Analysis of the Ramifications of Increasing the Slow Cook-off Test Heating Rate

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Abstract

The Slow Cook-off (SCO) test is intended to simulate accident scenarios in which munitions are slowly heated over an extended duration. Historically, this meant that munitions were heated at a constant rate of 3.3°C/hr until a reaction occurred. Recently, however, NATO subject matter experts (SMEs) met and agreed to increase the rate of future SCO tests to 15°C/hr; a heating rate increase of 350%. The increased heating rate ensures that SCO tests are better aligned with real-world accident scenarios. One major drawback of the rate change, however, is that tests conducted at the new heating rate will not be directly comparable to the historical database of test results built over many years which were conducted at the old (3.3°C/hr) rate. This means that the tests performed at 3.3°C/hr are not necessarily indicative of munition performance at the new, elevated heating rate. Furthermore, although the SMEs selected a new heating rate, some of the specific thermal parameters required to fully define the SCO test had not yet been agreed upon. These details were needed in order to complete the Allied Ordnance Publication (AOP) which specifies how the test must be performed. In an effort to help the SMEs determine the appropriate values for one of these remaining test parameters, and to start building a new database of test results, multiple tests were performed at the newly selected heating rate. This paper will summarize the results of these tests. Additional analysis is also presented that examines how the heating rate increase influences key test parameters.

Background

Both the Insensitive Munitions (IM) SCO test and the slow heating test used for Hazard Classification (HC) are performed to simulate accident scenarios in which a munition is slowly heated over an extended period of time. The SCO scenario can arise during logistical transport and storage when a fire occurs but is not in direct contact with the munition. The slow heating environment encountered during a SCO event results in heat fluxes two to four orders of magnitude lower than scenarios in which the munition is directly exposed to the fire. This results in proportionally smaller thermal gradients within the munition and a high average explosive fill temperature at the time of reaction. For many energetic materials, this elevated temperature can lead to sensitization and a more violent reaction. Additionally, the duration of the thermal insult also influences the violence of the subsequent reaction. Evidence suggests [1] that the thermal aging, and the damage that it imparts on the energetic fill, can further sensitize the explosive. This increased sensitivity can cause normally stable energetics, and materials that simply burn during fast heating events, to detonate during slow heating. The SCO test is used to help developers improve the response of munitions to this type of thermal threat and ensure that any reaction that occurs is as mild as possible.

The SCO test is performed by heating the munition in an oven at a constant rate until a reaction occurs. In order to pass the test, the item must demonstrate a reaction violence no more severe than burning, which is scored as a type V reaction. Since its introduction, the test documents defining the SCO and slow heating tests (STANAG 4382 [1] and TB-700 [2]) have specified a heating rate of 3.3°C/hr (6°F/hr). In the spring of 2016, AC326 approved the formation of the Slow Heating Custodial Working Group (SHCWG) to investigate the SCO heating rate and to revise STANAG 4382, creating a new Allied Ordnance Publication (AOP), which fully defines the parameters of the SCO test. Over the course of two years, the SHCWG met four times and discussed all aspects of the SCO test. Data presented by SMEs showed that, to better align the test with realistic threat scenarios, the heating rate should be increased significantly. Analysis of this data has been published in the past and includes a review of historical SCO incidents [3] and a modelling effort to predict the heating conditions within a magazine during a fire event [4]. Ultimately, the SHCWG selected a new heating rate of 15°C/hr. This new heating rate has the concurrence of all of the nations that participated in the SHCWG and is expected to be ratified in 2020.

Although the selection of the new heating rate was the most difficult parameter of the SCO test for the SHCWG to reach agreement on, there were additional test parameters that had to be selected. One such parameter was to specify the proper method for preconditioning the test item prior to beginning the SCO test. The study that investigated item preconditioning is described in detail in a separate paper [6]. Another parameter, investigated in this study, is the allowable thermal gradient within the oven during the SCO test. Ideally, the air surrounding the test item would be at a uniform temperature. Since this is not possible, the test documents must specify some limiting threshold. Additionally, it is known that increasing the heating rate will increase these thermal gradients. It is therefore unrealistic to expect test facilities to maintain the same level of uniformity at 15°C/hr that they were able to maintain at 3.3°C/hr. However, if the gradients are allowed to become too large the reaction physics could be altered by the formation of unrealistic hot spots at certain locations on the munition. In order to complete the AOP, the SHCWG needed to define the allowable gradient.

One drawback to increasing the heating rate used in the SCO test is that testing moving forward will not be directly comparable to the historical database of test results built over many years. Munition designs that pass the SCO test performed at 3.3°C/hr might not have the same result at the faster heating rate. For example, mitigation strategies that rely on the melting of vent plugs might not be effective when heated 4.5 times faster. Additionally, due to the larger thermal gradients that will exist within the munition, it is expected that the surrounding air temperature at the time of reaction will be much higher at the faster heating rate. This can cause non-energetic materials within the munition to ignite and burn before the reaction occurs, further complicating the reaction physics. There is also a concern that the increased heating rate would have an effect on the “typical” reaction temperatures associated with specific energetic materials. Not having a reasonable prediction for a munition reaction temperature would make it difficult for test ranges to predict the time at which a reaction would occur.

In this paper, the results of a series of SCO tests conducted on both inert and energetic items will be discussed. The first test series was conducted to help the SHCWG determine an appropriate value for the specified thermal gradient. The allowable gradient should be small enough to ensure that the test is appropriately simulating the thermal threat without being so small that it is overly burdensome for the test centers to meet. In a separate study, the temperature capability of SCO ovens was examined. Since it is anticipated that cook-off temperatures will increase at the faster heating rate, an investigation was performed to assess the performance of test ovens at temperatures higher than typically encountered during tests under the prior standard. During this test series the convective heat transfer coefficient within a standard oven design was also measured. Finally, multiple energetic items were tested at both 3.3°C/hr and 15°C/hr to assess the effect of the heating rate on reaction temperature and violence.

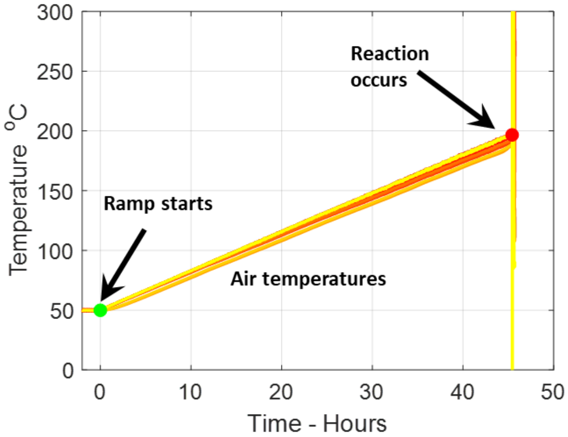
Part One: Required Oven Uniformity

To fully define the parameters of the SCO test the required uniformity of the air temperature within the oven must be specified. The wording used in STANAG 4382 was “Some gradient in temperature between the input and exit air streams is to be expected, but this should not be greater than 5°C”. This wording was insufficient because it didn’t specifically define the air temperature surrounding the item and it implied that all ovens have an inlet and outlet. This is not the case as some ovens simply heat and stir the air within the oven. Additionally, there was concern that the value of 5°C would be difficult to maintain at a heating rate of 15°C/hr. This study was performed to determine an appropriate value for the allowable temperature gradient. These results were presented to the SHCWG so that this parameter could be properly specified in the AOP. Note that since the test standard used the wording *should* and not *shall*, this is considered a recommendation and not a requirement.

During a SCO test, 6 thermocouples are used to monitor the air temperature around the item. In the new AOP their placement is specified as follows: “These thermocouples shall be mounted 40-60mm from the surface of the test item along planes through the centerline of the test item.” Instead of using the oven inlet and outlet air temperatures to define the temperature gradient (as stated in STANAG 4382), it was decided to define the gradient based upon these 6 required temperature measurements. The instantaneous oven gradient is therefore defined as the range of these 6 temperatures (the maximum minus the minimum) at each point in time. A gradient of zero would therefore be the ideal case in which the air surrounding the test item was perfectly uniform and all 6 thermocouples were reading the exact same temperature at that point in time.

Prior to examining the oven gradient for tests performed at 15°C/hr, past tests performed at 3.3°C/hr were examined to better understand how well the gradient had historically been controlled. The oven air temperatures from 60 different SCO tests that were performed at 3.3°C/hr were examined. The sizes of the test items in these 60 tests ranged from under well under a meter long and less than 50 kg to an item over 6 m long with a mass greater than 4,000 kg. For each of these tests the oven gradient was calculated throughout the test duration. An example of one test is shown in Figure 1. In the left figure, the temperature history over the duration of the 45+ hour test is shown. The black dots in the right figure show the temperature gradient calculated at each time step. In addition to the instantaneous oven gradient, the 1 hour running average of the temperature gradient was also calculated, as shown by the green dots in the right figure. The running average effectively filters out erroneous temperature spikes and short duration temperature excursions that could not have influenced the reaction of the item under test.

For each test, the maximum gradient and maximum of the 1 hour running average gradient were examined. The compilation of these results are shown in Figure 2. In 83% of the tests, the 1-hr running average of the gradient was below 5°C, which met the recommendation of STANAG 4382. However, in several tests the gradient exceeded the 5°C threshold and in three cases exceeded 15°C. These results demonstrate that even at the slow heating rate it can be very difficult to maintain oven uniformity when testing very large items.



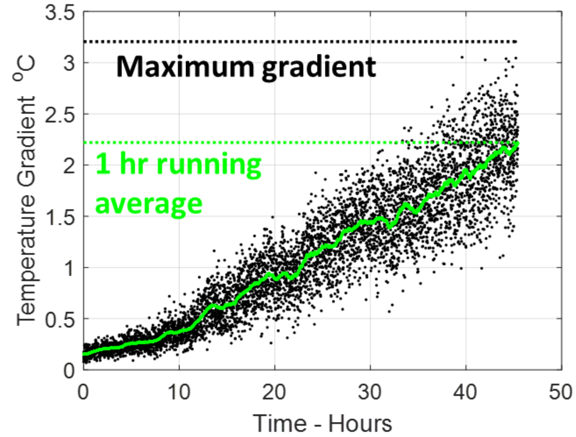


Figure 1: Temperature history (left) and calculated gradient (right)

To understand how increasing the heating rate would affect the temperature gradient, additional tests were carried out at both 3.3°C/hr and 15°C/hr. As can be seen in Figure 3, as the size of the test item increases, the temperature gradient increases and, as expected, increasing the heating rate also causes the gradient to increase, although not to the extent originally anticipated. Since the heating rate was increased by a factor of 4.5 there had been concern that the gradient would increase proportionally. However, as shown in the figure at right, the ratio of the measured gradient between the 3.3°C/hr test to the 15°C/hr test is approximately 2. That is, increasing the heating rate from 3.3°C/hr to 15°C/hr caused the temperature gradient to approximately double, not quadruple as originally feared. After these results were presented to the SHCWG, it was agreed that the new AOP should specify a maximum gradient of 15°C. It was also decided that the AOP would continue to use the word “should” instead of “shall” to allow the national authorities some discretion in accepting results for items in which holding a gradient under 15°C would be overly burdensome.

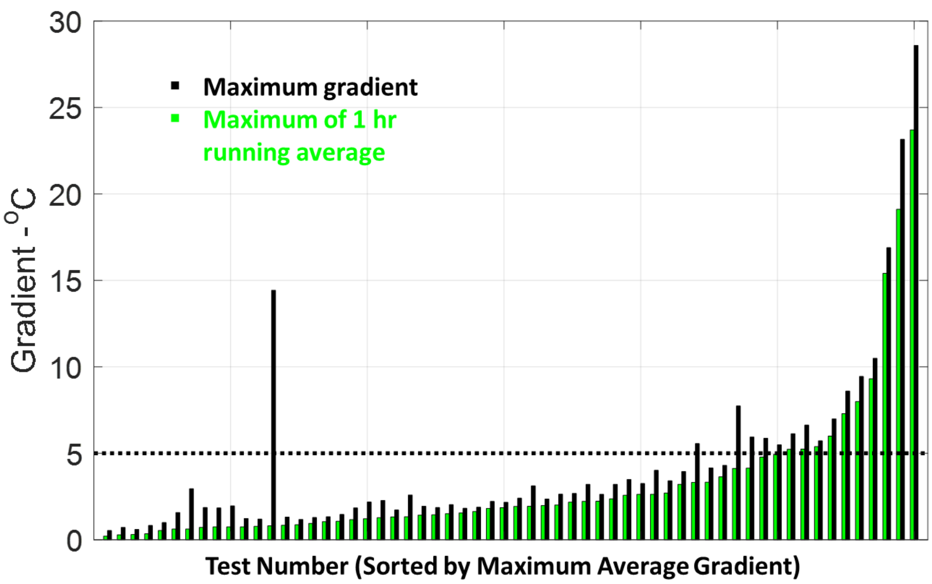


Figure 2: Measured gradient from 60 SCO tests performed at 3.3°C/hr

In addition to maintaining oven uniformity, it was decided to also use the gradient recommendation to ensure that the proper heating rate is maintained during the test. This is done by introducing a seventh "ideal temperature history" which is included in the gradient calculation. This ideal temperature history is to be a computer generated curve that would represent the exact temperature that the oven should be at each point in time. That is, a line with a slope of precisely 15°C/hr. By including this temperature in the gradient calculation, if any of the 6 measured air temperatures deviated from this ideal temperature by more than 15°C, it would be flagged as outside of specification. In this way, the oven gradient specification checks both the oven uniformity and the ramp linearity. The selection of the allowable gradient and its proper wording presented the last step in finishing the new AOP. It currently has the concurrence of all the nations that participated in the SHCWG and its ratification is expected in 2020.

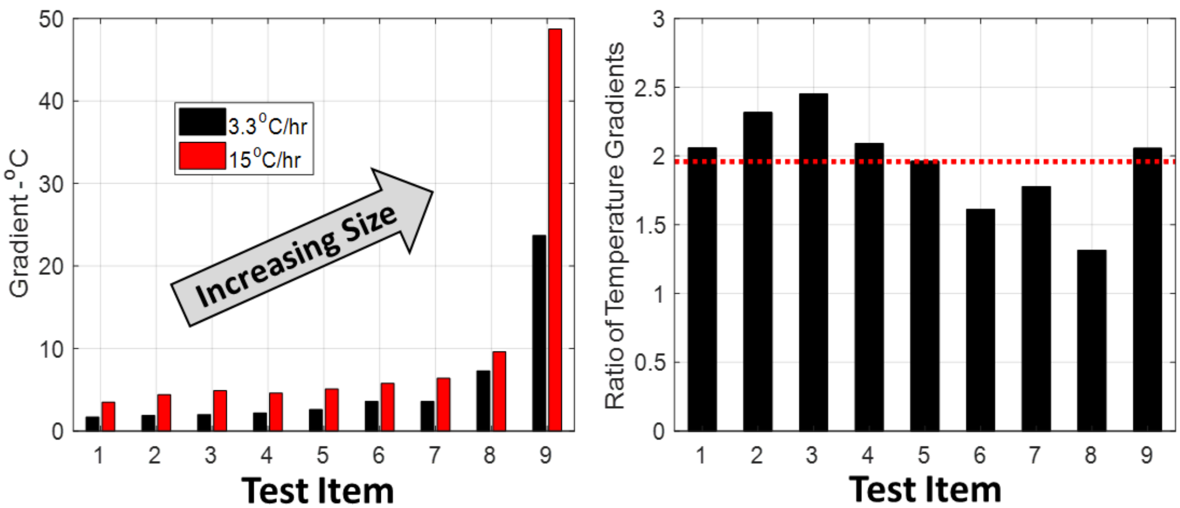


Figure 3: Comparison of oven gradient for SCO tests of 9 different items performed at both 3.3°C/hr and 15°C/hr

Part Two: Oven Capabilities

For SCO tests performed at the Naval Surface Warfare Center (NSWC) Dahlgren, a disposable oven is constructed above a reusable heater as shown in the schematic and a photograph of the standard SCO oven used at Dahlgren are shown in Figure 4. The reusable plate contains the heater tubes, circulating fan, and required ducting, all of which are protected by a top layer of steel armor plate. The disposable oven contains an inner box in which the test item is placed and an outer box that protects and insulates the inner box and ducting. The inner box is constructed from 25.4 mm thick duct board consisting of an inner layer of fiberglass insulation sandwiched between a reinforced aluminum foil facing and a woven fiberglass material. The outer box is made from a stack up of the same 25.4 mm duct board with an additional duct board layer made of fiberglass insulation that is 38 mm thick and faced on both surfaces with reinforced aluminum foil.

Historically, in SCO testing performed at 3.3°C/hr, the vast majority of munitions have reacted at oven air temperatures below approximately 260°C. During the discussions to increase the heating rate used for SCO testing, it was known that any such increase would also cause an increase in the oven temperature at the time of reaction. The magnitude of this reaction temperature increase is dependent on the amount of insulation between the outer most surface of the item under test and the energetic fill. Bare items will demonstrate a minimal increase whereas items that include thick layers of dunnage or large air gaps will require a much higher oven air temperature to reach their reaction temperature. Tests were conducted on inert items to better understand the current capabilities of the ovens used for SCO testing.

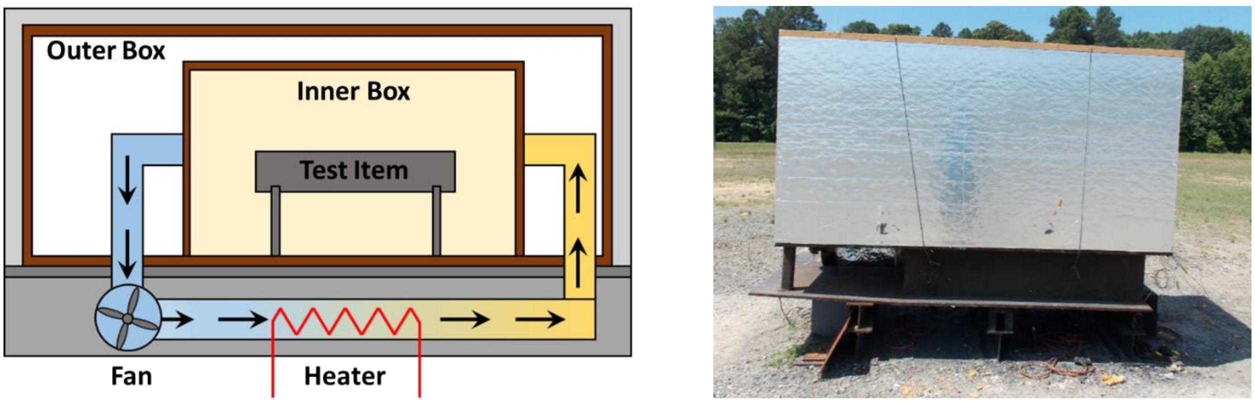


Figure 4: Schematic and photograph of SCO oven used

For the inert testing, a steel cylinder 700mm long and 127mm in diameter (approximately the size of a medium caliber shipping container) with a mass of 71.2 kg was used as the item under test. After an initial thermal soak at 50°C, the oven was ramped at 15°C/hr to a maximum temperature of 375°C. This is over 100°C hotter than what has typically been required to cause a reaction during a SCO test and was considered to be sufficient for the majority of anticipated testing. The results of one these tests are shown in Figure 5. Although the temperature difference between the inlet and outlet air streams increased to as much as 55°C as the temperature within the oven increased, the temperature gradient in the air surrounding the item was minimal and well below 15°C throughout the entire temperature range. Furthermore, the heaters had no trouble in maintaining the temperature ramp at the highest temperatures as can be seen by the linearity of the air temperature traces. These results show that this oven met all requirements specified in the new AOP throughout the entire temperature range.

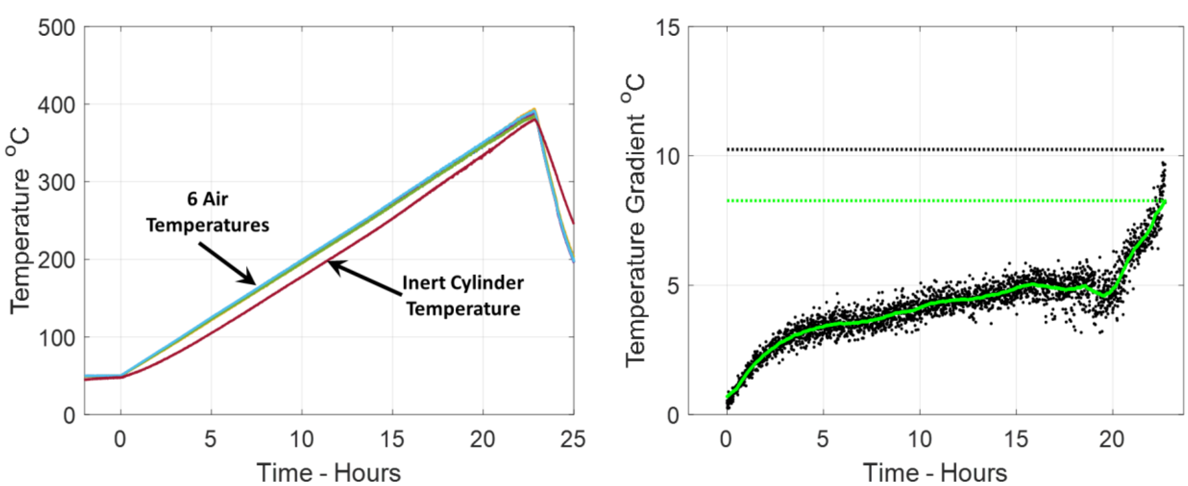


Figure 5: Temperatures measured during elevated temperature testing (left) and measured temperature gradient (right)

In addition to being able to provide the required temperature environment, the oven must also be able to survive the temperatures produced. The condition of an oven after performing one of the inert tests to 375°C is shown in Figure 6. In this photograph, the outer box has been removed and flipped onto its side to allow the inner surface to be inspected. While the material has experienced slight discoloration, it was found to be structurally sound and was easily removed intact. The inner box also maintained its structural integrity, although it did appeared that the duct material was starting to lose some of its rigidity. These results indicate that this oven design can be used to perform SCO testing at temperatures up to approximately 375°C. It is anticipated that this maximum temperature could be extended with the use of a higher temperature material for the inner box. Currently, the suitability of mineral wool panels is being investigated for this purpose.

Figure 6: SCO oven condition after testing to 375°C

The testing of the inert steel cylinder allowed further characterization of the SCO oven. During munition development, modelling is often used to predict and improve the IM performance of the munition. One issue encountered when attempting to model the SCO test is applying the proper boundary conditions. The heat that is transferred from the air to an object is given by:

$$q = \bar{h}A[\overline{T_{air}} - \bar{T}_S]$$

where q is the heat transfer rate, $\bar{h}$ is the average convective heat transfer coefficient, A is the surface area of the object, $\overline{T_{air}}$ is the average temperature of the air surrounding the object, and $\bar{T}_S$ is the average surface temperature of the object. While the temperatures and the area are easily measured, it is typically difficult to predict the convective heat transfer coefficient. Modelers are often forced to use empirical correlations that can feature a large degree of uncertainty and require information not always known such as air velocity and boundary layer condition. The inert tests conducted in this test series presented an opportunity to directly measure the average convective heat transfer coefficient within these ovens. The heat that is transferred to the cylinder is the thermal mass of the cylinder (mass times specific heat) multiplied by the rate of temperature increase. In this case, the rate of temperature increase was constant at 15°C/hr. The specific heat for the steel used increases with temperature from 434

J/kg K at 25°C to 590 J/kg K at 375°C. This means that, at 15°C/hr, the heat transferred to the cylinder starts out at 130 W and increases to 175 W as the oven temperature increases. Dividing this heat addition (q) by the product of the surface area and the difference between the cylinder surface temperature and the average surrounding air temperature ($A[\overline{T_{air}} - \overline{T_S}]$) yields the average convective heat transfer coefficient. For this oven, testing this item, the heat transfer coefficient was found to be 27±2.6 W/m^2 K. While this value can serve as an approximate value, it is important to note that the heat transfer coefficient is dependent not only on the oven, but also on the geometry of the item under test. If a high degree of precision is required, testing of a mock item that closely approximates the test item's geometry is required. However, for items that are approximately the same size as the inert test cylinder, the calculated value is more useful than an empirically calculated value.

Part Three: Energetic Item Testing

A series of energetic tests were performed in an attempt to better understand how the increased SCO heating rate will influence the reaction temperature and violence of munitions. Five different energetic items were tested at both 3.3°C/hr and 15°C/hr. Generically, these items were:

1. A medium caliber vented high explosive (HE) projectile inside a shipping container
2. A medium caliber gun cartridge featuring a live propelling charge and inert projectile inside a shipping container
3. A medium caliber unvented HE projectile inside a shipping container
4. A small diameter vented rocket warhead inside a shipping container
5. Mortar propelling charges in a shipping container

After performing each test, the blast pressure data, video footage, and the fragmentation/debris data were used by a member of the Navy's Munition Reaction Evaluation Board (MREB) to asses an official reaction violence score. The results of these tests are summarized in Table 1.

Table 1: Overview of results of energetic testing

Test Item	Heating Rate (°C/hr)	Average Oven Temperature (°C)	Increase in Oven Temperature (°C)	Score
Medium caliber vented High-Explosive (HE) projectile, containerized	3.3	171	47	V
	15	218		V
Medium caliber gun ammunition, live propelling charge, inert projectile, containerized	3.3	142	53	IV
	15	194		IV
Medium caliber unvented HE projectile, containerized	3.3	180	67	I
	15	247		I
Small caliber vented rocket warhead, containerized	3.3	203	31	V
	15	234		V
Mortar propelling charges, containerized	3.3	131	35	IV
	15	166		IV

In each of these five cases, the reaction violence was scored identically at both heating rates. The vented warhead exhibited a type V reaction in both tests. This was considered a positive result because there had been concern that at the higher rate the venting might not be able to relieve the pressure quickly enough to mitigate the reaction violence. In the medium caliber gun ammunition with the live propelling charge and inert projectile, both tests were scored a type IV reaction because in both tests the cartridge case was ejected from the container, through the oven wall, and landed more than 15m away. As expected, the unvented ammunition, which featured a composition B fill, detonated (type I) at both heating rates. In similar fashion, the vented rocket warhead and mortar propelling charges reacted very similarly in testing at both heating rates

While the score of each munition's reaction did not change, the oven temperature at which the reaction occurred increased significantly in each test performed at the faster heating rate. As shown in the fourth column of Table 1, the oven temperature increased by 31°C to 67°C for the 15°C/hr tests. This is due to the fact that all the munitions were containerized and the space between the energetic item and the inside surface of the container was typically made up of materials that are not thermally conductive. Since the temperature difference across a material is proportional to the magnitude of the heat flux through the material, and because increasing the heating rate increases the heat flux proportionally, the temperature drop across any layer is significantly larger for tests conducted at the faster heating rate. Furthermore, becasue the temperature drop is larger, the oven must be proportionally hotter to raise the energetic fill to a given cook-off temperature.

To further examine this phenomena, a simple thermal model was used to study the temperature profile within the energetic item during the test. The thermal model used was a 1-D axis-symmetric (radial heat flow only) implicit finite difference code that treated the item as a finite number of concentric slices. The self-heating of the energetic fill immediately prior to reaction was not included because the thermal model was used to estimate temperatures for comparison to actual test data, not to predict the time or violence of the resulting reaction or to understand the cook-off physics.

The plots shown in Figure 7 depict the estimated temperature profile of the unvented HE projectile. At left is the modelled temperature profile every hour for the 15°C/hr test and at right is the temperature profile immediately prior to reaction based off the live test data. The projectile was modeled for both 3.3°C/hr and 15°C/hr heating scenarios. These plot represents a radial slice of the munition; the left side of each plot is the munition centerline and the far right is the surface of the container. The simplified munition consists of four layers: the HE fill, the steel projectile wall, the packaging dunnage, and the steel shipping container. At right, the red line is the predicted temperature profile for a test performed at 15°C/hr and the blue line represents the predicted temperature for the test conducted at 3.3°C/hr. The dots are the actual temperatures at those two radial positions, pulled from the test data from the two SCO tests, immediately prior to the item's detonation. For each run, the air temperature followed the prescribed ramp up to the final air temperature recorded in the test. For example, for the 15°C/hr case, the model was run until the air reached 247°C (approximately 15 hours) and for the 3.3°C/hr case, it was run until the air reached 180°C. These temperatures represent the air temperature at which a reaction occurred in each test respectively. In each case a constant convective heat transfer coefficient of 27 W/m^2 K was used for the boundary condition, as measured in the previous section.

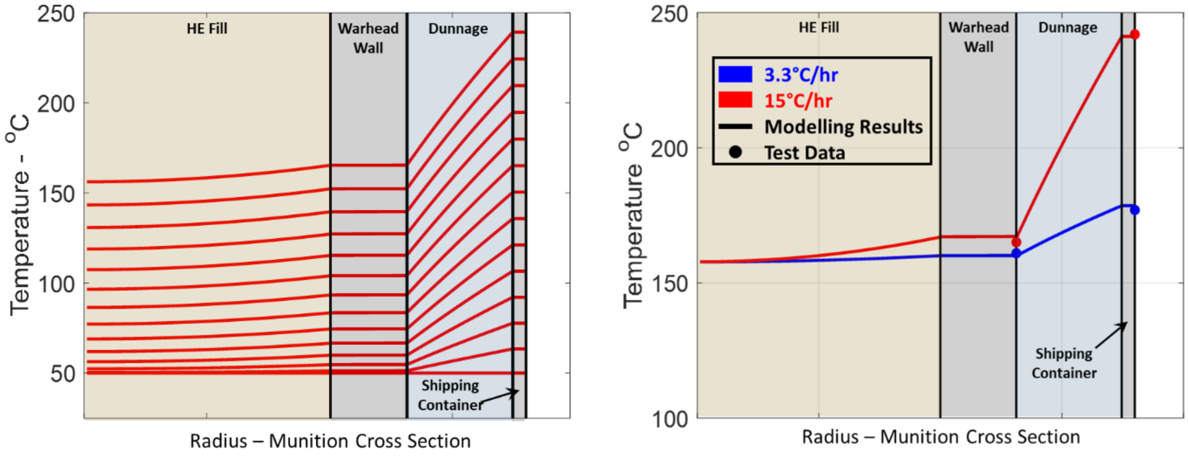


Figure 7: Model estimated temperature profiles. At right: temperature slice every hour during 15°C/hr test. At left are the temperature profiles immediately prior to reaction. Dots are data pulled from actual live test at same time as model

In examining the right plot in Figure 7, although the oven temperature is almost 70°C hotter for the faster heating rate test, the temperature profile within the actual munition is quite similar. In fact, the measured skin temperature at the time of reaction was 161°C and 165°C for the 3.3°C/hr and 15°C/hr tests respectively, a difference of only 4°C. Figure 7 also demonstrates how increasing the heating rate increases the temperature gradient within materials with low thermal conductivities such as high explosives. For the 3.3°C/hr case, the temperature within the HE fill is very nearly uniform, only varying by about 2°C from the centerline to the inside surface of the projectile case. At the higher heating rate, this discrepancy increases to almost 10°C. Increasing the diameter of the munition would further increase this thermal gradient.

The extent to which the larger temperature gradient within the explosive fill at 15°C/hr reduces the chances of internal hot spots and moves the ignition location towards the outer surface of the explosive is an area that will need further investigation. It is anticipated that larger munitions are more likely to pass the SCO test at the new heating rate due to this phenomena. Indeed, it can be shown that for large munitions heated at 15°C/hr, the center of the explosive has not even begun to heat up at the time when the outer surfaces of the fill reaches cook-off temperature. By eliminating the excessive thermal damage, and the subsequent sensitization that comes with it, at least some munitions should react less violently at the faster heating rate. This was one of the reasons that the heating rate was increased. The rate of 3.3°C/hr was determined to be too slow to represent any credible threat and the difficulty associated with designing munitions to pass the test at that rate was considered unnecessarily onerous.

Conclusions

This paper documents the results of an examination into some of the issues which resulted from the recent decision to increase the SCO test heating rate from 3.3°C/hr to 15°C/hr. The results of these studies are intended to help test sites smoothly transition to the new SCO test heating rate.

The first analysis looked into the thermal gradient surrounding the item within the test oven and helped specify this value in the upcoming AOP. Based on the results of this study, the SHCWG decided that the thermal gradient should be held below 15°C. In the second study, the temperature capability of SCO ovens was examined. The increase in the heating rate causes an increase in oven temperature at the time of reaction. This can present difficulties since, typically, the ovens used are disposable and are made as inexpensively as possible. Testing was performed in which a disposable oven was heated to a temperature of 375°C and shown to still meet all required test parameters at the new heating rate. Finally, a series of energetic items were tested and their reactions were compared to tests performed at 3.3°C/hr. For the five items tested, the reactions were scored identically between the two different heating rates. However, the oven temperature at the time of reaction was quite different in each case. These cook-off temperatures represents the start of a new database of reaction temperatures for testing performed at 15°C/hr. This data is valuable for test sites that wish to predict the reaction temperature to ensure that the reaction occurs when personnel are present and when lighting conditions are optimal.

Acknowledgments

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