Novel Slow Cook-Off Test Method to Replicate Worst Case for Munitions Containing Internal Fuel

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The Insensitive Munitions Advanced Development (IMAD) program sponsored an effort to improve the Slow Cook-Off (SCO) response of a munition containing more than one energetic item and liquid fuel. The Naval Air Warfare Center Weapons Division (NAWCWD), China Lake, California in collaboration with the US Army Redstone Test Center, responded by developing a novel test setup to consistently replicate the worst case threat cook-off posed by the liquid fuel within the weapon.

The test setup incorporated standard SCO features along with features similar to a fast cook-off test to replicate a SCO with a subsequent fire resulting from ignition of the weapons fuel. A detailed description is provided including the instrumentation, setup, features, and operations involved in this setup.

The novel test method significantly reduced the development testing required to validate design improvements with significant cost savings. The test method reliably transitioned a SCO to a fuel fire environment in a manner which represented the system under study. Assumptions and simplifications for this effort may not apply for other systems thus more refinement of this approach may be desired to broaden its applicability.

1.0 INTRODUCTION

There exist munitions which contain internal liquid fuel. Some of these munitions may also contain one or more energetic warheads. Historically, during an event such as Slow Cook-Off (SCO), one of the energetic components reacted first causing dispersal and ignition of the internal fuel. Depending on the violence of such an event, the remaining energetic components may become engulfed within the newly formed fuel fire. While some munitions have sufficient violence to project the remaining components clear of the fuel fire, this occurs in an unpredictable and non-repeatable manner. In essence, a munition in one test event may project the remaining components clear, but in a subsequent test event leave the remaining components within the fuel fire.

Components exposed to a fuel fire following or during exposure to a SCO environment have exhibited more severe reactions than when subjected to the standard Fast Cook-Off (FCO) test. Figure 1 below shows snapshots of a system that exemplifies this behavior. Furthermore, a first reaction with sufficient violence to project components clear of a fire typically fails to comply within the standardized response levels and the necessary changes to reduce the first reaction typically increases the likelihood of exposing the remaining components to the fuel fire. Thus munitions containing liquid fuel possess an intrinsic risk of being exposed to a FCO type environment during non-FCO IM tests.

The Insensitive Munitions Advanced Development (IMAD) program sponsored an effort to improve the SCO response of a specific munition which exhibited some of these characteristics. The approach consisted of designing and implementing a mechanism which would ignite a burn of the main fill energetic at a time earlier than the fuel dispersion and ignition. For testing the new design, it was desired to test the warhead under the worst case environment exhibited in the system level test. The worst case environment was defined by a slow heating of the munition, then during a specific temperature range, the rupture, dispersion, and ignition of the liquid fuel. This latter event resulted in fast heating of the pre-damaged munition, see Figure 1. For many programs testing an All-Up-Round (AUR) remains very expensive such that testing enough times to replicate a worst case event proves unpractical and costly. The major challenges in this worst case testing revolved around the inconsistency in the time to reaction and ensuing reaction violence exhibited in the system level tests. On similar lines the stochastic nature of where the warhead resided after the first reaction also proved a significant challenge. Given that the primary purpose of the effort was to assess functionality of new design technology, these challenges needed mitigation.

The design of the test was to provide a practical method to replicate the worst case test consistently, at minimized cost, to enable assessment of engineering solutions. Such a test must replicate both the standard SCO environment as well as the fuel fire intrinsic to the system response, in order to assess the redesigned system components. The primary problem with a system level test was the random distribution of the warhead's trajectory. To ensure the fire engulfs the warhead required controlled replication of the effects of the first reaction in the system level test. This drove a need for a method to reliably ignite a fuel fire, at a time consistent with the system's response during the SCO portion of the test. Also, this method must not impart translation or any trajectory to the warhead in order to ensure the warhead becomes engulfed in the fire. Additionally, the test should have a means of removing the SCO oven so the warhead is directly exposed to the fire. Such a scope fit within the limits of a component level test.

(a) First Reaction, Ignition (b) Fuel Fire (c) Warhead Reaction, Type III Explosion

Figure 1: Sequence of SCO of Item Containing Liquid Fuel without Mitigation Features

2.0 TEST DESIGN

Of utmost importance in performing any Insensitive Munitions (IM) test was adherence to the relevant standards. This work, to the extent possible, was performed under conditions dictated by MIL-STD-2105D and STANAG 4382 [1, 2]. Herein a component level test of the warhead was deemed the best approach to ensure it was tested under the worst case environment possible for a system level test. While system level or AUR tests were preferred, several such tests would be required to ensure the worst case environment occurs. A controlled component level test could, arguably, better replicate the worst case environment of the known system response. See Figure 2 below for the overall test layout; see Figures 3-4 for internal and external details of setup. The known system response could be viewed as occurring in two distinct phases. The first phase consisted of the standardized SCO environment, see Figure 5. The second phase consisted of the munition being exposed to a fuel fire environment, similar, but not held to the same requirements, as the standardized FCO test, see Figure 6. It should be noted that a transition period occurred in between these two phases.

As was typical in engineering efforts, several assumptions were made in regard to replicating the environment within practical and programmatic constraints. The first assumption was that the difference in heat flux during the time elapsed of 115 seconds for this replicate test versus 32 seconds in the system level test, for the opening of the oven and ignition of the fuel fire was negligible.

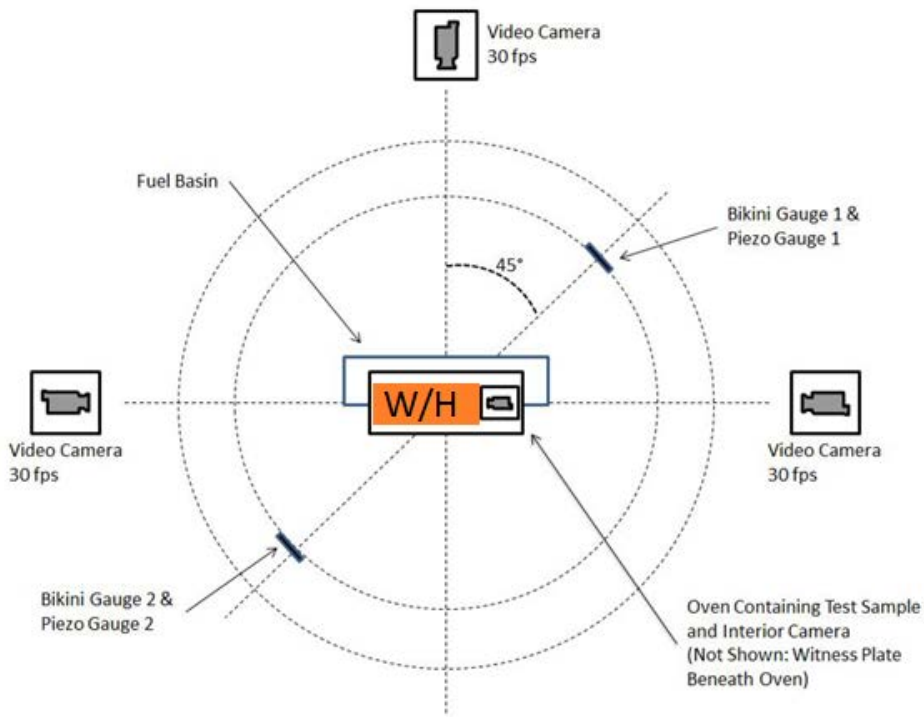

Figure 2: Overview of Test Layout

The remaining assumption(s) were specific to the system and technology under test. One must take care in using this setup to ensure the primary heat paths are adequately represented. What is defined as primary depends on the system and the intent of the test. Also, any simplifications should not appreciably alter the outcome in favor of the designed mechanism. Several key considerations should be examined. First, conductive and convective heat flow processes characterize the environment [4]. Second, thermal damage and decomposition in energetic materials determine reaction temperatures and times [5, 6, 7, 8].

Figure 3: SCO Configuration, SCO Oven Sealed, Fuel Pan Closed and Sealed

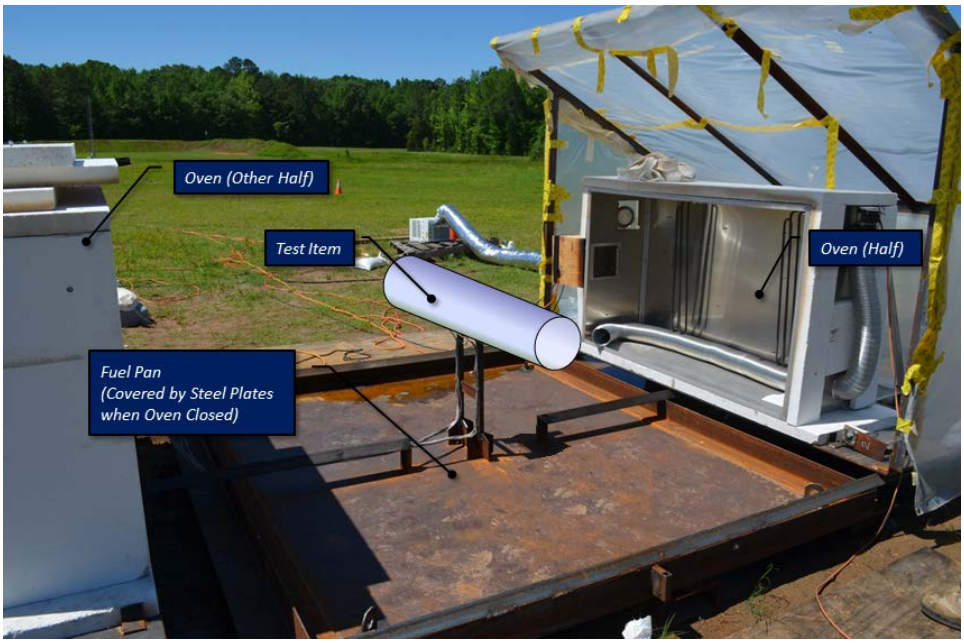

Figure 4: Fuel Fire Configuration, SCO Oven Separated, Fuel Pan Open

2.1 PHASE I: SLOW COOK-OFF PORTION

The SCO portion was to replicate the standard SCO test conditions. The design was based on the standard SCO best practices for oven construction, insulation, convection fans, heating method, heat controller, instrumentation, etc. However, some modifications were required to facilitate transition to the fuel fire portion.

The first modification consisted of the SCO oven being designed into two halves, see Figure 4. The oven in two halves could easily be separated to ensure exposure of the warhead to the fuel fire. This was desired since in the system level test the reaction severed the connections between warhead and the rest of the system and removed the warhead from the oven, directly exposing it to the fire. The oven was instrumented much the same as a standard SCO test with thermocouples and cameras, see Figures 2-3. It should be noted that the thermocouples were installed using the item stand so they remained with the warhead as the oven was opened. This enabled temperature data recording of the item for the full duration of the test. The two halves were sealed with insulating tape and foam to prohibit convective heat transfer between the internal and external air. This seal was also intended to restrict any fuel vapor from entering the oven in effort to provide mitigation against premature ignition of the nearby fuel.

The nearby fuel was contained in a steel pan underneath the SCO oven covered with two horizontally situated steel doors, see Figure 3. Affixed atop each horizontal steel door was one half of the oven. The seam between the steel doors was also sealed through use of insulating tape in a likewise fashion to restrict fuel vapor from leaving the fuel pan. The fuel pan was not filled until just prior to test commencement.

Figure 5: SCO Portion, Tent and Aluminum "Roof" Provide Wind/Rain Protection

Oven separation was achieved through a system of redundant electrically driven winches connected via steel cables to each of the two steel doors covering the fuel pan, see Figure 6. Upon opening, the steel doors slide on simple rails kept on track by guiding features built into the doors. The system was designed such that the two oven

halves were removed far away from the fuel pit to ensure full exposure of the warhead to the fire.

2.2 PHASE II: FUEL FIRE PORTION

The fuel fire portion was to be initiated at the average time of the first reaction in the system level response, unless the warhead completes reaction sooner. Upon command from the control room the oven would first be opened. The opening time was based on the capabilities of the winching system. Once the doors were removed over majority of the fuel pan a command signal was sent from the control room to function the electric igniters which in turn started the fuel fire. During this time the winching system continued until the doors and oven halves were far removed from the fuel pan.

Replication of the fuel fire environment was a key concern. To ensure this the fuel pan was filled with the same fuel as was used in the system. Estimates were performed to increase the total quantity in the pan to account for losses due to evaporation. These estimates assumed the fuel was allowed to freely evaporate into the open air, this was conservative since efforts to seal the pan and oven likely restricted this occurrence. Typically for a standard FCO test, the best practices called for performing the test during times of calm to no winds. Due to the unpredictable nature of the SCO portion of the test, the dimensions of the pan were chosen to provide a large volume of fire to increase the likelihood that the warhead would remain fully engulfed in the event of winds.

Figure 6: FCO Portion, Oven Separated, Warhead Engulfed

3.0 DISCUSSION

The test(s) were conducted, demonstrating the designed IM solution. For ease of comparison the results without the IM mitigation features were shown below in Figure 7. The result from the test with the IM mitigation features was shown in Figure 8. Without the IM mitigation features, the initial reaction was violent enough to rupture the SCO oven as shown in Figure 7a. With the IM mitigation features, the warhead reacted sooner with less violence during the SCO portion, shown in Figure 8a. Comparing Figures 7b and 8b shows that the fuel fires were similar. Comparing Figures 7c and 8c showed that with the mitigation features the final reaction was more benign.

(a) First Reaction, Ignition (b) Fuel Fire (c) Warhead Reaction, Type III Explosion

Figure 7: Sequence of SCO of Item Containing Liquid Fuel without Mitigation Features

(a) First Reaction, (b) Fuel Fire (c) Warhead Reaction, Type V Burn

Figure 8: Sequence of SCO of Item Containing Liquid Fuel with Mitigation Features

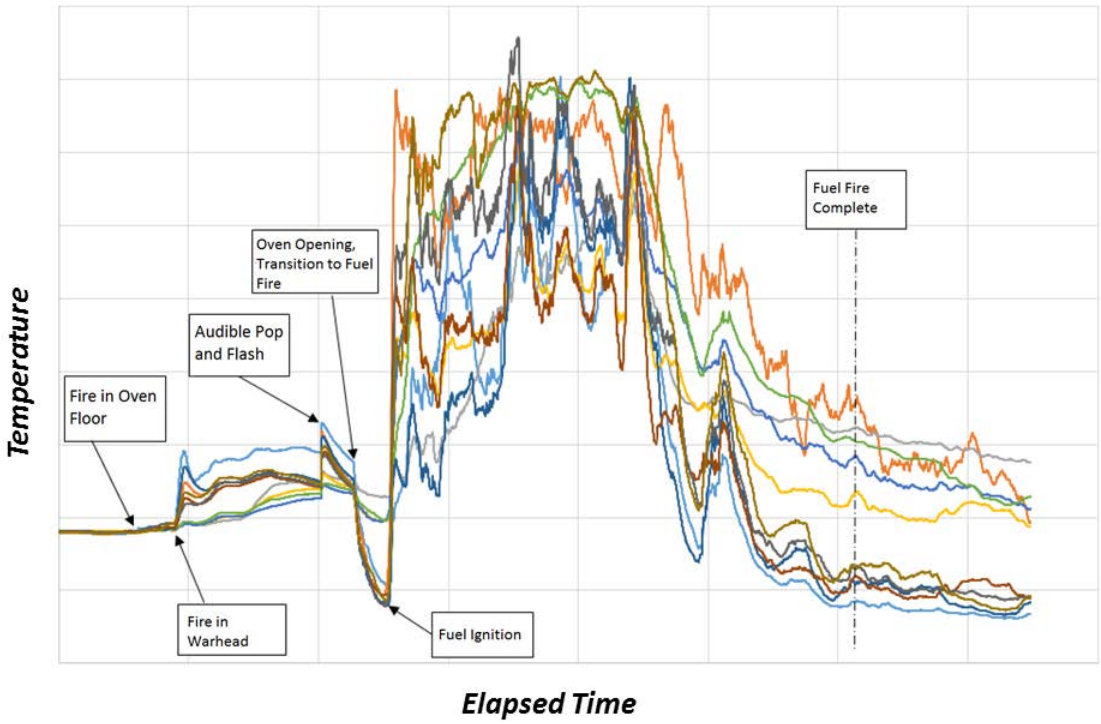

Figure 9: Temperature Data for Entire Test, SCO and Fuel Fire Portions Labeled

Some evaluation on the assumption(s) discussed prior was warranted. In regard to the first assumption, as seen in Figure 9, the thermocouples in open air dropped significantly on oven opening. On the other hand, while the skin temperature thermocouples also dropped they were still at or above the temperature when the warhead started reacting. Furthermore, based on the internal camera coverage it seemed that the warhead's reaction was complete, as was intended with the designed mechanism.

4.0 SUMMARY

A method was developed to consistently test munition component(s) to SCO conditions subsequently followed by exposure to a fire produced by the munitions liquid fuel. This method enabled successful engineering design development of a component level solution, which was demonstrated in an environment replicating the worst case system level response. This method proved useful in the assessment of design improvements in a manner that provided consistency and repeatability between numerous test events. In order to achieve consistent replication and cost savings, certain system components were replaced with representative mechanisms. As a result, this method satisfactorily replicated the worst case system response in SCO, including the intrinsic fuel fire, with significant cost savings.

5.0 ACKNOWLEDGEMENTS

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