1</sup> <https://nso.nato.int/natoterm/>

## 1.7 TEST LIMITATIONS

1. The Slow Heating Test is designed only to simulate a consistent thermal condition that a munition might experience when exposed to an adjacent heating source over a prolonged period. This test does not, however, simulate a particular in-service or accident scenario. Should it be desired to represent specific in-service or accident scenario, Method 2 may be modified to simulate the actual event scenario reflected by the heating rate and test configuration. The heating rate identified for the Standard Test (Method 1) may not represent the most hazardous condition for all energetic materials.
2. Test items filled with energetic materials that are 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 this test should not be extrapolated with respect to either temperature or time in order 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.

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<b>CHAPTER 2      TEST SPECIFICATIONS</b>
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## 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 AOP.

2. Guidance on variations to the production standard and condition (e.g. live vs inert, pre-conditioning, packaged vs unpackaged, single vs multiple test items, All-Up-Round vs component-level) as given in SRD AOP-39.1 Annex B shall be considered.

## 2.2 TEST DETAILS

### 2.2.1 Test Methods

There are three methods for performing the Slow Heating Test for Munitions:

- a. Method 1 (Standard): Precondition the test item in the oven at 50 °C ( $\pm 3$  °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, modelling 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.]

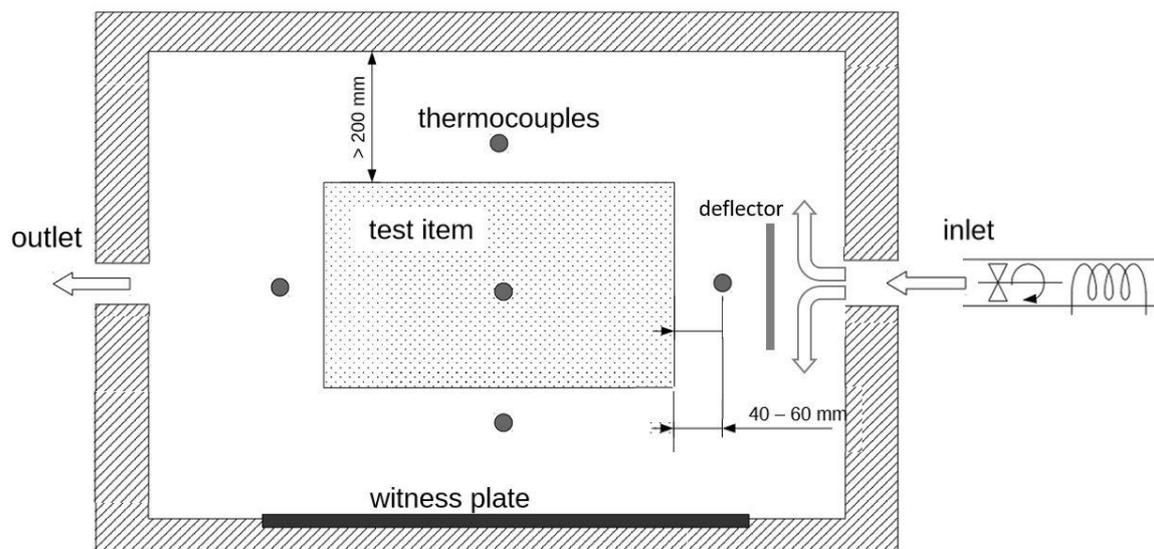
- b. Method 2 (Alternative): Temperature preconditioning may be used but is not required with this test method where **the heating rate is based on a Threat Hazard Analysis (THA)**. Real scenarios for slow heating can lead to many heating rates. If a THA analysis suggests that a particular heating rate is appropriate for the test item, the heating rate identified by the analysis may be used as approved by national authorities. Details of the relevant THA should be provided with the test data in the test report.
- c. Method 3. (Hazard Classification Alternative): 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. This Method is currently used for **Hazard Classification** purposes and may be used if required.

### 2.2.2 Test Requirements

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.

- a. **Test Facility (Oven)**. 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.

- b. **Oven Construction and Instrumentation.** 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.



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

**ADVISORY NOTE:** Figure 1 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. 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.

### 2.2.3 Test Set-Up

1. The test item condition and orientation shall be applied in coherence with the life cycle phase represented by the test, or representative as approved by the National Authority.
2. Additional guidance on variations to the test conditions (positioning/orientation, restraints, conditioning, marking, reuse, etc.) as given in SRD AOP-39.1 Annex B shall be considered.

### 2.2.4 Number of Tests

A minimum of two tests shall 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, thus, 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.

## 2.3 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 upon 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.

## 2.4 OBSERVATIONS AND RECORDS

Guidance on specific aspects of the conduct of testing, observations and data recording is discussed in more detail in SRD AOP-39.1. Unless noted as “optional”, for IM purposes, the following minimum observations must be made and records kept. Test recommendations, records, and observations for HC testing and assessment are included in the UN Manual of Tests and Criteria and the Globally Harmonized System of Classification and Labelling of Chemicals, are not optional.

- a. Test item identification and configuration (model, serial numbers, number of test items, etc.); Type of energetic material and weight, listing of environmental preconditioning tests performed; 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. Record of events, versus time from the start of preconditioning to the end of the test.
- d. Record of Thermal data: A record of temperature versus time (heating rate), from the start of preconditioning to the end of the test (time zero = start of oven temperature rise) and thermocouple readout (versus time) for all sensors.
- e. Nature of any reactions by the Test Item.
- f. Photo imagery of the test item and the test setup before and after performing the test.
- g. Nature and distribution of remains/residue and debris including: range, position, photographs, identification (as possible), and mass of each piece.
- h. Meteorological data (wind speed, direction) during the test.
- i. Indication of propulsion (video or other suitable means).
- j. Audio and video records: A recording device shall be placed near the trial site to record all audio and enable correlation between visible events and indicated time.
- k. Suitable Blast or overpressure gauges should be positioned around the test item to record pressure-time history with a record of gauge location and height.
- l. Witness plates and screens (optional) as a measure of projection severity; Photographs of witness plates and screens (if used). Number and depth of penetrations in fragment recovery panels (if used).
- m. A complete data record shall be compiled to include pressure, sound, imagery, fragmentation, debris and propulsion information.

## **2.5 EVALUATION OF TEST RESULTS**

Policy and procedures for evaluation of test results are given in:

- a. AOP-39, Policy for Introduction and Assessment of Insensitive Munitions (IM);
- b. AASTP-03, Manual of NATO Safety Principles for the Hazard Classification of Military Ammunition and Explosives.

<b>ANNEX A BEST PRACTICES</b>
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**A.1 METHODS TO DETERMINE TEMPERATURE PRECONDITION TIME**

1. There is a temperature preconditioning requirement for Test Method 1 and optional for Methods 2 and 3. The test item shall be soaked at  $50\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$  until it reaches thermal equilibrium. In this case, thermal equilibrium is defined as  $50\text{ }^{\circ}\text{C} +3\text{ }^{\circ}\text{C} / -5\text{ }^{\circ}\text{C}$ . 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 chosen to determine when thermal equilibrium has occurred be included in the test plan. The test plan must be 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 heat transfer 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  $50\text{ }^{\circ}\text{C}$  oven before all of the energetic material within the item reaches a temperature of at least  $45\text{ }^{\circ}\text{C}$ . 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  $10\text{-}25\text{ W/m}^2\text{K}$  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.

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

Note:

- 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.

<b>ANNEX B HISTORICAL OVERVIEW</b>
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**B.1 REVISION PROCESS****B.1.1 IM Test AOP Standardization Working Group (2020-2021)**

1. In the time between April 2020 and April 2021, AOP-39, -39.1, -4240, -4241, -4382, -4396, -4496, and -4526 have been revised. The objectives of these revisions, executed by the IM Test AOP Standardization Working Group, were:

- a. Fix grammatical and spelling mistakes, clerical errors, and enforce a uniform structure, format, and wording across all AOPs for the sake of readability and ease-of-use.
- b. Ensure that the AOPs only contain requirements.

2. Altering any technical content was not permitted, because the group aspired to merely update each AOP's Version and not release entirely new Editions.

3. To achieve the second goal, guidance and best practices were to be moved into the SRD AOP-39.1. However, accomplishing this was not entirely possible. It was agreed that all AOP-specific guidance remains in each AOP's Annex A, while all guidance that applied to two or more AOPs was marked to be moved into the SRD.

4. The IM Test AOP Standardization Working Group also made notes about topics that could potentially be discussed at future gatherings of each AOP's respective Custodian Working Group.

5. A total of 26 meetings took place, all of them virtually. The involved people were the Custodians of the various documents as well as representatives of MSIAC and AC/326 SG/B.

**B.1.2 Creation of AOP-4382 Edition A**

1. In 2010 NATO's Ammunition Safety Group (AC/326) empowered their munition Subgroup B (Ammunition Systems Design & Assessment) to establish Custodian Working Groups for each of the IM-related STANAGs as a means of reviewing and updating the IM test requirements where needed. Several nations participated in these Working Groups to address the individual IM test requirements in succession, including fast heating, bullet impact, shaped-charge jet impact fragment impact, slow heating and finally sympathetic reaction. Each topic required multiple meetings to produce the desired end product – a draft AOP document that contained the revised, updated test requirements. These new AOPs would then become companion documents to their respective STANAGs with the STANAG as the lead or referencing document only.

2. There were four Slow Heating Custodian Working Group (SH CWG) meetings during the period April 2017 – September 2018. These meetings were conducted to review and update the test requirements of STANAG-4382 and create AOP-4382. The SH CWG deliberations included very lengthy discussions, sometimes supported by detailed technical investigations, on many topics related to this test and its procedural requirements. The following topics were addressed:

- a. Purpose & Goals of the SH test
- b. Test Procedure
- c. Heating Rate
  - (1) Historical records related to heating rate
  - (2) New/updated requirements
  - (3) Heating rate based on test item size
- d. Oven Design
  - (1) Forced flow
  - (2) Requirement for a standard design
- e. Temperature Preconditioning
- f. Reaction Temperature

### B.1.3 Changes from STANAG 4382 Edition 2

Many changes to the documented test requirements are apparent when comparing STANAG 4382 (Edition 2) and AOP-4382 (Edition A). An improved standardized format was used for all of the new IM test AOPs that were established. IM and Hazard Classification test harmonization was considered during the formulation of the updated SH test requirements. The most significant changes in this update are summarized below.

a. **Purpose & Goals of a Slow Heating Test**

STANAG – Test objective/purpose/goals not explicitly stated. Two test procedures are listed under the “AIM” of the test.

AOP – Clearly states the purpose and intent of this test under the “AIM.”

b. **Definitions**

STANAG – Refers to AOP-38 for definition of terms.

AOP – Refers to NATO Term Database (AOP-38 now obsolete) for definition of terms.

c. **Standard Test Item**

STANAG – Describes a “Standard Test Item” as a subparagraph under “Test Facilities.”

AOP – Provides similar details under a new paragraph “Test Item Configuration in Chapter 2, Test Specifications.

d. **Test Procedures/Methods**

STANAG – Lists two test procedures under subparagraph “Test Requirements” in the “Test Facilities” section: (1) a Standard Test with a heating rate of 3.3 °C/hr.; and (2) an alternate procedure with a tailorable heating rate determined by a THA.

AOP – Lists three test methods under the “Test Methods” subparagraph in Chapter 2, “Test Specifications”: (1) a Standard Test with a heating rate of 15 °C/hr.; (2) an alternate test with a tailorable heating rate determined by a THA; and (3) the Hazard Classification test that is the UN 7(h) test for HD 1.6 assignment.

e. **Preconditioning**

STANAG – Provides requirement for test item preconditioning for the Standard Test.

AOP – Also states preconditioning requirement as part of the Standard Test description but a new Annex provides three methods to determine the temperature preconditioning time.

**f. Oven Details**

STANAG – Details of a disposable oven are provided in a subparagraph listed in the “Test Facility” section. It limits a temperature gradient between input/output air streams to 5 °C. Also states a minimum of 4 thermocouples for surface temperature monitoring.

AOP – Details of the oven/test facility are given in three paragraphs under the “Test Requirements” section. Temperature gradient around the test item is limited to 15 °C. A minimum of 6 thermocouples are required with an option for 2 additional thermocouples if needed.

**g. Test Documentation**

STANAG – No specific guidance or statements are provided for test documentation and compliance.

AOP – A “Documentation and Compliance” section was added that cites Test Directive, Test Plans and reporting and refers to SRD AOP-39.1 for details.

**h. Instrumentation**

STANAG – Detailed descriptions of required test instrumentation, constraints, and observations and records are listed.

AOP – Information and requirements regarding test instrumentation and test data that are unique for this test are given in the “Observations and Records” subparagraph. Additional instrumentation guidance is now given in the referenced SRD AOP-39.1.

## **B.2 BACKGROUND AND TEST ORIGIN**

### **B.2.1 Background**

The objective of this historical report is to provide background information that established the new Slow Heating Test requirements and provide an historical record of the research and work to determine 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 for Test Method 1.

### **B.2.2 Test Origin**

1. A Slow Cook-off Test (now titled Slow Heating Test) was originally part of a System Safety Test Series, WR-50, in the US. No pass/fail criterion was established for this test. The purpose of the test was to determine the time to a reaction, not the reaction violence. This was deemed critical information for the firefighting community. However, the US Navy recognized that major improvements to weapon safety requirements must be made in response to the accident aboard the USS Forrestal on 29 July 1967. A Zuni rocket misfired flying across the deck striking the fuel tank of an A-4 Skyhawk aircraft. It ruptured a fuel tank, caught fire and caused a massive amount of damage on and below deck. This accident resulted in 134 casualties, 161 injured crew members and destroyed 21 aircraft. The ship lost its operational capability for an extended period.

2. The Navy's highest priority within the improved safety program was to fully characterize the thermal properties of munitions and to transition technologies that would help minimize the reaction level of the munition during exposure to a slow heating event. Thermal tests included testing new materials and weapons at several different heating rates to establish a thermal profile. At one extreme a very high heating rate was generated for a live test munition placed in a fuel fire, the original Fast Cook-off Test (now renamed as the Fast Heating Test). And at the other extreme, the live test item was placed in an oven and heated slowly at a rate of 3.3 °C/hr. The responses from these tests were compared often and used to establish a thermal response profile. The heating rate prescribed for this test was the major issue when the requirements for this test were first established and remained a controversial issue for many years.

### **B.2.3 Heating Rate Requirement Investigation**

1. During the period when slow cook-off testing was only a system safety test procedure, it was speculated that the slowest possible heating that the oven controllers could reliably function at that time was 3.3° C/hr. (6 °F/hr. or one degree increase for every 10 minutes). Later, that rate was justified by presuming a large steam leak in an adjacent magazine filled with munitions. This 3.3 °C/hr. rate was conservative, based upon the knowledge at the time, but this specific event scenario used to justify this heating rate was eventually proven to not be valid in that maximum temperatures in

this scenario were below critical temperatures of energetic materials. Regardless of the origins, the slow cook-off testing 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 B-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

**NAVSEA**  
NAVAL AIR SYSTEMS COMMAND  
Naval Ordnance Safety & Security Activity

**Slow Cook-Off**  
Providing Ordnance Safety For Our Warfighters

- **Not documented**
- **WW II hot gun – most violent reaction**
- **Worst case lab test**

**IM Policy**

**Harmonize with TB 700-2 HC Slow Heating test**

Approved for public release: Distribution is unlimited. 10

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

2. Historically, the slow heating rates have been periodically reviewed, using the best available data at the time. Joint Army, Navy, NASA, and Air Force (JANNAF) workshops were 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 to assess the best heating rate, with varying results. A conclusion 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.”*

3. There had been increasing interest within the IM community to conduct an in-depth evaluation of the heating rate requirement for slow cook-off, now slow heating, testing. If a change to this requirement would be established, then the rate specified in Method 1 would better represent realistic heating scenarios. However, there was a 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 rate.

4. A study was conducted to summarize any slow heating related accidents and previously performed slow heating analyses. Additional modeling was also performed to specifically examine slow heating rates. The investigation that was performed was done in three stages:

- Stage 1: A review of historical incidents

- Stage 2: A review of existing slow heating related analysis
- Stage 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 reaction.

5. 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 explosive-filled munitions. 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 focused on determining total heating duration prior to reaction.

6. 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 explosive-filled munitions 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 the period 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):

- Depot – incident occurred at a military facility where munitions are stored.
- Warship - incident occurred on a military ship other than a transport ship.
- Transportation - incident occurred transporting energetics by truck, train, or ship.
- Plant - incident occurred at a production facility where munitions with energetic materials are manufactured.

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





2. 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.

3. The final scenario examined an intermediate pressure (saturated at 3100 kPa 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.

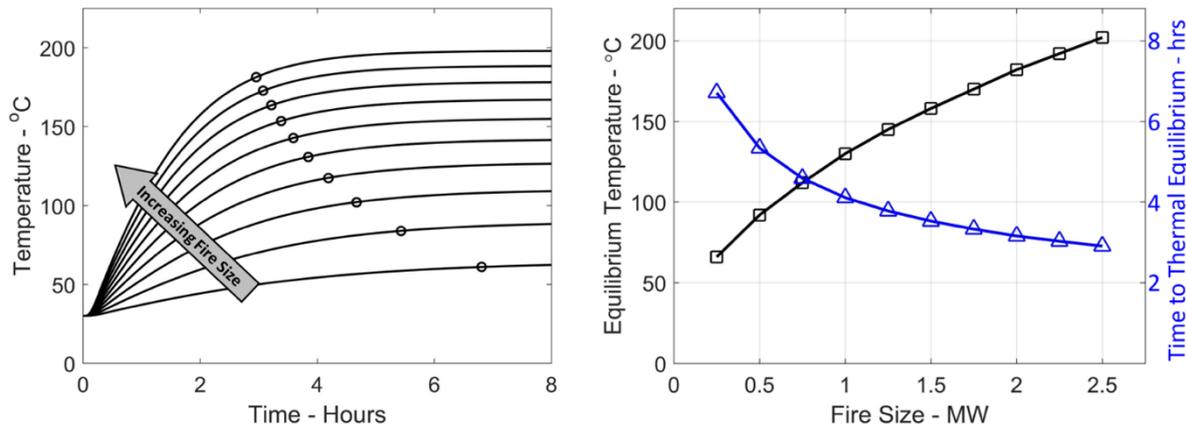
4. In a later report, Mansfield (Mansfield, 1996) identified the below deck fire as the most likely scenario that would result in a slow heating event and created a computer model that allowed it to be examined in detail. Specifically, the model allowed parameters such as fire size, bulkhead thickness, 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.

5. 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. ( $[150\text{ °C} - 30\text{ °C}] / 8\text{hrs}$ ) which is significantly faster than the 3.3 °C/hr. currently being used.

### B.2.5 Additional Modeling

1. 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.

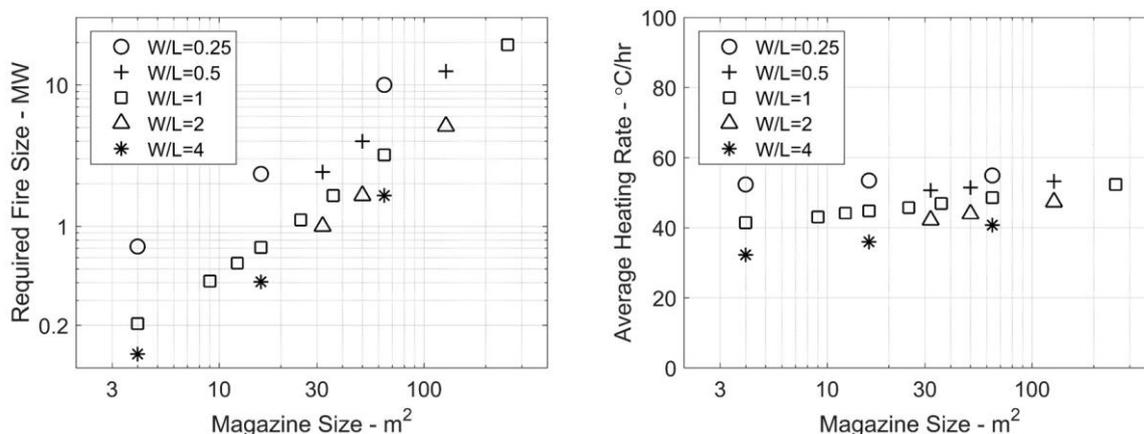
2. The model allowed a number of parameters to be varied throughout the study and one that had a large impact on the results was the size of the fire. For example, the left figure in Figure B-4 demonstrates this effect by showing ten different magazine gas temperature curves where the fire sized was varied from 0.25 MW to 2.5 MW. 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  $\Delta T$  is increasing and  $\Delta t$  is decreasing. Also, for the case shown here, the slowest rate of concern occurs for a fire size of 1 MW 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 B-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  $\Delta T$ ) and then dividing by the time to equilibrium ( $\Delta t$ ). Note that as the fire size model results are presented.



**Figure B-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.**

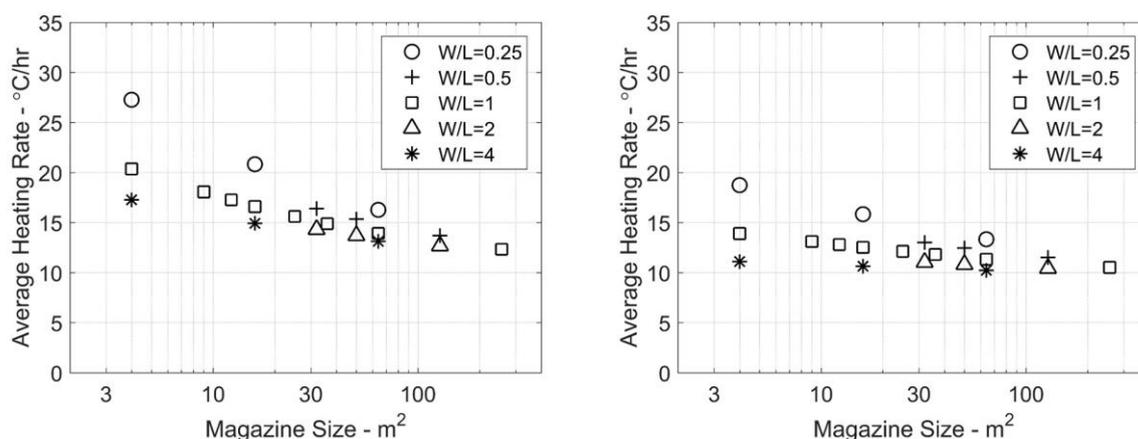
3. The effects of changing the size and aspect ratio (width/length) of the magazine was investigated. The results for an empty magazine with 12.7 mm thick walls are shown in Figure B-5. For each set of magazine parameters (wall thickness, area, and aspect ratio) the model was run a number of times to 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.

4. 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 B-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.**

5. The results shown in Figure B-5 were for an empty magazine with 12.7 mm thick walls. The addition of ordnance to the magazine significantly affects the heating rate as shown in Figure B-6. Here, the average heating rates for full magazines are shown for two different wall thicknesses: 12.7 mm thick walls in the left figure and 25 mm 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 12.7 mm thick walls is 12 °C/hr. and increasing the wall thickness of the same magazine to 25 mm only reduces the average heating rate to 10.5 °C/hr.



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

6. 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 of 3.3 °C/hr. 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 scenarios.

### B.3 REFERENCES

D. Pudlak, K. Tomasello, “Revisions and Improvements to the NATO Insensitive Munitions Test Doctrine Portfolio”, NATO AC326 SG/B Spring Meeting, April 15-16, 2021

"TB 700-2 Department of Defense Ammunition and Explosives Hazard Classification Procedures," 2012.

"North Atlantic Treaty Organization Standardization Agreement (NATO STANAG 4382) Slow Heating Munitions Test Procedures," 2003.

"MIL-STD-2105D, Department of Defense Test Method Standard, “Hazard Assessment Tests for Non-Nuclear Munitions”,” 2011.

D. O. Hubble, "An Investigation into a Proper Heating Rate for Slow Cook-off Testing," in IMEMTS, Portland, OR, 2018.

D. O. Hubble, " Investigating a Proper Heating Rate for the Slow Heating Test Using Documented Incidents," in International Explosives Safety Symposium & Exposition, San Diego, CA, 2018.

T. L. Boggs, K. P. Ford and J. Covino, "Realistic Safe-Separation Distance Determination for Mass Fire Hazards," 2013.

"MSIAC Accident Database eXchange," 2018. [Online]. Available: <https://portal.msiac.nato.int/>.

Bailey, J. T. (1995). Validation of Fire/Smoke Spread Model Using Ex-USS Shadwell Internal Conflagration Control Fire Tests. NRL/MR/6180-95-7781.

Jacobson, J. S. (1988). Analysis of Heating Rate for the Insensitive Munitions Slow Cook-off Test.

Mansfield, J. A. (1996). Preliminary Analysis of the Heating of Ordnance in Ship Magazines Due to a Fire in an Adjacent Compartment".

Wickstrom, U. (2016). Temperature Calculation in Fire Safety Engineering. Springer

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