Development and Characterization of a Propane Fueled Fast Cook-off Burner

David Hubble and Jon Yagla
Naval Surface Warfare Center Dahlgren Division, Dahlgren, Virginia

Ephraim Washburn and Kevin Ford
Naval Air Warfare Center Weapons Division, China Lake, California

Abstract

Fast cook-off testing using liquid hydrocarbon fuel pits has been a standard test method for insensitive munition classification. Recently, environmental concerns over the pollution caused by these tests have pushed many nations to look for a cleaner alternative. This paper reports on work done by the US Navy to develop and characterize a propane fueled burner that produces a thermal stimulus similar to that produced by a liquid hydrocarbon fueled fire. The burner transports liquid propane into a number of burner tubes within the hearth of the test area. Once ignited, radiative feedback from the fire vaporizes the liquid propane within the tubes which produces propane gas that exits the burner tubes and combusts within the burner volume. The resulting fire is very fuel rich in the test region which creates fire with sufficient soot to produce the thermal radiation levels seen in a typical liquid hydrocarbon fueled fire. To verify the thermal characteristics of the propane fire, both temperature and heat flux measurements were collected. Testing showed that the propane burner produced temperatures that were comparable to those produced by a liquid hydrocarbon fueled fire and easily met the temperature requirements of STANAG 4240. Additionally, and perhaps more importantly, total heat flux measurements were also similar between the two fires. Both temperature and heat flux measurements showed that the heating was also uniform within the burner. The totality of these results indicate that the propane burner produced by the US Navy is an acceptable alternative to liquid hydrocarbon pool fires for fast cook-off testing.

Introduction

Fast cook-off (FCO) testing is a standard insensitive munitions test that is used to determine how munitions react when subjected to rapid heating. These tests are used to simulate real-world scenarios such as carrier deck fires or transportation accidents where ordinance items have the potential to be exposed to a fire. Traditionally, these tests have been performed by positioning the item over large pools of liquid hydrocarbon fuels such as kerosene or jet fuel. During the test, the fuel is ignited and the item is completely engulfed in the flame. The response of the item to this fire exposure is then measured. This response can range from a severe detonation (type I) to more mild reactions such as burning (type V) or no reaction whatsoever (type VI). It is the goal of weapon development to produce ordnance items that have the mildest possible reaction during fast cook-off testing.

The fuel-fire test is required by both the Department of Defense Explosive Safety Board (DDESB) and the Insensitive Munitions (IM) office in the United States. The fuel-fire test is specified as the external fire test as described in TB 700-2 for hazards classification relative to transportation and storage while operational scenarios are covered in MIL-STD-2105D.[1,2] These tests are performed at a system level in accordance to STANAG 4240, “Liquid Fuel/External Fire, Munition Test Procedures”[3]. However, in recent years environmental pressure has forced nations to re-examine how they perform FCO testing. The large black clouds of soot produced by these tests attract unwanted attention from communities surrounding test sites. Additionally, the large open pools of fuel create the opportunity for spills leading to ground contamination. These environmental concerns prompted a debate on whether a cleaner alternative could be used for FCO testing.

Early work on the development of a cleaner FCO burner focused on proving that alternative fuels could reproduce the thermal environment of a liquid-pool fire. This work was begun in 2009 at WTD 91, Meppen, Germany where a liquid propane injection burner was constructed. Testing with thermocouples and calorimeters showed that the temperatures and heat transfer to test items were nearly identical to pool fires of comparable size. The results of these tests were presented at the first Fuel Fire Experts Meeting in Meppen. The US Team expanded on this work by measuring similar temperatures and heat fluxes in the WTD 91 fire and in a liquid JP-5 fire at Dahlgren[4]. These preliminary test results became the initial thermal requirements for the design of a burner using alternative fuels.

The thermal requirements were developed further at subsequent Fuel Fire Experts Meetings in The Netherlands and Sweden. Prior to each meeting, the US Team performed testing on the host country's burner designs. Results of these tests showed that the data were comparable to the data from testing in the WTD-91 and Dahlgren fires. Measurements consistently showed that temperatures in these burners were over 800°C and heat fluxes to test items were on the order of 100 kW/m^2. These results convinced the Fuel Fire Experts that these burners could indeed produce the heating environment of a liquid-pool fire. Technical discussions then shifted from investigating the possibility of an alternate burner to practical matters of burner design, instrumentation, and facility qualification. A set of preliminary thermal requirements for FCO burners were then presented at the IMEMTS in October 2013[5].

The final set of design requirements used to guide the design of the US burner includes both thermal and logistical requirements. The following list of thermal requirements, pulled from the previous meetings and the testing documents, was used to ensure that the thermal environment was representative of that within a liquid-pool fire and would be accepted by the international test community.

1. The flame temperature must be at least 800°C degrees C – (must also reach 550°C within 30 seconds)
2. The heating must be uniform
3. The average heat flux over the first 20 seconds after the 800°C temperature is met must be greater than 80 kW/m^2
4. The heating should be primarily radiative

Additionally, the following requirements guided the design from a logistical standpoint. These requirements ensure that the burner produced will be easy for the user to build, operate, and maintain and should help ensure a smooth transition to operation.

1. Made from inexpensive, commercially available parts to make it affordable/expendable
2. Quick and simple to repair in the event that it is damaged during testing

3. Design should be scalable or modular for testing of larger items

Burner Design

Early in the design phase it was noted that propane had several characteristics that made it a good choice of fuel for the development of a cleaner FCO burner. First, propane is widely available and easily purchased and delivered. Second, propane can be stored as a liquid at ambient temperature which allows a large amount of fuel to be stored in a relatively small tank at moderate pressures. Third, the price of propane is comparable to typical liquid fuels. Finally, propane can produce a sooty flame which more closely mimics the environment in typical liquid-pool fires. For these reasons, propane was selected and a burner was designed that could produce a suitable thermal environment utilizing propane as the fuel.

The burner consists of burner tubes within a square burner box as shown in Figure 1. The burner tubes are made from nominal 2 inch schedule 40 galvanized steel pipe. Each burner tube contains 26 holes, oriented vertically, with a diameter of 0.081 inches (2 mm) located 5 inches (127 mm) apart along the length of the tube. At each end of the burner tube there are two additional holes located 180 degrees around the pipe from the main line of holes and are oriented downward. These serve to allow any water that finds its way into the pipe to escape prior to testing. 26 of these burner tubes are then oriented side by side with a tube to tube spacing of 5 inches (127 mm). This produces a square with a side of 125 inches (3.18 m) containing an even grid of 676 gas ports on 5 inch (127 mm) centers.

Figure 1: At left is a photograph of the US Navy's propane burner. Note that only one of the side shields is installed to allow the inside of the burner to be viewed. At right is a photograph of the burner in operation with all four side shields installed.

The burner tubes are held in place using a 12 foot (3.66 m) square frame made from C6X10.6 structural steel channel. On the two sides through which the burner tubes pass, holes were bored to support the tubes and control their spacing. These two sides were then split down the center, lengthways, which allows the top half to be removed. This aids in disassembly of the burner for repairs. The four channel pieces are bolted together at the corners using pieces of L3X3X1/4 structural steel angle that extends upward 30 inches (0.76 m) above the burner. These pieces also serve to hold the side shields which will be discussed later. The whole assembly is placed on a refractory base made from fire bricks placed on a flat level plate.

Fuel is supplied to the burner tubes using a pair of manifolds, each of which supplies one half of the burner tubes. The manifolds are supplied from the middle which helps to equalize pressure throughout the burner area. Also, by supplying fuel from both sides and having the flow in the burner tubes alternate directions for every other tube, any pressure drop along the burner tube length will be canceled out within the burner area. This produces a nearly uniform flow of gas within the burner area and mimics the uniform production of fuel vapor over an ignited pool of liquid fuel.

Side shields are placed on all four sides of the burner. These shields are made from 29 gage galvanized steel flashing and are supported by the angle steel corner posts. The side shields are 26 inches (66 cm) tall and serve to limit the amount of air entrained by the fire. This helps to ensure that the fire is fuel rich and therefore produces a sooty flame which increases the radiation percentage within the fire. The limited air entrainment also helps to limit the maximum temperature of the flame to a value more representative of kerosene based fires. The light gage steel is easily penetrated by fragments and should not affect scoring of munitions. Moreover, the ordinance item is typically placed in the burner higher than the top of the side shields. This implies that any fragments that hit the shields would necessarily be on a downward trajectory and would therefore not have traveled very far before hitting the ground anyway.

Figure 2 shows a schematic of the fuel delivery system. Liquid propane fuel is supplied to the burner at tank pressure and is then decreased to a pressure of 10 pisg at the pressure regulator R_1. At this pressure, the boiling point of propane is approximately -29°C. The fuel cools the delivery pipes to this temperature then flows to the burner tubes where it is boiled. The heat transfer feedback from the fire prevents the burner tubes from cooling down so that the fuel exiting the gas ports is always in gaseous form. Essentially, the burner tubes act as a large propane vaporizer supplying propane gas to the burner volume. Because liquid propane is drawn from the tank, the pressure in the tank remains nearly constant during extraction as only a small amount of propane is actually boiled off in the tank. That is, for every liter of liquid propane removed from the tank, only enough propane is boiled in the tank to produce a liter of propane gas within the tank. The vast majority of the phase change occurs within the burner tubes with energy supplied from the burning propane.

During operation, all of the manual valves (blue valves) shown in Figure 2 are in the open position. This allows complete remote operation of the burner. Ignition of the propane burner is accomplished with a pilot burner ignited by an electric spark. A small torch is used to produce a flame within the burner prior to introducing fuel to the burner tubes. To ignite the burner, first the primary fuel solenoid valve (A) is opened. Next, 6000 VAC at 60 Hz is sent to a spark plug within the pilot torch. Then the pilot solenoid valve (C) is opened which supplies fuel to the pilot at approximately 2 psig through pressure regulator $R_{2.}$ This fuel is ignited by the spark in the pilot torch. Once pilot ignition is verified by a nearby thermocouple, the spark is deactivated and the primary burner valve (B) is opened supplying fuel to the burner tubes as described above. The three pressure transducers verify proper operation of the burner.

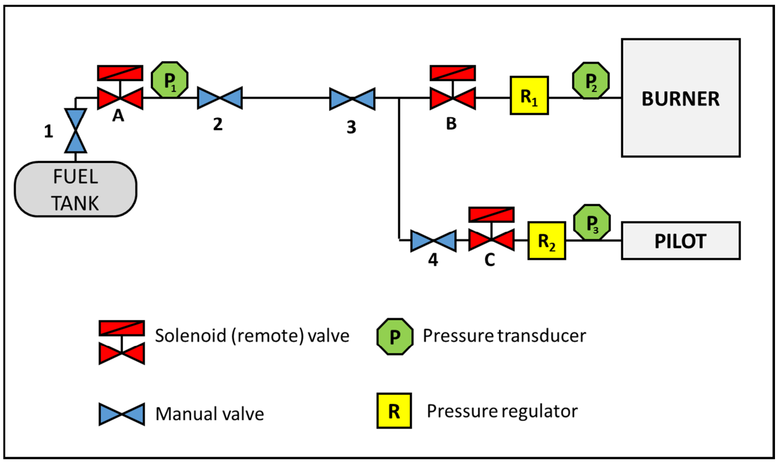

Figure 2: Schematic of piping for fuel delivery to propane burner.

Instrumentation

To characterize the thermal environment produced by the propane burner, both thermocouples and heat flux sensors were used. This section will discuss the instrumentation used and how the data produced were analyzed.

One of the thermal requirements listed in the STANAG is that the flame temperature must be at least 800°C surrounding the test item. Tests were performed to determine the size of the region within the burner volume that meets this temperature requirement. The full temperature field within the burner was measured using 48, 30 gage type K thermocouples with silica insulation. The thermocouples were placed on a cross within the burner on two orthogonal planes as shown in Figure 3. The thermocouples were placed at heights of 18, 36, 54, and 72 inches (45.7, 91.4, 137.2, and 182.9 cm) above the burner tubes and 0, 16, 32, and 48 inches (0, 40.6, 81.3, and 121.9 cm) from the center of the burner in each of four directions. Due to a data acquisition limit of 48 channels, the top outside corner of each plane were omitted. Since the thermocouples used were made from small gage wire, their readings are assumed to be the gas temperature at that location. The temperatures reported are average values for the duration of the 2 minute test. After only a few seconds the flame was stable and longer tests produced no change in the results.

A heat flux requirement was also specified by the Fuel Fire Experts. Directional slug calorimeters (DSCs) were developed and used to collect total absorbed heat flux measurements within the burner volume. Total absorbed measurements were made instead of total heat flux measurements because total absorbed heat fluxes can be easily measured. To obtain the total heat flux requires determining the incident radiation which is very difficult when convective heating is also present. Slug calorimeters directly measure total absorbed heat flux by measuring the temperature history of a known thermal mass then calculating the total absorbed heat flux required to cause the measured temperature rise. The DSC is basically four slug calorimeters in one unit which allows it to measure heat flux in four directions simultaneously; on top, bottom, left, and right.

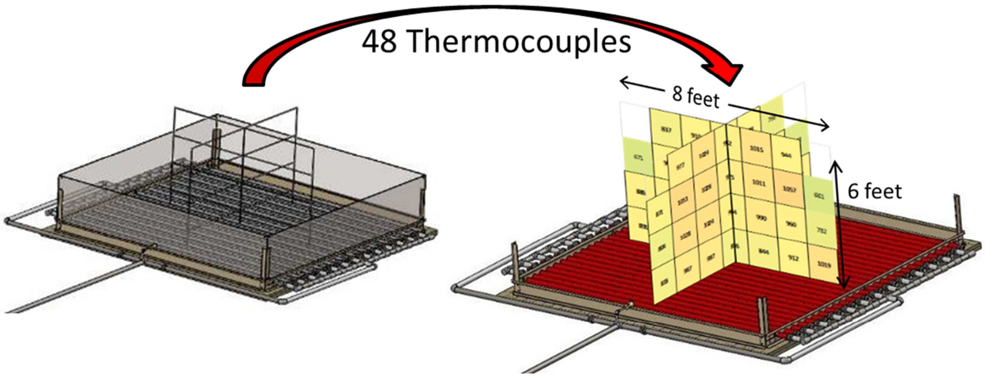

Figure 3: Thermocouple gird at left produces two orthogonal planes of temperature measurements as shown at right.

The DSC consists of a thick walled tube made from 304 stainless steel. The DSC is 3 inches (76.2 mm) long, has an outside diameter of 2.70 inches (68.6 mm), and a wall thickness of 0.425 inches (10.8 mm). Four slots are cut, one every 90 degrees around the cylinder, which thermally isolates the four quadrants of the cylinder as shown in Figure **4**. Within the center of each quadrant, a hole is drilled that is 1.5 inches (38.1 mm) deep which accepts a mineral insulated metal sheathed (MIMS) thermocouple. The thermocouple is potted into the hole using a high thermal conductivity, aluminum nitride based ceramic potting compound. This ensures that the thermocouple is in thermal equilibrium with the center of the thermal mass. Prior to use, the DSC is soaked in a furnace at 900°C for 12 hours to ensure full oxidation and a uniform surface emissivity of 0.87 as measured by Surface Optic's ET-100 reflectometer.

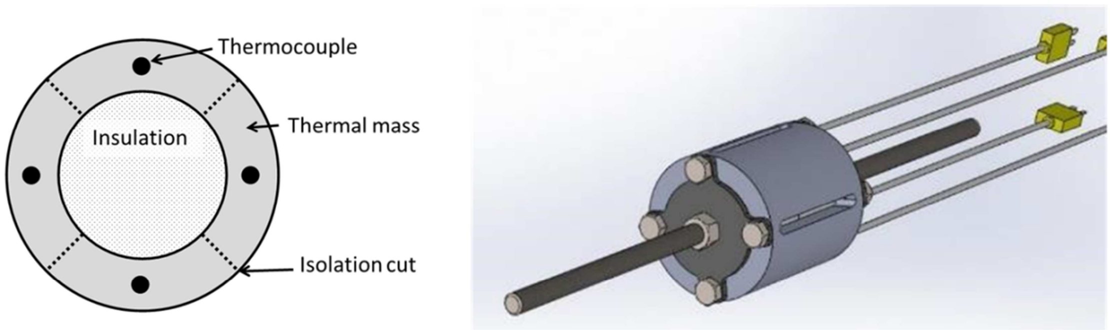

Figure 4**: Directional slug calorimeters are used to measure heat flux within the fire. The calorimeter measures heat flux on top, bottom, left, and right of device.**

The total absorbed heat flux (q_{in}) is the sum of the absorbed radiative heat flux and the convective heat flux. This is the total heat flux that enters the quadrant and, from an energy balance, is equal to the sum of the heat emitted by the surface (q_{rad}) and the energy stored within the quadrant (q_{stored}).

$$q_{in} = q_{rad} + q_{stored}$$

The heat into a surface is the heat flux ($q"_{in}$) times the surface area (A_s) and the energy stored is the mass of the slug times the specific heat (which is a function of temperature) times the temporal derivative of the average slug temperature. The emitted heat (q_{rad}) is the surface area times the surface emissivity (ε) times the Stefan-Boltzmann constant (σ) times the absolute temperature to the fourth power. Combining these gives the following equation.

$$q"_{in} \cdot A_s = A_s \varepsilon \sigma T^4 + mC(T)\frac{dT}{dt} \qquad or \qquad q"_{in} = \varepsilon \sigma T^4 + \frac{mC(T)}{A_s} \cdot \frac{dT}{dt}$$

For the DSC, the temperature (T) is measured and dT/dt can be calculated easily from the temperature history using a central difference. The remaining properties for the DSC are given in Table 1. It is assumed that the temperature measured by the thermocouple is an accurate measurement of the average temperature of the quadrant and also an accurate measurement of the quadrant's surface temperature. Due to the high thermal conductivity of the slug, this assumption results in minimal error.

Table 1: Properties of the DSC

A_s	36.19 cm^2
ε	0.87 (measured using Surface Optic's ET-100 reflectometer)
σ	5.67e-8 (W/m^2K^4)
m	0.2576 kg
C(T) (T in Kelvins)	131.08·ln(T)-285.6 (J/kg K) curve fit to table in reference 6

During testing, slug calorimeters were placed within the burner at the same locations as the thermocouples discussed earlier. However, only four slug calorimeters were available for testing. Therefore, the four calorimeters were placed on a stand that produced a single vertical rake of measurements each test. This stand was then moved within the burner and the tests repeated. Also, due to the symmetry found in the temperature measurements, only one quadrant of the burner was tested using the slug calorimeters. That is, the symmetry in the temperature measurements implied symmetry in heat flux as well and it was assumed that the heat flux results from a single quadrant would apply to the other quadrants.

Test Results

Temperature Results

The results from the temperature testing are shown in Figure 5. These are the average temperatures (Celsius) measured during a test. Average values across multiple tests are very similar but examining the temperatures from a single test can be more revealing. In this test, the temperature exceeds the 800°C minimum in 46 of the 48 test locations. The two regions that do not meet this minimum are 4.5 feet above the burner and 4 feet from the center. The minimum temperature was in fact easily met over most of the burner volume with an overall average temperature of 907°C. Also, the temperatures are not excessively high. The highest temperature recorded was 1047°C which means the minimum temperature was met without producing an environment that might over-test an item in other locations. Also noteworthy is the uniformity of the temperature field. The coefficient of variation (the standard deviation normalized by the mean) is 8% for the entire data set.

Figure 5: Results of temperature testing within burner. Note that two diagrams are the two orthogonal planes produced by the temperature grids.

From a more qualitative standpoint, the temperature field matches what has been seen in liquid-fuel fire testing. Notice that the temperatures are not highest at the bottom center of the burner but instead are highest above this bottom region. This matches the vapor dome region of a liquid fuel fire. Also, as shown in Figure 1 the flames look like those seen in a liquid fuel fire with the exception of the missing large black soot cloud above.

Heat Flux Results

After analyzing the data, the heat flux in each of four directions at each DSC location can be determined as a function of time. The average value of each of these four signals is then calculated for the first 20 seconds after the 800°C temperature requirement is met. This gives the average heat flux in each of the four directions for that test. The average heat flux at each location is then found by averaging these four average heat flux measurements. These average heat flux values are shown on the left side of Figure 6. In 14 of the 16 measurement locations, the burner exceeds the goal of 80 kW/m^2. As previously mentioned, due to the symmetry in the temperature data, it was decided to only measure the heat flux in one quadrant of the burner and assume that the other three quadrants would be similar. If symmetry holds true and the other quadrants have similar heating, then the volume produced that meets the heat flux requirement is over 5 feet (1.5 m) wide and 6 feet (1.8 m) tall. Similar to the temperature data discussed above, the burner meets the heating requirement in a large volume without being excessively high anywhere so no region would over-test the item.

In addition to the average heat flux levels, the directional uniformity of the heating was analyzed. Previous work has indicated that the heating within a large pool fire is from all directions but it has been a concern that propane fires would heat primarily from the bottom. The directional uniformity of the heating was found by taking the coefficient of variation of the four time-averaged heat fluxes (the standard deviation divided by the mean) for each DSC location. These were then converted to a percentage and subtracted from 100% so that a value of 100%

means that the heating from all four directions is identical while a low value would imply that the heating is primarily from a single direction. The threshold value for the directional uniformity was discussed at the fourth Fuel Fire Experts Meeting and a value of 75% was suggested as a minimum value. Future discussions will determine if directional uniformity is a requirement and how directional uniform the heating must be. The results from this analysis are shown at right in Figure 6. Here, 13 of the 16 locations meet the directional uniformity requirement and the ones that do not are on the outer edge of the fire. This region does not meet the requirement because the fire has begun to neck-in and the DSCs were primarily heated from the bottom and inside while the top and outside were not heated. Again, if symmetry is assumed, a volume over 5 feet (1.5 m) wide and 6 feet (1.8 m) tall meets the directional uniformity requirement.

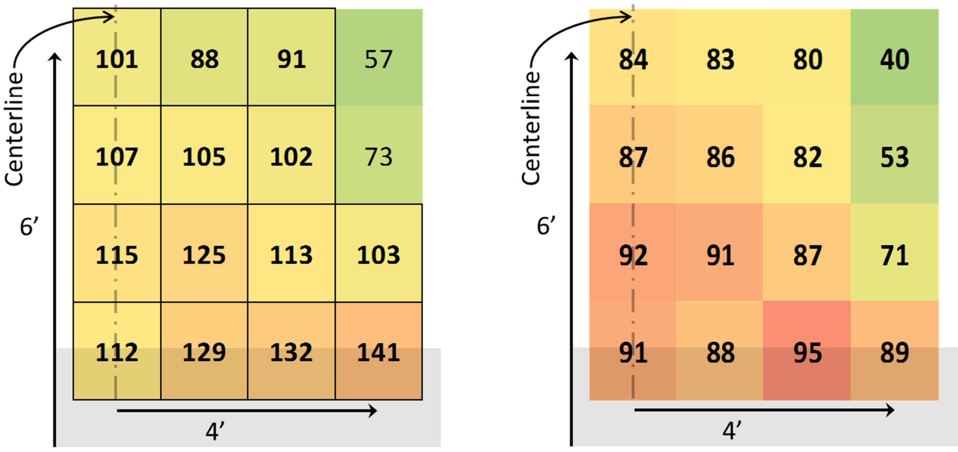

Figure 6: At left, average measured heat flux (kW/m^2) for one quadrant of the burner. At right, the directional uniformity of the measured heat fluxes for the same data. In each graph, the left hand column is the center of the burner.

Another requirement for the burner was that the heating be mostly radiative. While measuring heat flux by individual components is difficult, analyzing the temperature and heat flux data gives insight into whether the heating is primarily convective or radiative. First, the high level of directional uniformity within the flame implies a high percentage of radiation. If the heating was primarily by convection, one would expect the bottom to see much higher heating compared to the sides but this was not observed. Furthermore, by examining the videos of the fire, it was estimated that the gas velocity was no more than 5 m/s. Using the correlations for a cylinder in cross flow[6] the convective heat transfer coefficient is approximately h=27 W/m^{2}K. For the center of the fire 1 meter above the burners the temperature is 900°C. This gives a convective flux of 24 kW/m^2. The measured heat flux at this location was 115 kW/m^2 which implies that the heating is at least 80% radiative. Therefore, the heating within the burner is mostly from radiation.

Conclusions

A propane fueled burner has been developed by the US Navy to perform FCO testing. Testing has demonstrated that the thermal requirements imposed by international standards upon the burner have been met as summarized below:

1. *The flame temperature must be at least 800°C degrees C.*
   Testing showed that nearly the entire burner volume exceeded 800°C. The average temperature within the burner was 907°C.
2. *The heating must be uniform.*
   Both temperature and heat flux testing indicated a high level of uniformity. The temperature field was uniform to within 8% and the directional uniformity of the heat flux measurements was above 75% everywhere within a volume that was over 5 feet (1.5 m) wide and 6 feet (1.8 m) tall.
3. *The average heat flux over the first 20 seconds after the 800°C temperature is met must be greater than 80 kW/m^2.*
   The measured average heat flux was greater than 80 kW/m^2 in the same 5 feet (1.5 m) wide by 6 feet (1.8 m) tall volume described above.
4. *The heating should be primarily radiative.*
   When examined as a whole, the data from the heat flux and temperature measurements implies that radiation accounts for more than 80% of the heating.

By meeting these requirements, the Navy burner provides a test-volume that simulates the heating of a liquid-fuel pool fire. This volume is large enough to be useful for ordnance testing.

Acknowledgments

This work was jointly funded by the Environmental Security Technology Certification Program and by Insensitive Munitions Advanced Development program.

References

1. TB 700.2 NAVSEAINST 8020.5C, to 11A-1-47, DLAR 8220.1, Joint Technical Bulletin, “Department of Defense Ammunition and Explosives Hazard Classification Procedures,” final draft, May 2004.

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

3. North Atlantic Treaty Organization Standardization Agreement (NATO STANAG 4240), Liquid Fuel/External Fire Test.

4. Jon Yagla, David Griffiths, John Busic, “Heat Flux and Thermal Response Measurements for Designing a Propane Fuel Fast Cook-Off Test Apparatus,” IMEMTS, May 2012

5. Jon Yagla, David Hubble, David Giffiths, Kevin Ford, and Ephraim Washburn, “Experimental Development of Propane Burners for Fast Cook-off Testing,” IMEMTS, October 2013

6. F. P. Incropera and D. P. DeWitt. *Fundamentals of Heat and Mass Transfer*, 5th Edition, John Wiley & Sons, New York, NY, 2002.