FINAL REPORT

Liquid-Fuel Fire Alternative

ESTCP Project WP-201320

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US DoD ordnance items, except those exempt i.e. pyrotechnics and small caliber ammunition, are required to be tested in a liquid-fuel-fire fast heating test and have the results reported. The liquid fuel fire test, commonly known as the fast cookoff (FCO) test, is used to simulate exposure in a fire, and is one of a suite of tests used to determine if the munition meets Insensitive Munition (IM) requirements. The test subjects full-scale ordnance to a liquid-fuel fire and assesses the violence of reaction and susceptibility of the item to fire. During the life cycle of an ordnance item, exposure to fire may result from an accident related to transportation, storage, and/or mishap on the deck of an aircraft carrier.

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List of Acronyms and Symbols

AOP-39	Guidance on the Assessment and Development of Insensitive Munitions (IM)
AVCAT	Aviation Fuels
CHFD	Controlled Heat Flux Device
COMPB	Composition B Explosive Material
DDESB	Department of Defense (DoD) Explosive Safety Board
DoD	Department of Defense
EC	Elemental Carbon
EEA	Explosive Experimental Area
EPA	Environmental Protection Agency
FCO	Fast Cookoff
HazMat	Hazardous Material
HC	Hazard Classification
IM	Insensitive Munitions
IMAD	Insensitive Munitions Advanced Development Program
JSIMTP	Joint Services Insensitive Munitions Technical Panel
MCE	Modified Combustion Efficiency from the Entire Burn
MREB	Munition Review and Evaluation Board
NATO	North Atlantic Treaty Organization
NAWCWD	Naval Air Warfare Center Weapons Division
ND	Not Detected
NSWCDD	Naval Surface Warfare Center Dahlgren Division
OC	Organic Carbon
PAH	Polycyclic Aromatic Hydrocarbons
PM	Atmospheric Particulate Matter
SOP	Standard Operating Procedure
STANAG	Standardization Agreement
TC	Total Carbon
VAC	Volts Alternating Current
VOC	Volatile Organic Compounds

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Executive Summary

US DoD ordnance items, except those exempt i.e. pyrotechnics and small caliber ammunition, are required to be tested in a liquid-fuel-fire fast heating test and have the results reported. The liquid fuel fire test, commonly known as the fast cookoff (FCO) test, is used to simulate exposure in a fire, and is one of a suite of tests used to determine if the munition meets Insensitive Munition (IM) requirements. The test subjects full-scale ordnance to a liquid-fuel fire and assesses the violence of reaction and susceptibility of the item to fire. During the life cycle of an ordnance item, exposure to fire may result from an accident related to transportation, storage, and/or mishap on the deck of an aircraft carrier. The liquid-fuel fire test required for both Insensitive Munitions (IM) and hazard classification (HC) for the military is currently performed in accordance with STANAG 4240. In this test, the ordnance item is suspended or positioned 1 meter above the fuel. The fuel is ignited, producing a flame that completely engulfs the item under test. The quantity of fuel used is sufficient to produce a fire duration which is 50% longer than the anticipated item reaction time. After the ordnance item reacts, its response is scored based on the pressure output of the event and relative violence of reaction based on the overall video along with the number, size, and distance of any fragments thrown. The STANAG designates the use of liquid hydrocarbon fuels, such as JP 4, JP 5, Jet A 1, AVCAT, or commercial kerosene. However, increasing environmental concerns with respect to air quality, as well as soil and groundwater contamination have begun to impact the ability of the United States and other nations to perform the liquid-fuel fire test. Limitations are being placed on where and how the test can be run due to the environmental effects.

This project demonstrated and validated the use of propane as a viable alternative to kerosene-based fuels for the liquid-fuel fire test. A full-scale demonstration device was constructed and operated during the project. As part of the project, collaboration with the DoD Explosive Safety Board (DDESB), IM community, and international community occurred to establish a method to adopt and recognize propane and other fuels as alternates for kerosene-based fuels in the liquid-fuel fire test.

The first performance objective of the project was to reduce the fuel usage by greater than 50%. Less fuel usage will lead to lower costs and lower pollution. The fuel usage for the pool fires was determined by the amount of fuel added to the pool before ignition. The fuel usage for the propane fires was determined by recording the propane fuel in the tank before and after the tests. For the FCO propane tests with ordnance items compared to FCO tests with pool fires with the same ordnance items, the average reduction in fuel was 83%. The smallest reduction in fuel usage was 60% and the largest reduction in fuel usage was 93%.

The second performance objective was that the propane burner met all of the requirements of STANAG 4240. The test would not be accepted for use both nationally and internationally if the test did not meet the STANAG 4240 requirements. The average temperature must be greater than 800°C and reach 550°C within 30 seconds of ignition. The total absorbed heat flux, as measured by a device of specified dimensions, must be greater than 80 kW/m2 when averaged over a minimum 30-second period after a minimum temperature of 800°C is achieved. This was determined by thermocouple and heat flux gauge measurements. All of the requirements of STANAG 4240 were met in the 8 ft (2.4 m) by 8 ft (2.4 m) burner, the 12 ft (3.7 m) by 12 ft (3.7

m) burner, and the 10 ft (3.0 m) by 20 ft (6.1 m) burner. This also demonstrates that this technology is scalable.

A suite of emissions' measurement hardware was flown above a 12 ft (3.7 m) square propane burner fire and a JP-5 pool fire to determine the difference in emissions between the two FCO test fires. This objective is important as it will facilitate testing as the environmental emissions regulations increase in stringency. The success criterion was that the emissions be reduced by greater than 50%. This criterion was met. The particulate matter emissions were reduced by 99.96%. The CO2 emissions were reduced by 94%. The CO emissions were reduced by 99.3%. The polycyclic aromatic hydrocarbon (PAH) emissions were reduced by 99.6%. The volatile organic compounds were reduced by 99.1%. The elemental carbon (EC) emissions were reduced by 99.99%. The organic carbon (OC) emissions were reduced by 99.6%. The total carbon (TC) emissions were reduced by 99.97%.

The final quantitative performance objective was that an ordnance item tested in a 12 ft (3.7 m) square propane burner FCO would receive the same assessment for violence of reaction as the same ordnance item in a pool fire FCO. This was an important objective as this was necessary to be able to compare future propane FCO data with past pool fire FCO data. The insensitive munitions community would not accept the propane FCO test if there were substantial differences in the reaction violence. All four ordnance items tested received the same engineering assessment reaction violence rating in both the12 ft (3.7 m) square propane burner and pool fire FCO tests.

As far as the qualitative performance objectives, it was desirable that the propane burner be modular in design. Different test sites will test different sized ordnance items and having flexibility in the size of the burner will make it applicable to any site adopting the technology. Three burners were built and tested. They were the 8 ft (2.4 m) by 8 ft (2.4 m) burner, the 12 ft (3.7 m) by 12 ft (3.7 m) burner, and the 10 ft (3.0 m) by 20 ft (6.1 m) burner. All three burners performed as designed and met the STANAG 4240 requirements.

The success criterion for the reduced cost of the burner was greater than 50%. The initial calculated reduction in cost per test was 30%. The annual maintenance cost was reduced by 80%. Having a reduction in cost will make this technology more appealing to customers requesting the FCO testing. Related to cost is the convenience of replacement. Three pipes were damaged in a test in which the test item had a violent reaction and it took an hour to replace the pipes.

The final performance objective was that the flame above the propane burner would qualitatively appear similar to the flame produced during the liquid pool fire test. This was important as there is a long community history with the pool fires and there is an initial resistance to change. The fire above all the propane burners is luminous, turbulent, buoyant, and it fills the burner. All of these characteristics are qualitative characteristics of a pool fire. The temperature and heat flux measurements were important for community acceptance of the burner; however, the qualitative appearance of the flame greatly assisted the acceptance of the burner as well.

These results indicate that the propane burner used in the study is an acceptable alternative to liquid-hydrocarbon fueled burners for fast cookoff testing.

1.0 INTRODUCTION

1.1 BACKGROUND

US DoD ordnance items, except those exempt i.e. pyrotechnics and small caliber ammunition, are required to be tested in a liquid-fuel-fire fast heating test and have the results reported. The liquid fuel fire test, commonly known as the fast cookoff (FCO) test, is used to simulate exposure in a fire, and is one of a suite of tests used to determine if the munition meets Insensitive Munition (IM) requirements. The test subjects full-scale ordnance to a liquid-fuel fire and assesses the violence of reaction and susceptibility of the item to fire. During the life cycle of an ordnance item, exposure to fire may result from an accident related to transportation, storage, and/or mishap on the deck of an aircraft carrier. The liquid-fuel fire test required for both Insensitive Munitions (IM) and hazard classification (HC) for the military is currently performed in accordance with STANAG 4240 [1, 2, 3]. In this test, the ordnance item is suspended or positioned 1 meter above the fuel. The fuel is ignited, producing a flame that completely engulfs the item under test. The quantity of fuel used is sufficient to produce a fire duration which is 50% longer than the anticipated item reaction time. After the ordnance item reacts, its response is scored based on the pressure output of the event and relative violence of reaction based on the overall video along with the number, size, and distance of any fragments thrown. The STANAG designates the use of liquid hydrocarbon fuels, such as JP-4, JP-5, Jet A-1, AVCAT, or commercial kerosene. However, increasing environmental concerns with respect to air quality, as well as soil and groundwater contamination have begun to impact the ability of the United States and other nations to perform the liquid-fuel fire test. Limitations are being placed on where and how the test can be run due to the environmental effects.

One of the environmental concerns with the liquid-fuel fire test is the pollutant emissions. On average, these liquid-fuel fire tests utilize 2,000 gallons of jet fuel and emit over 400 pounds of CO, 70 pounds of NO_x, 60 pounds of SO_x, 550 pounds of soot, 250 pounds of unburned hydrocarbon, and 40,000 pounds of CO_2. Multiply these emissions by the greater than 300 tests performed on Department of Defense (DoD) ordnance items each year, and this is a significant environmental concern [4, 5, 6, 7].

Contamination of the soil and water from the fuels used in the external fire and fast cookoff (FCO) tests is also a major concern. Unburned fuel is blown out of the test pit during a liquid-fuel fire. Kerosene or JP-8, which is a kerosene distillate, represents middle distillates. If the fuel is spilled, it can evaporate and contribute to atmospheric smog. If the liquid fuel is exposed to soil, petroleum middle distillate fuels strongly adsorb which can lead to groundwater contamination. These distillates are toxic to freshwater and saltwater ecosystems. Aromatic compounds of concern include alkyl benzenes, toluene, naphthalene, and polycyclic aromatic hydrocarbons (PAHs). These compounds have acute toxicity to aquatic life, and ground water contamination threatens potable water supplies. PAHs may have long term health effects, including changes in the liver, and have an effect on the heart, kidneys, lungs, and the nervous system [8].

Increasing environmental concerns have begun to limit when and where liquid-fuel fire testing can occur. Edwards Air Force Base in California and Tooele Army Depot in Utah are limited in when they can perform the test due to air quality emission limitations of air permit requirements. Germany and Canada can no longer perform the test using liquid fuels such as kerosene or jet fuel due to their concerns with respect to water and soil contamination. Sweden must test at night to prevent offending their Norwegian neighbors due to air quality aspects due to the visible emissions[9]. These increasing environmental concerns have led to considering propane as the alternative to liquid kerosene fuels.

The technology that was demonstrated under this effort is a liquid-propane burner. It uses propane that is ejected from a series of nozzles which, when ignited, produces a flame that generates a thermal environment (temperature and heat flux) that is similar to a liquid-fuel pool fire. Using the propane burner allows for a more controlled and reproducible test compared to the liquid-fuel pool fire. In addition, soil and ground water contamination is no longer an issue as propane is a gas at ambient temperature and atmospheric pressure. Propane also offers greater combustion efficiency compared to larger hydrocarbons and produces significantly fewer atmospheric emissions. It is also readily available and easier to acquire than many kerosene based fuels.

1.2 OBJECTIVE OF THE DEMONSTRATION

This project demonstrated and validated the use of propane as a viable alternative to kerosene-based fuels for the liquid-fuel fire test. A full-scale demonstration device was constructed and operated during the project. As part of the project, collaboration with the DoD Explosive Safety Board (DDESB), IM community, and international community occurred to establish a method to adopt and recognize propane and other fuels as alternates for kerosene-based fuels in the liquid-fuel fire test. This project produced a technical data package, publications, a database comparing liquid-fuel fire results to those of propane, and possibly a licensing agreement to produce the technology so that other services or companies may purchase and operate the technology. Table 1 summarizes the implications of switching from kerosene to propane for the liquid-fuel fire test.

Table 1. Target Hazardous Material (HazMat) Summary.

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
Keresone-based fuels	Fuel for the liquid-fuel fire test	HC and IM Testing	STANAG 4240	All new and existing programs needing a new HC or IM testing	N/A – Developing new test bed to use propane

The propane burner operates cleaner than kerosene-based fires with 75% less soot. Propane is a gas at room temperature, preventing soil and groundwater contamination and is cheaper and easier to obtain than the JP-8, AVCAT, and other kerosene-based fuels currently used in the liquid-fuel fire test. A propane burner system would be significantly more efficient than the pool fire configuration and would emit less CO and almost no unburned hydrocarbons. Furthermore, because of the carbon to hydrogen ratio difference between propane and kerosene, propane produces 5% less CO_2 per mass of fuel. The propane burner system would consume less than 10% of the fuel of the liquid-kerosene fuel fire because the heat would be more efficiently used and the fire could be stopped when the test item reacts, something that is not possible with liquid-fuel pool fires. This leads to even further reduction in environment emissions per test.

1.3 REGULATORY DRIVERS

The main impetus for switching from kerosene to propane is coming from the international community. As stated in the background, the inability for Germany to perform liquid-fuel fire tests at their government facilities, Sweden testing at night, and Canada sending their testing to the U.S. has required the need to change the standard and allow for the use of propane. Currently, the North Atlantic Treaty Organization (NATO) AOP-39 standard has been changed to allow for alternative fuels and a new version is being written that will allow for the use of other fuels such as propane in the liquid-fuel fire test as long as the heat load conditions are met.

It is anticipated that air quality restrictions in the U.S. will increase in the future, either further reducing the locations where the test is performed or forcing the U.S. to switch to propane or another alternatively greener fuel. Therefore, the technology needs to be available and demonstrated to ease this likely transition. There are current limitations in some states on liquid-fuel fire testing because of air permits restricting the amount of emissions.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Several different fuels were considered as candidates for an alternative fuel FCO burner. These included natural gas, propane, butane, and hexane. Early in the design phase it was noted that propane had several characteristics that made it the best choice of fuel for the development of a cleaner FCO burner. First, propane is universally 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, but its saturation pressure is high enough to eliminate the need for pumps. This is not possible with natural gas which must be refrigerated to be stored as a liquid. Additionally, both butane and hexane have sufficiently high boiling temperatures that they would have to be pumped from the tank to the burner. Third, the price of propane is comparable to typical liquid hydrocarbon fuels. And finally, propane contains enough carbon to produce high levels of soot within the flame which more closely mimics the environment in typical liquid-fuel 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.

Before a cleaner FCO burner could be built a set of requirements needed to be established. Requirements development started in 2009 at Meppen, Germany. Germany built a liquid propane injection burner and used thermocouples and calorimeters to show the temperatures and heat transfer to test items in the new burner 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, Germany. The US Team expanded on this work by measuring similar temperatures and heat fluxes in the propane burner at Meppen, Germany and in a liquid JP-5 fire at Dahlgren, VA [10]. The burner at Meppen, Germany is shown in Figure 1. From the Meppen propane burner it was determined that liquid propane needed to be used instead of gaseous propane to get the mass flow necessary for the high heat fluxes. The Meppen burner had expensive infrastructure and needed wind screens that would affect the fragment throw results and therefore the exact design was not used.

Figure 1. Liquid Propane Burner at Meppen, Germany.

The requirements were developed further at subsequent Fuel Fire Experts Meetings in The Netherlands and Sweden. Prior to each meeting, the US Team performed testing for the host country on their burner design. The burner designs are shown in Figure 2. These were premixed designs where the fuel and air were mixed prior to ignition. This led to very efficient combustion and high temperatures and heat fluxes. However, the design relied on convective flow to heat the items so the heat flux was considerably higher on the sides with impinging flow. Since a uniform heating profile was desired, these designs were not used. Results of these tests showed that the data were comparable to what was previously reported in other fires. Measurements consistently showed that temperatures in these burners were over 800°C and heat fluxes were on the order of 100kW/m2. These results convinced the meeting attendees 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 presented at the IM and EM Technical Symposium in San Diego [11].

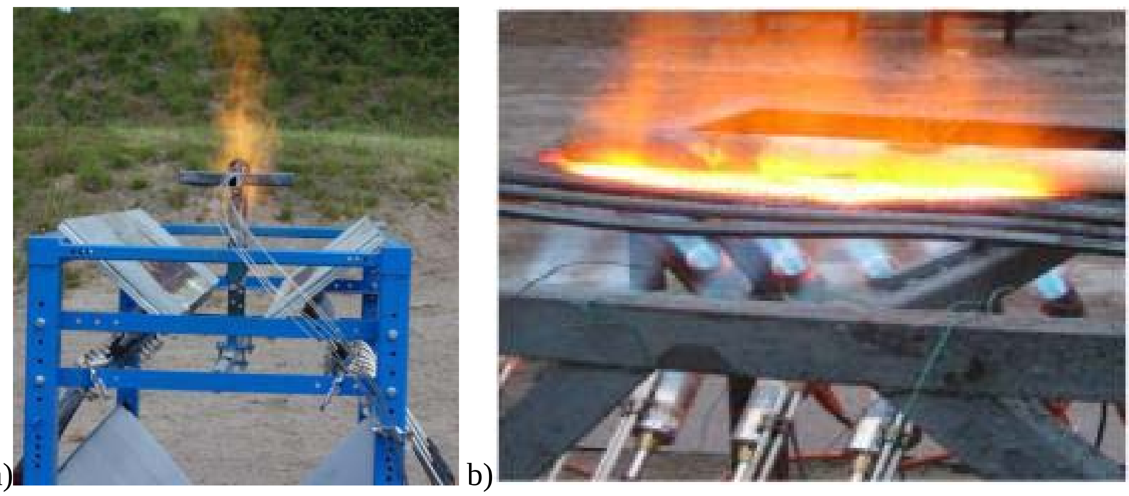

a) b)

Figure 2. Premixed Propane Burners a) 't Harde, the Netherlands b) Bofors, Sweden.

The 12 ft square Dahlgren burner consists of burner tubes within a square burner box as shown in Figure 3. The burner tubes are made from nominal 2 inch (51 mm) schedule 40 galvanized steel pipe. Each burner tube contains 26 holes with a diameter of 0.081 inches (2mm) located 5 inches (127mm) apart along the length of the tube. These holes are oriented straight up. 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 straight down. 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 (127mm). This produces a square with a side of 125 inches (3.18m) containing an even grid of 676 gas ports on 5 inch (127mm) centers.

The burner tubes are held in place using a 12 ft (3.66m) 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 12 inches (0.3m) above the burner. These pieces also serve to hold the side shields which will be discussed later. The whole assembly is positioned above a refractory base made from fire bricks.

Fuel is supplied to the burner tubes using a pair of manifolds, each of which supplies 13 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 pipes alternate directions for every other pipe, any pressure drop along the burner 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 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 ordnance item is typically placed in the burner at a height that is greater 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 travel very far before hitting the ground.

Figure 3: At left is a photograph of the US Navy's 12 ft (3.7 m) square 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.

Figure 4 shows a schematic of the fuel delivery system. The controls are located in two shelters, the tank shelter and the burner shelter. The tank shelter is located at a distance of 75 meters from the burner which allows the large propane tank to be adequately protected from potential fragments generated during testing. The burner shelter is located much more closely, only about 7 m from the burner. Liquid propane fuel is supplied to the burner at tank pressure and is then decreased to a pressure that will supply a constant fuel flow rate of 20 gpm (75 lpm) by the flow control valve. Typically, this pressure is approximately 8pisg (55kPa). At this pressure, the boiling point of propane is approximately -29 °C. The fuel cools the delivery pipes and manifold 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 (for every liter of liquid propane removed, only enough propane is boiled to produce a liter of propane gas within the tank). The vast majority of the phase change occurs within the burner tubes with heat supplied by the burning propane.

During operation, all of the manual valves (valves 1, 2, and 3) shown in Figure 4 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 valve (A) is opened. Next, 6000 volts alternating current (VAC) at 60Hz is sent to a sparkplug within the pilot torch. Then the pilot valve (C) is opened which supplies fuel to the pilot at approximately 2psig through the pilot pressure regulator. This fuel is ignited by the spark producing a continuous pilot flame. Once pilot ignition is verified by a nearby thermocouple, the spark is deactivated and the burner valve (B) is opened supplying fuel to the burner tubes as described above. The three pressure transducers (P1, P2, and P3) and the flow meter verify proper operation of the burner. Note that all plumbing upstream of valves B and C must be able to handle tank pressure and are therefore rated for a minimum of 300 psi (2000kPa).

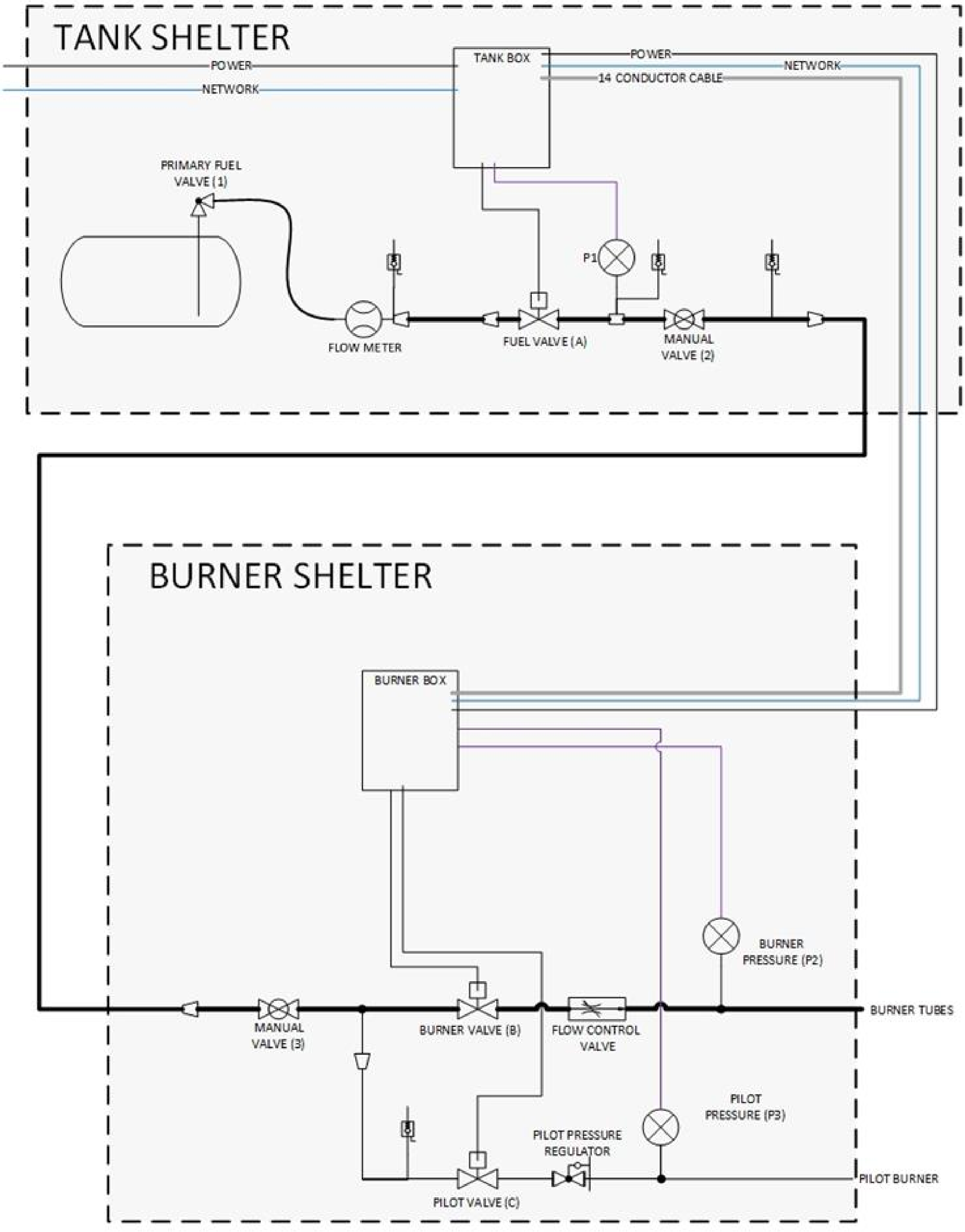


Figure 4: Schematic of piping for fuel delivery to 12 ft (3.7 m) square propane burner.

An additional burner was built at a separate site that allows the testing of larger munitions. The burner piping layout and orifice spacing were designed to allow the incorporation of an A-frame style test stand (see Figure 5) and an area of 10 ft (3.0 m) by 20 ft (6.1 m). In order to accommodate the A-frame, the burner pipe spacing was designed to handle pipe spacing's equal to either 12 in (0.30m) or 6 in (0.15 m). Along the length of the pipe, the orifices were spaced every 6 in (0.15 m) and had an initial diameter of 0.079 in (2 mm).

Figure 5. Fast Cook-off A-Frame Stand

The burner is supplied with liquid propane using a single supply line. The single supply line is used for cost, ease of construction, and lowers the probability of propane supply line failure in the event of catastrophic item failure. The supply line directs propane to the burners using an assembled manifold. The manifold is constructed from 2 in nominal (5.1 cm) pipe fittings, totaling 20 ft (6.1 m) in length. The manifold is assembled using a single cross pipe, multiple tee fittings, and two 90 degree elbow fittings for the ends. The fittings are connected using pre-determined pipe nipples to acquire the correct 6 in (0.15 m) burner pipe adaptor spacing. All fittings in the manifold are constructed from standard galvanized steel.

The overall construction of the burner pipes consists of 2 in nominal (5.1 cm) diameter schedule 40 steel piping. Using 12 in (0.30 m) spacing, the burner is constructed using 21 pipes. With 6 in (0.15 m) spacing, the burner is constructed using 39 pipes (2 pipes are removed to accommodate the A-frame legs). The orifices are drilled into the 10 ft (3.0 m) pipe sections to create the pipes used for the burner tubes. The burner tubes are threaded on both ends with a cap on one end and a 2 in (5.1 cm) union connected on the other end. The union is used to align the burner tube orifice upward and will allow for simple replacement in the event of catastrophic damage. The other end of the union is connected to the manifold by a 5 in (13 cm) long, 2 in (5.1 cm) diameter nipple. All pipe fittings used in the burner are standard galvanized steel. The propane burner in the 12 in (0.30 m) pipe spacing configuration can be seen in Figure 6.

Figure 6. 10 ft (3.0 m) by 20 ft (6.1 m) Propane Burner in 0.30 m Pipe Spacing Configuration.

Propane is supplied to the burner using a 4350 liter propane tank. The tank is a standard propane tank with a 1 in nominal (2.5 cm) drain plug at the bottom of the tank. The 1 in (2.5 cm) plug was replaced with a 1 in (2.5 cm) angle globe valve from Squibb Taylor. This valve allows for maximum liquid propane extraction from the propane tank. The valve consists of 1 in (2.5 cm) extra heavy schedule 80 pipe. This piping is used to withstand the higher pressure provided by the propane tank. This pipe leads to a 1 in (2.5 cm) solenoid valve. A solenoid valve is used to control the flow of propane to the burner remotely during burner operation. This allows operators to be at a safe distance from the burner and item during testing. The valve used is a Magnetrol solenoid valve, which is a fail close valve. If a problem were to occur, such as power loss or catastrophic damage, the valve will automatically close, shutting off the burner. The valve is also usable for cryogenic service (-40 ^{o}C to 204 ^{o}C) which falls within propane's service range. This is followed by a 2070 kPa range pressure transducer to determine the pressure of the propane being withdrawn from the propane tank. A redundant manual valve is placed behind the solenoid valve to ensure the flow of propane is stopped while personnel are working on or around the system. This setup can be seen in Figure 7 and Figure 8.

Following the propane tank setup, propane is directed to the regulatory system. A manual valve is placed directly before the regulatory system to provide a quick shut off. This allows for easier regulation system repairs. The initial regulation system was split into two sections. One directed propane to the burner system the other directed propane to the pilot system. For the burner system, the 1 in (2.5 cm) piping was directed to a solenoid valve. Following the valve, the piping was expanded from 1 in (2.5 cm) to 2 in (5.1 cm) diameter and connected to a B Series Flomec Regulator. This was followed by a 1030 kPa range pressure transducer to determine the pressure of the propane flow through the regulator. The propane was then directed to the propane burner. For the pilot system, the 1 in (2.5 cm) piping was reduced to 0.5 in nominal (1.2 cm) piping. A manual valve was placed directly after to provide a quick shut off. Following the manual valve, propane was directed to a solenoid valve followed by a G-60 Series Flomec Regulator. This was followed by a 1030 kPa range pressure transducer. Propane was then directed to the pilot ignitor. This setup can be seen in Figure 9 and Figure 10. The overall schematic of the propane burner design is shown in Figure 11. The propane tank and critical valves were behind a large concrete wall to protect them after catastrophic reaction of the tested ordnance item. The regulation system was later changed and the pilot ignition system was not used.

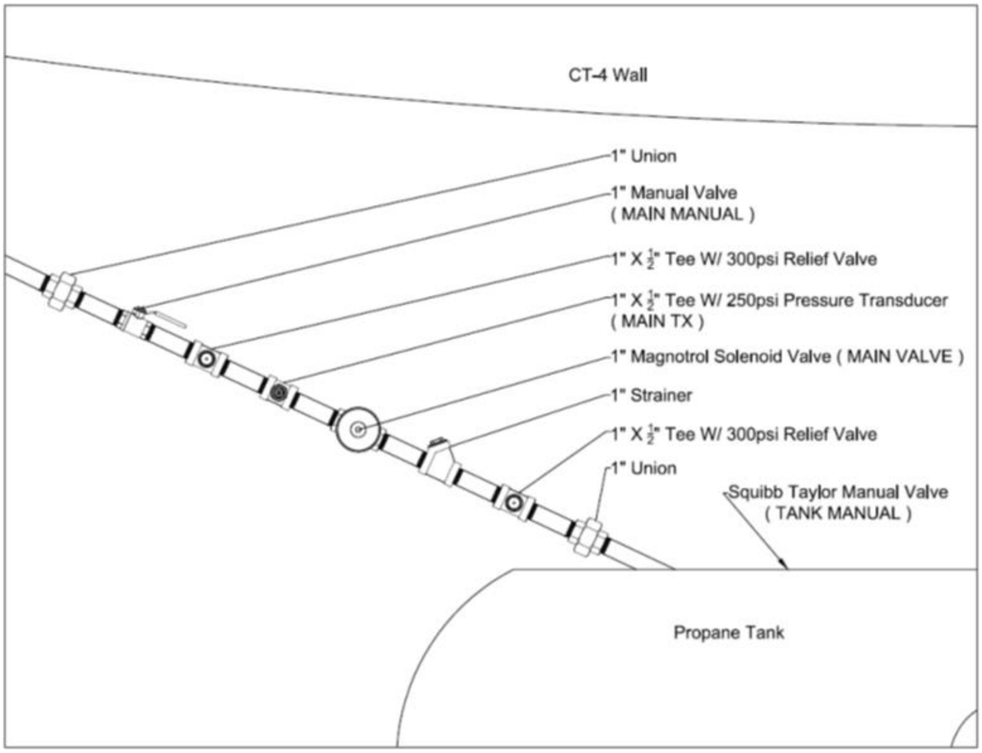


Figure 7. Propane Tank Setup Schematic

Figure 8. Propane Tank Setup

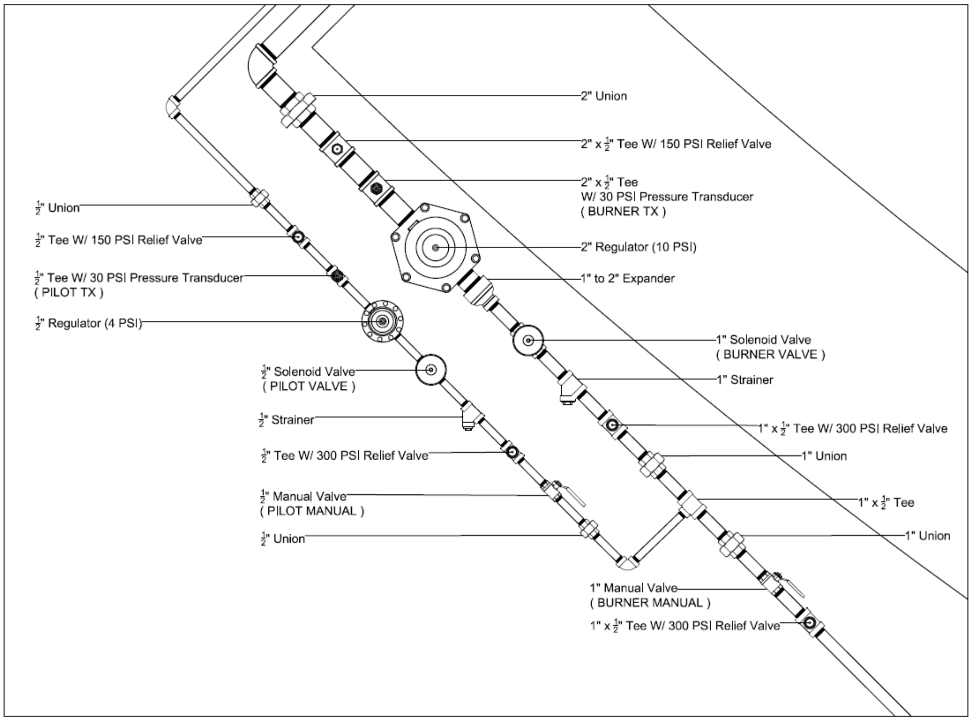


Figure 9 - Regulation System Setup Schematic

Figure 10 - Regulation System Setup

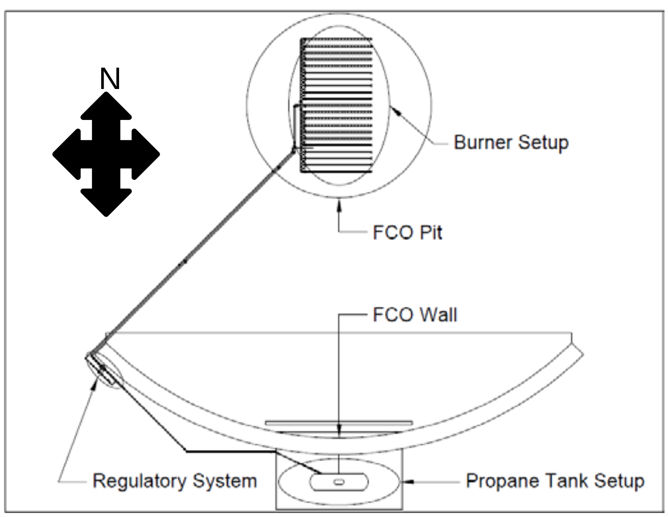


Figure 11. 10 ft (3.0 m) by 20 ft (6.1 m) Propane Burner Test Site.

Originally, a particulate strainer was placed before each solenoid valve. During the initial burner testing it was found that particulates from the tank would clog the strainer causing the strainer to freeze as the propane expanded through it. This restricted the flow of propane and directed the removal of the strainer. During further testing, the solenoid valves would begin to partially freeze as the propane expanded through it. This limited the flow of propane and in some cases did not allow any propane movement. The solenoid valves were replaced with electrically actuated ball valves which feature a large spring to ensure that in the event of power failure they will fail close. This ball valve not only solved the valve problems, it also provided a smaller pressure loss through the valve by creating a more direct flow. Similar problems were also experienced with the pressure regulators. The regulators were changed out with manual ball valves and the pressure was “throttled” manually via the ball valves. A different style pressure regulator will be selected for future testing.

The firing system directs and monitors the flow of liquid propane and manages the ignition system used to initiate the burner. The firing system is run through a lockout box to prevent the system from inadvertently obtaining power. This setup adds extra insurance that the burner system is inoperable while personnel are preparing for a test and is also compliant with US Navy safety regulations. Once the firing lines are transferred, power can be provided to the ball valves, opening the valves and directing propane to the respective system. The valves are operated remotely using a programmable logic controller (PLC) as a sequencer inside the control room. Pressure transducers are used to measure the liquid propane pressure leaving each ball valve. The pressure transducers are located in line with the propane tank valve and in line with the two pressure regulators. This allows for tank pressure, pilot pressure, and burner pressure to be remotely monitored through the entirety of the test. Originally, the ignition system lit the burner using a small ignition torch. Low pressure propane gas was supplied, for the pilot line, to the torch and was ignited using a Carlin electronic igniter. The ignitor provided a continuous-duty voltage for creating the spark.

During testing, the Carlin electronic ignitor had intermittent issues providing a spark. The ignitor functioned by arcing 14,000 VAC across two probes to provide a spark. If the two probes moved out of range, the probes would not arc and create a spark. Additionally, due to the high voltage required over a long length of copper wire, it was difficult to isolate the system from ground, even when utilizing wire with very high insulative properties. The wire was also very expensive. These two issues created problems in consistent pilot ignition. The Carlin ignitor was replaced with a hot surface igniter which operates from 120 VAC. This eliminated the issues with the spark gap spacing and the grounding, and provided a very affordable and reliable ignition source.

The firing system is controlled by a sequencer in the control room. The sequencer provides an interface to control the ignitor and ball valves and allows monitoring of the pressure from the pressure transducers. An emergency stop button is connected to the system to provide a quick means of system shutdown and was programmed to remove all power from the ignitor and ball valves in the event that the emergency stop button is pressed.

2.2 TECHNOLOGY DEVELOPMENT

The initial work on this technology was through the development of a subscale liquid-fuel fire burner to predict the response of an ordnance item in the liquid-fuel fire test. The program developed the controlled heat flux device (CHFD) that produced heat fluxes that were controllable and reproducible—unlike a liquid-fuel fire. The apparatus resembled a hair dryer where air was blown down a chamber across a propane injection system, ignited and the combustion gases then traveled across the ordnance item, as shown in Figure 12. However, the ordnance item was placed in a chamber during the test, where the chamber would act like a witness plate. This complicated the evaluation to not simply be distance of fragments but also indentions on the witness plate and complicated the pressure measurement [12, 13, 14, 15, 16, 17, 18, 19, 20].

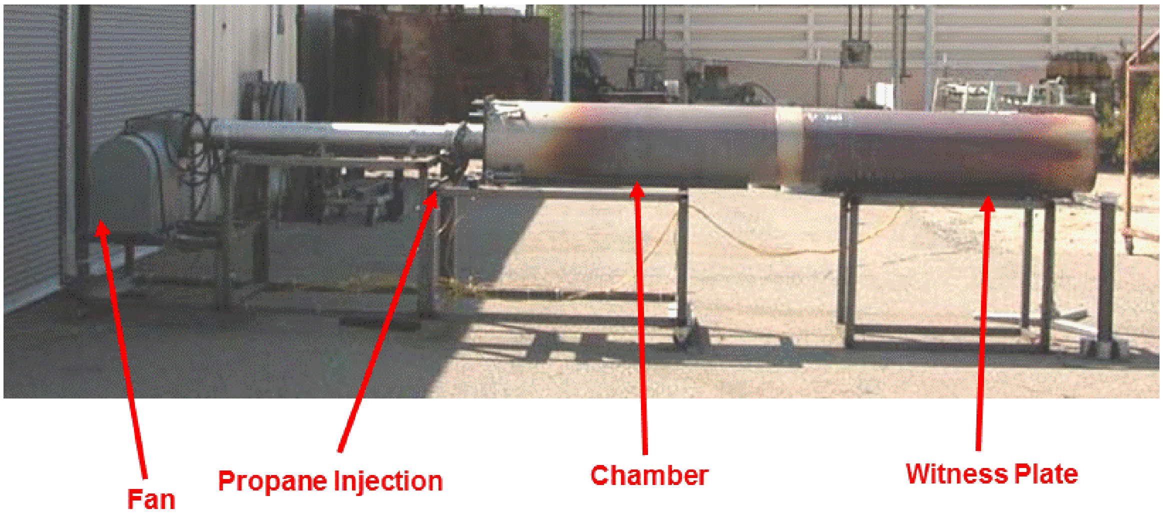


Figure 12. Controlled Heat Flux Device.

Following the completion of the CHFD design, the need to produce a full-scale propane design developed and two approaches were pursued. The first approach was to use a series of nozzles that would inject liquid propane at a measurable and controllable rate. The nozzle design for the liquid-fuel injection was innovative in its ability to properly atomize the propane at high flow rates with minimal pressure loss and prevent the flame from blowing off. The nozzle design had been used previously to generate fine scale turbulence in several combustion devices and initial tests using liquid propane support the feasibility for this concept [21, 22]. Each injector could potentially produce between 1-2 megawatts over a surface area of 1 square meter based on the flow rate of the liquid propane (3 lb/min propane per injector = 1.1 MW).

Figure 13shows the first design for a propane injector at 2 mass flow rates. The injector on the right of both pictures was developed to generate fine-scale turbulence to assist in the vaporization of the liquid fuel. It is compared to a standard type injector on the left of each picture. It can be seen that the flame is initiated sooner and appears more intense, which is a characteristic of the stepped nozzle that has been used to promote higher mixing rates in other combustors. The high flow rate is 2 MW per injector and the low flow on the right picture is 1 MW per injector. Figure 14 shows the concept of mixing a large mass flow rate of liquid propane to a flame stabilizer, the flame stabilizer in this example is a 6-inch stainless steel pipe. This demonstrates in larger scale the importance of how air entrainment can influence flame development and increase temperature by expanding the region where the combustion is taking place. The increased temperature on the flame holding device will also be a source of radiation that will add to the total heat flux the test article will receive.

Figure 13. Injector Comparison.

Figure 14. Liquid Propane Impingement on 6-Inch Pipe.

Figure 15 shows a schematic and actual test of the propane fueled test device. The partially evaporated propane would impinge on metal slats where the jet would spread and entrain additional air for combustion. These metal slats, once optimized by determining the correct size, thickness, location, and material, would stabilize the flame and provide a location for flame attachment. With a stable flame, the test article could be located where the heat flux was maximum.

Figure 15. Propane Fuel Fire Technology.

Two instrumentation structures were built to probe the flame structure of the impinging jet propane burner. The first structure consisted of an array of directional flame thermometer heat flux gauges in a single plane at the mid-point between the injectors and perpendicular to the injector flow. This was done to determine the heat flux variability across a vertical 5 ft (1.5 m) surface. The heat flux measurements were made from injectors positioned at 57 in (1.4 m) and 69 in (1.7 m) with and without an impingement fence. The results can be seen in Figure 16 through Figure 19.

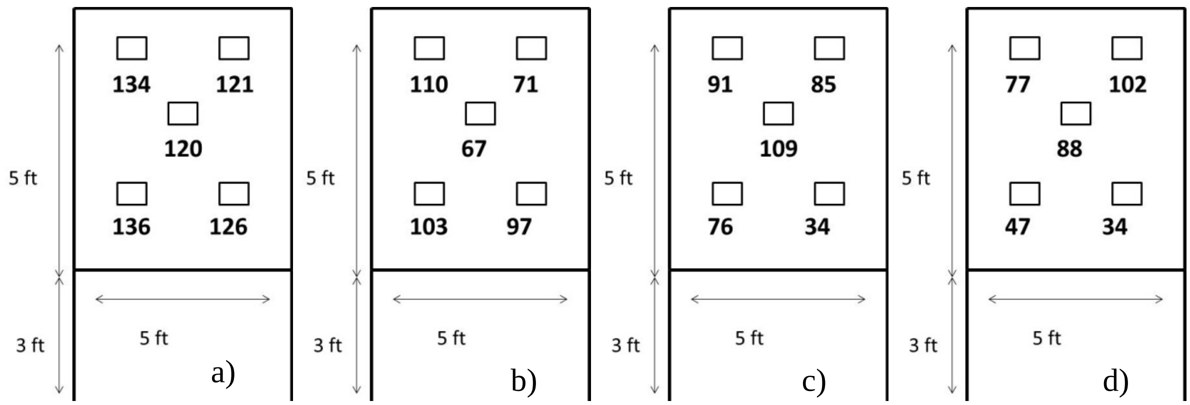


Figure 16. Heat Flux Gauge Reading (kW/m^2) from Instrumentation Structure. Nozzle Distance of 57 in (1.4 m) from Structure and 1 in (2.5 cm) Diameter Pipe Impingement Fence. (a) 2 Nozzles, West Facing, (b) 2 Nozzles, East Facing, (c) 1 Nozzle, West Facing, and (d) 1 Nozzle, East Facing.

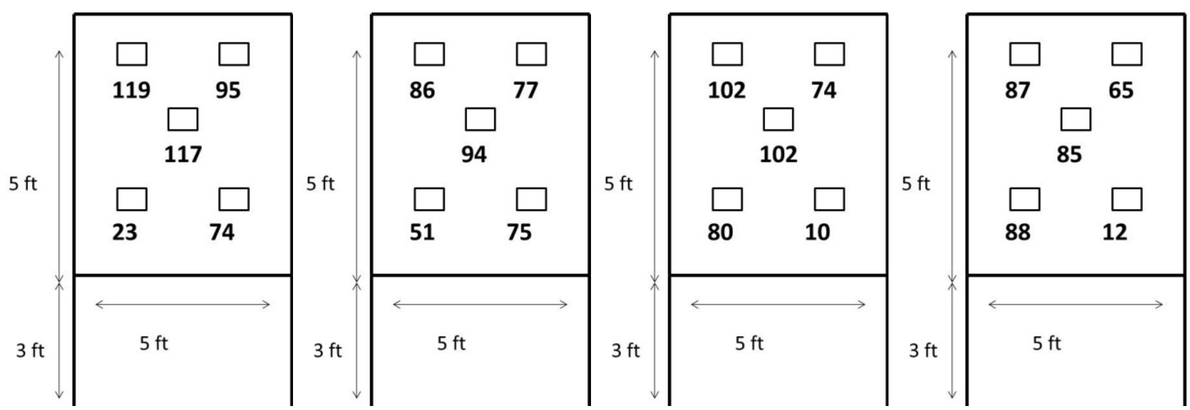


Figure 17. Heat Flux Gauge Reading (kW/m^2) from Instrumentation Structure. Nozzle Distance of 69 in (1.7 m) from Structure and 1 in (2.5 cm) Diameter Pipe Impingement Fence. (a) 2 Nozzles, West Facing, (b) 2 Nozzles, East Facing, (c) 1 Nozzle, West Facing, and (d) 1 Nozzle, East Facing.

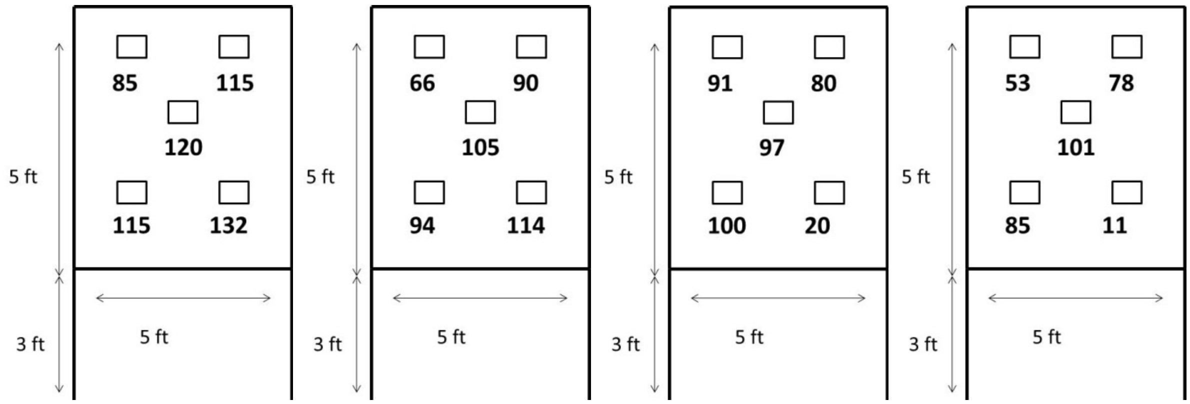


Figure 18. Heat Flux Gauge Reading (kW/m^2) from Instrumentation Structure. Nozzle Distance of 57 in (1.4 m) from Structure and No Impingement Fence. (a) 2 Nozzles, West Facing, (b) 2 Nozzles, East Facing, (c) 1 Nozzle, West Facing, and (d) 1 Nozzle, East Facing.

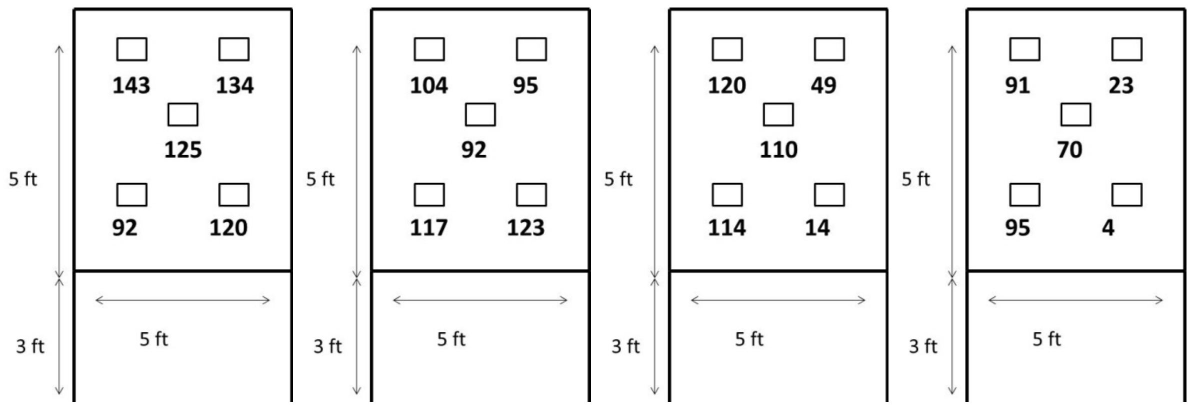


Figure 19. Heat Flux Gauge Reading (kW/m^2) from Instrumentation Structure. Nozzle Distance of 69 in (1.7 m) from Structure and No Impingement Fence. (a) 2 Nozzles, West Facing (b) 2 Nozzles, East Facing (c) 1 Nozzle, West Facing, and (d) 1 Nozzle, East Facing.

There is variability among the measured heat fluxes. Some of this came from wind that was not quantified in these tests. Measurement of the propane flow rate was not performed during these tests and it appeared that there was some variability in the propane flow rate from day to day. The propane tank was heated to maintain a high pressure in the tank to increase the flow rate.

Even with these inconsistencies in data, some conclusions were made. First, in the center plane heat fluxes above 80 kW/m^2 were achievable. The area was almost 5 ft (1.5 m) by 5 ft (1.5 m), which would encompass many ordnance items. The heat fluxes with two nozzles were of higher value than the heat fluxes with one nozzle. There was control on the location of the hottest regions by changing the distance between the nozzles. The impingement fence increased the heat fluxes to the sensors with the nozzles separated by 57 in (1.4 m) and it decreased the heat fluxes with the nozzles separated by 69 in (1.7 m).

The next group of tests sought to determine a heat flux “hearth”. This was done by constructing a wired box that contained a heat flux gauge at each face and suspending the box in the path of the impinging flames. Figure 20 shows a schematic and then an actual test of this configuration.

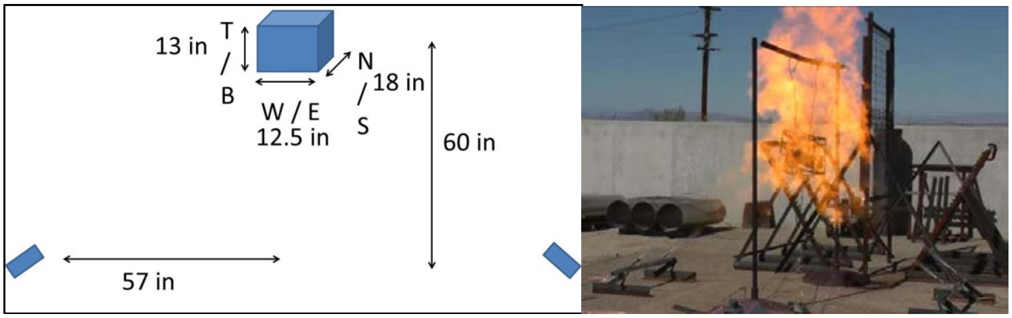


Figure 20. Schematic and Photo of Test Configuration for Heat Flux Measurement Box.

The wired box location was held constant and the nozzles were moved to measure different locations in the flame. It is recognized that the box will change the flame structure at its location because it changes the flow path and absorbs heat from the flame. Making the box wired was done to minimize this flame disturbance.

Table 2 through Table 4 gives the results from these tests. The tests consisted of 1 to 3 nozzles on each side. For these tests, the wind speed and direction were recorded and are shown in the tables. The heat fluxes are reported in kW/m^2 and report the values at the center of the faces of the wired box, both on the inside and outside of the gauge. Looking at Tests 1, 7, and 8, where the box is centered in the flame, the impinging jet burner can provide greater than 80 kW/m^2 heat fluxes in the volume needed. The fluxes increased with increasing number of nozzles. In Test 2 and 3, it was shown that the fluxes dropped rapidly as the nozzles were moved 12 in (0.3 m) to 24 in (0.6 m) away from the center of the box in a direction perpendicular to the nozzle spray. Wind did play a role as the wind was blowing the flames away from the location of the box.

In Tests 4 through 6, the nozzles were moved in a direction parallel to the nozzle spray. In these tests the heat flux would drop rapidly outside of the internal flame. In Test 6, the nozzles were moved opposite the wind direction to place the wire box it a region of high heat flux. In Tests 7 through 9, additional nozzles were added to each side. In comparison to Test 1, Test 7 had smaller heat fluxes and Test 8 had larger heat fluxes. This appears to be conflicting results where it would be hypothesized that the heat fluxes would increase as the number of nozzles increased. Inconsistent flow rates between tests could be the cause of different trend than expected.

As confirmed by the first test configuration, this impinging jet burner could supply the needed heat flux along the center plane of the impinging jets. The second test configuration showed that there was a 12 in through 18 in (0.3 m – 0.46 m) region parallel to the nozzle flow that had the proper heat flux values. Work was done to change the angle of the nozzle flow in an effort to change the impingement characteristics. The size of the propane tank and flow restriction led to inconsistent propane flow rate and limited the ability to increase the number of nozzles on each side. As it was evident that more nozzles were needed, the final design would be impeded by the propane delivery configuration. Therefore, this design was down selected in favor of a different approach.

Table 2. Wind Speed (km/hr) and Direction Noted, Heat Flux (kW/m^2) Measured with Wired Box. One Nozzle on Each Side. Test 1-Box Centered, Test 2-Nozzles Moved 12 in (0.3 m) North, Test 3-Nozzles Moved 24 in (0.61 m) North.

	Test 1		Test 2		Test 3	
Wind	1.9 from W		7.4 from S		4.8 from SW	
Side	out	in	out	In	out	In
Top	132	113	51	51	45	32
Bottom	80	107	41	51	2	15
East	99	107	4	27	8	10
West	89	102	107	64	13	10
North	118	103	95	97	100	49
South	96	138	1	31	1	18

Table 3. Wind Speed (km/hr) and Direction Noted, Heat Flux (kW/m^2) Measured with Wired Box. One Nozzle on Each Side. Test 4-Nozzles Moved 12 in (0.3 m) West, Test 5 Nozzles Moved 12 in (0.3 m) West, Test 6-Nozzles Moved 12 in (0.3 m) East.

	Test 4		Test 5		Test 6	
Wind	4.8 – 9.7 from E		4.8 – 9.7 from E		9.7 – 14 from E/NE	
Side	out	in	out	In	out	In
Top	34	41	30	21	111	110
Bottom	83	96	74	87	78	110
East	15	38	8	29	78	112
West	110	104	101	82	96	116
North	19	46	50	40	99	119
South	10	31	36	44	112	130

Table 4. Wind Speed (km/hr) and Direction Noted, Heat Flux (kW/m^2) Measured with Wired Box. Test 7-Two Nozzles on Each Side Centered, Test 2-Three Nozzles on Each Side Centered, Test 3-Three Nozzles on Each Side Moved 12 in (0.3 m) East.

	Test 7		Test 8		Test 9	
Wind	4.8 – 8 from S		0 – 3.2 from SE		4 – 9.7 from E/SE	
Side	out	in	out	In	out	in
Top	109	94	132	123	126	119
Bottom	45	62	71	104	89	103
East	66	76	109	126	123	119
West	106	86	120	113	117	110
North	113	84	112	117	113	120
South	105	122	91	123	109	135

The second approach pursued as part of the burner development was a bed burner configuration. This consisted of rows of pipe arranged in a parallel configuration with numerous small holes on the top of the pipe. The initial design was 30 in (0.76 m) by 48 in (1.2 m) with 11 pipes. Eight of the pipes injected propane, and three were not used in the testing but were added for the option of injecting more air. Propane gas was supplied to the pipes and through the nozzles. The initial design and experimental results are shown in Figure 21. The heat flux on three of the four sides of the heat flux gauge was above 80 kW/m^2. The heat flux dropped off quickly above the bed injectors and the flame was not very luminous. It was determined that the small size of the initial burner was limiting the optical thickness of the flame which was in turn limiting the maximum heat flux obtainable.

The bed injector was expanded to 8 ft (2.4 m) by 8 ft (2.4 m) with 18 pipes providing the next scale for measurement. A schematic and photo of the completed burner are shown in Figure 22. In this initial design, propane gas flowed from the propane tank and exited through a series of nozzles in the 18 pipes. An empty ammo can is shown in the photo to demonstrate where the test article would go. Two in (5.1 cm) piping was used to increase the area of the flow path to hopefully increase the fuel flow rate.

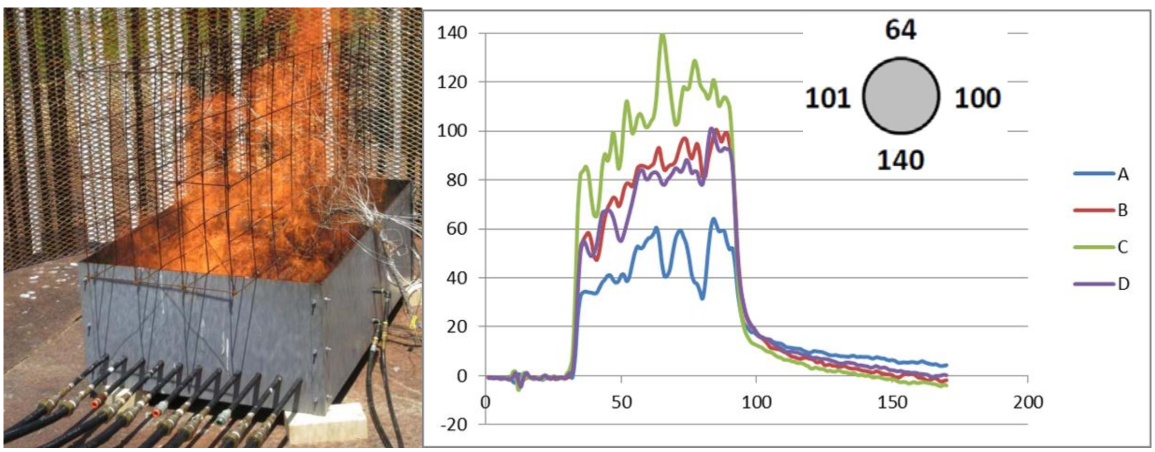


Figure 21. Photo of Initial Bed Injector Burner Design with Experimental Heat Flux Results.

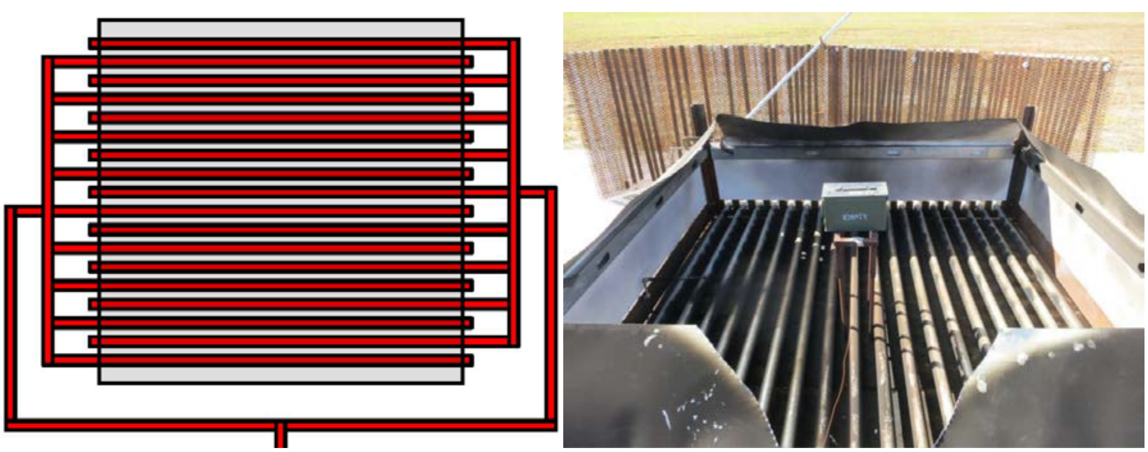


Figure 22. Larger Version of Bed Injector Schematic and Photo.

Figure 23 shows the burner in action and reports initial heat flux data that were taken. The flame was weak and the fluxes were significantly below the desired 80 kW/m^2. At this point there was serious doubt on the ability to continue with the bed injector development. It was hypothesized that insufficient fuel flow causes the weak flame. One approach to increase the flow rate was to purchase an inline liquid vaporizer with a pump to increase the flow rate of the gas. This was an expensive alternative and the procurement process would take more time than available in the final development period of the project.

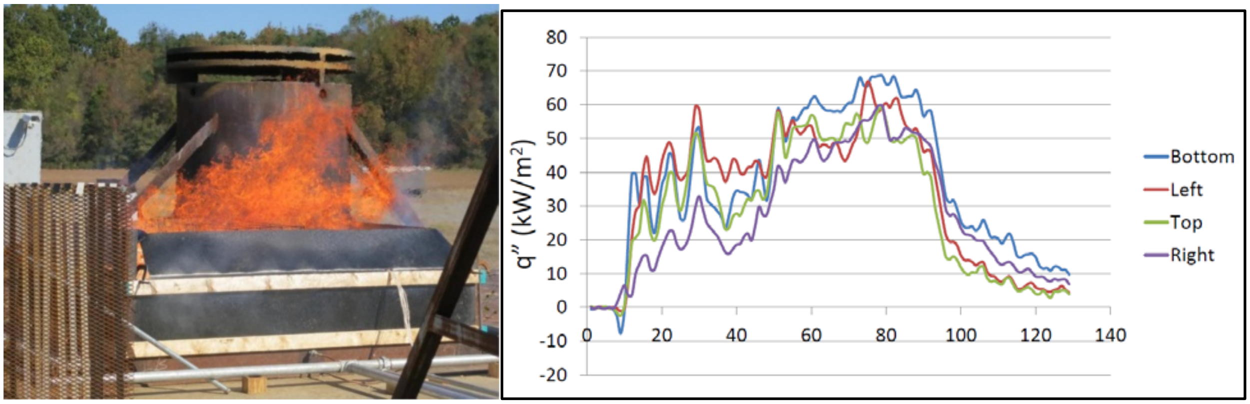


Figure 23. Photo of 8 ft (2.4 m) by 8 ft (2.4 m) Bed Burner Test and Experimental Heat Flux Results.

The next approach to increase the flow of fuel to the burner was to remove the constraint that only gas be flowed through the pipes. Liquid propane is 20 times denser than gaseous propane and therefore could substantially increase the mass flow rate. The liquid propane was flowed directly from the bottom of the tank through the 2 in (5.1 cm) pipes to the burner. The 2 in (5.1 cm) pipe was originally chosen to enable the gas flow and was not replaced with the switch to flowing liquid in order to have a larger external pipe surface area to increase the heat transfer to the liquid propane to help vaporize the fuel. It was hypothesized that the liquid propane would evaporate before it reached the injection holes in the pipe.

Comparing Figure 23and Figure 24, the flame intensity increased dramatically. The flame heights were 2 or 3 times higher and the optical thickness was qualitatively greater. The injector hole diameter was originally .0565 in (1.44 mm), but with the increase fuel flow rate the flame was blowing off the pipe. The area of the hole was doubled and the injector hole diameter was increased to 0.081 in (2.1 mm) to produce the flame shown in Figure 24. The measured heat fluxes were well over 80 kW/m^2. An instrumentation structure was built inside the bed burner to quantify the temperatures and heat fluxes inside the volume of interest. A schematic and photo of the structure are shown in Figure 25. It was a 5 ft (1.5 m) cube of rebar placed within the burner. The grid allowed for accurate positioning of temperature and heat flux instrumentation.

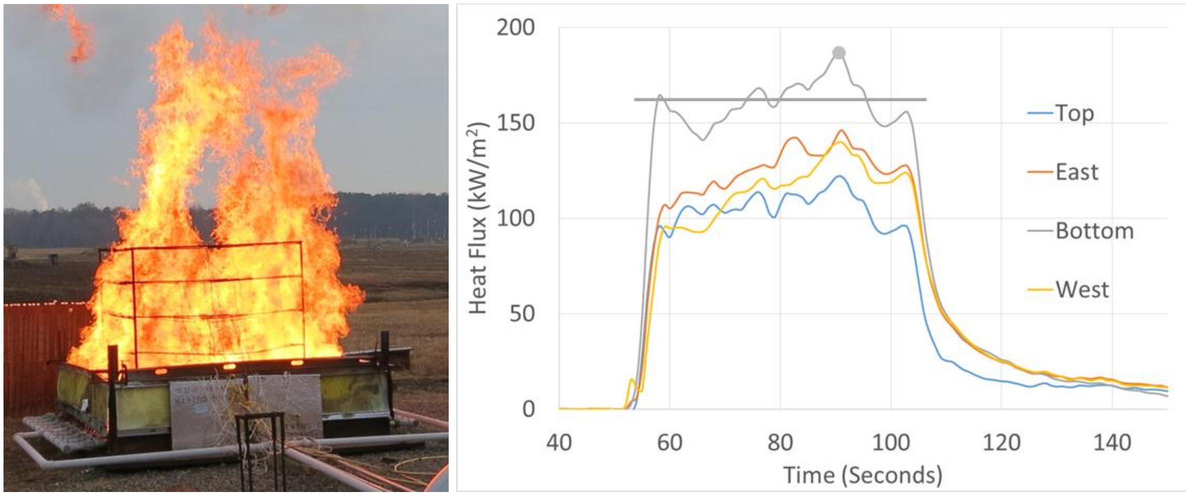


Figure 24. Propane Bed Injector with Liquid Propane Feed, Photo, and Experimental Heat Flux Results.

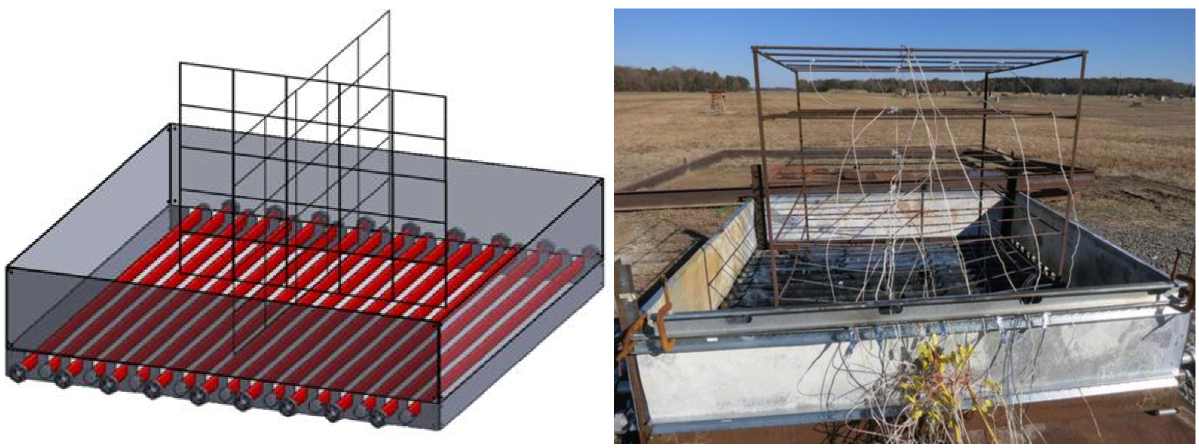


Figure 25. Schematic and Photo of Instrumentation Structure.

Figure 26 shows the experimental results from the thermocouples in each square to produce intersecting temperature fields. Thermocouples were located on 1 ft (0.3 m) centers and the temperatures shown are the average temperatures for the test duration. Both the UN 6(c) External Fire (Bonfire) specification, used for hazard classification testing, and STANAG 4240, used for insensitive munition testing, require the temperature to be above 800 °C. The majority of the fire was above this temperature requirement. The fire is symmetric about the vertical centerline axis and the center bottom temperatures are representative of the vapor dome region in liquid-fuel fires. Wind did have a significant effect on the measured temperature. Figure 27 shows the measured temperatures with a 5 km/hr wind. Depending on the size of the item, 5 km/hr would be too large of a wind to test.

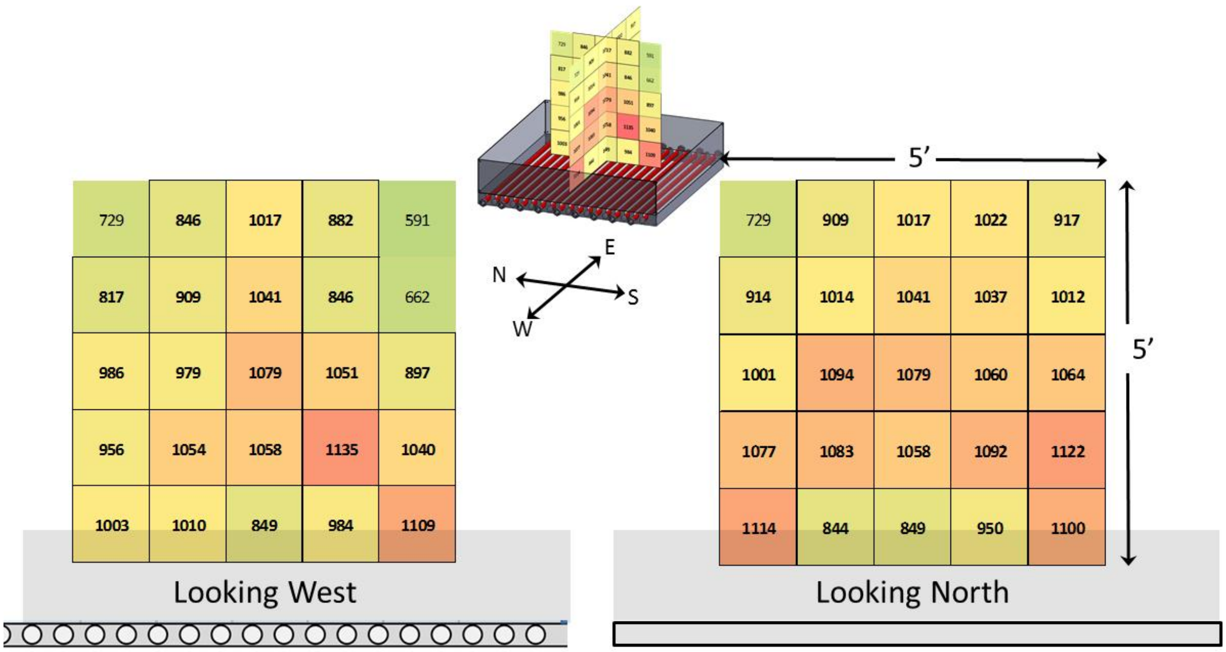


Figure 26. Temperature Measurements with Instrumentation Structure.

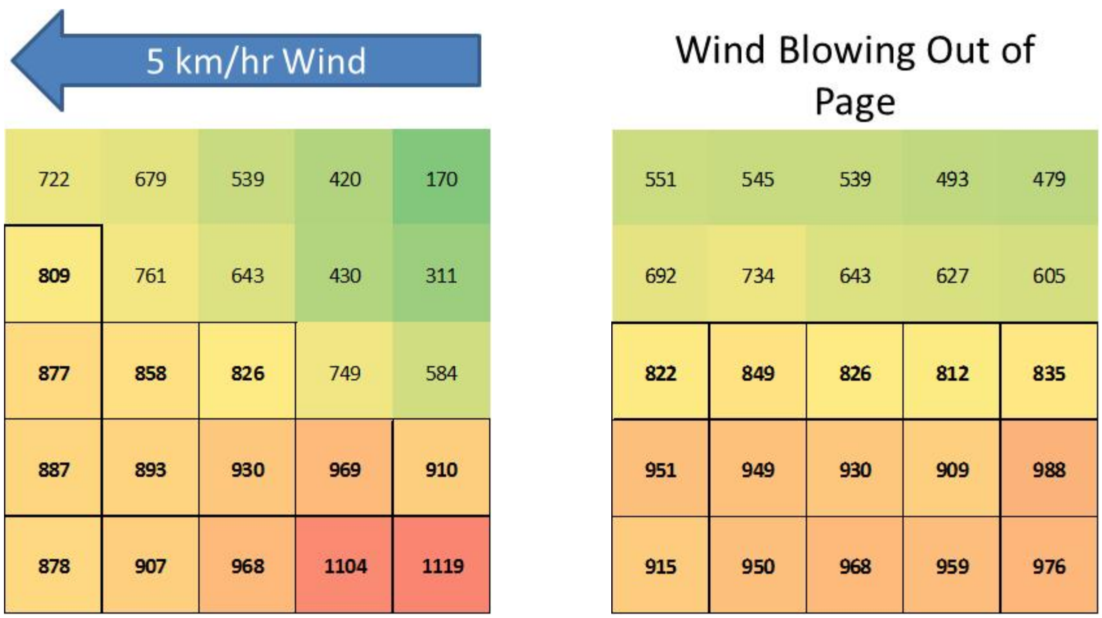


Figure 27. Temperature Results with 5 km/hr Wind.

Directional slug calorimeters were used to measure the heat flux in the flame. These heat flux gauges can measure heat fluxes to the top, bottom, left, and right of the gauge. The direction slug calorimeters were used to measure the heat flux at nine locations shown as red stars in Figure 28. Both the maximum value and the average are displayed for each direction in Figure 29. The averages of these four are displayed in yellow for each test. The data shown are maximum or average values from a 1-minute burn. When averaged over four directions, all locations exceeded 80 kW/m^2 for both a maximum and average heat flux.

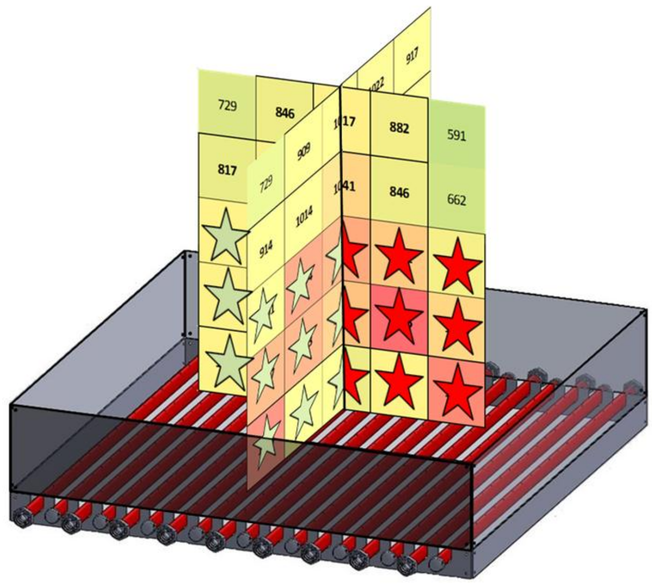


Figure 28. Heat Flux Gauge Placement on Instrumentation Structure.

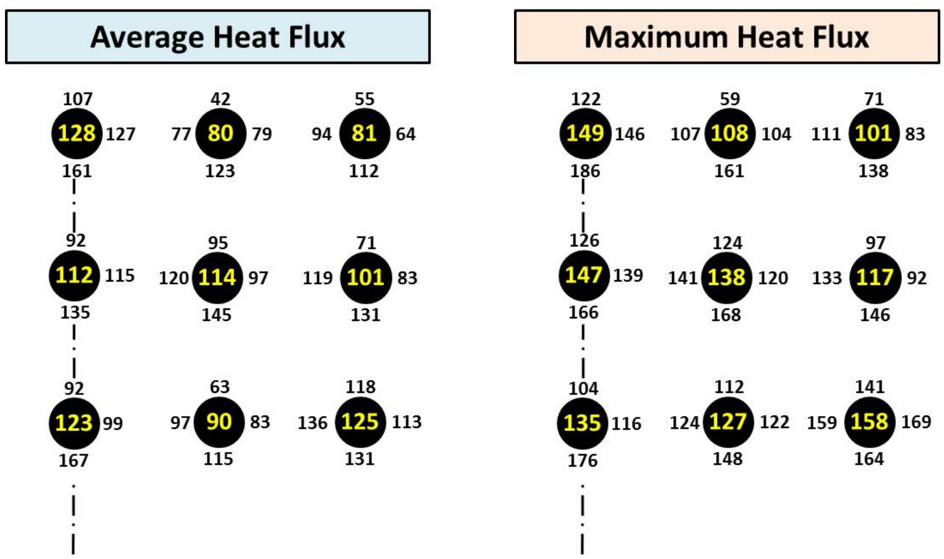


Figure 29. Heat Flux Measurement (kW/m^2) for Bed Burner.

The bed burner fulfilled the requirements of the UN 6(c) External Fire (Bonfire) specification and was chosen as the final design.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Liquid propane is readily accessible and inexpensive compared to other fuels. It is cleaner burning than jet fuel. It is a gas at atmospheric pressure and temperature and will not pollute the soil or groundwater. The liquid propane burner can be turned off after the ordnance item reacts saving thousands of dollars per test. The test setup is inexpensive and easy to manufacture making rebuilding of the burner easy after a violent reaction. The burner setup provides an even flame and has the appearance of the liquid-fuel fire test. The design is scalable and can test small or large items. Currently, the jet fuel must be pumped into the pool container with the test item set up. This process takes time and there is the possibility that the wind will suddenly increase and prevent further testing. If this were to happen then an energetic item would be suspended above a pool of jet fuel for an unknown amount of time or a test would be required to be performed during non-ideal wind conditions. With liquid propane, the fuel is immediately ready for use and no pumping before the test is required. This and the fact that the fuel can be shut off after the item reacts reduces the total test time and improves the test turnaround time. Also if the winds were to increase to prevent the test, there is no fuel in the vicinity of the test item and the test will not be forced to occur during non-ideal weather conditions. Workers setting up and taking down the test dislike working around jet fuel as it has a strong smell and can lead to headaches. They prefer the propane burner where the fuel is only fed to the test fixture when the workers are gone and leaves behind no strong smell.

A paper study on the feasibility of natural gas to the liquid propane was also conducted. The main component of natural gas is methane with a chemical structure of CH_4. Commercial liquid propane is mainly propane with a chemical structure of C_3H_8. Various properties of propane and natural gas are given in Table 5, Figure 30, and Figure 31 [23, 24, 25]. Both propane and natural gas have similar adiabatic flame temperatures and therefore will have similar radiative heat transfer. The ignition temperature of natural gas is about ~10% higher than for propane. This should not make any difference because any suitable ignition source should be able to provide either temperature. Natural gas has a 33% larger flammability region. This should increase the combustion efficiency of the injected natural gas as it will be able to burn in a wider concentration region. Since natural gas has a higher stoichiometric air/fuel weight ratio, less fuel is needed to burn at stoichiometric conditions. Couple this with the 7.5% more energy content per mass in natural gas and less natural gas would be needed per test. Both natural gas and propane have similar flame speeds. This means that they could have similar orifice exit gas velocities before the flame would blow off and combustion could not be sustained. With the same flame temperature and similar heat content, both fuels will be able to supply the necessary heat fluxes and temperatures.

The largest difference in physical properties that would affect the alternative burner is gas mass density. Propane has a molecular weight that is 2.75 times that of methane. Therefore, as gases at the same temperature and pressure, the mass density of propane would be 2.75 times that of methane. If the same pipe pressure is maintained and the same velocity out of the orifices is maintained then the area of the orifices would need to be increased by 2.75 times. If the orifice size remained constant, the velocity would need to be increase 2.75 times. Since velocity is proportional to the square root of the pressure difference, the pressure difference would need to be increased by over 7.5 times. At the higher velocity, care would need to be taken that the flame is not blown off the orifices. Another factor that will affect the mass density is the temperature of the gases. The current design of the burner flows liquid propane in 2 inch piping to evaporate the propane and supply gas to the exiting orifices. The temperature of the exiting propane gas will be close to the boiling temperature at 101 kPa, which is 231 K. If the natural gas is supplied at room temperature or 298 K, the mass density difference between propane and natural gas could reach over 3.5 times. It should also be noted that propane is heavier than air and natural gas is lighter than air. With the current orientation of the orifices, this should not make a difference, but it could make a difference if the orifices were placed on the bottom of the piping. The best option would be to increase the orifice size. Therefore, the burner could not be switched from propane to natural gas without modification.

One final consideration is the manner of delivery of the fuel. Propane is easier to store and to transport as a liquid. It can be delivered to remote and changing locations. Propane would be delivered as a liquid and the coupling to the burner would be unique. Natural gas can be stored and transported as compressed natural gas (CNG) or liquid natural gas (LNG). CNG is relatively common. It is still gas and will not have the density of liquid propane. The boiling temperature of natural gas at 101 kPa is 112 K, which makes LNG expensive for refrigeration requirements even at higher pressure. Many locations have permanent natural gas delivery systems. This would be the most economical way to deliver the natural gas. Whether CNG, LNG, or piped natural gas is used, a different coupling system would need to be implemented. If available and depending on markets, piped natural gas could be significantly less expensive than liquid propane and allow for unlimited burn durations.

The conclusions of this study were: 1) With the same flame temperature and similar heat content, both fuels will be able to supply the necessary heat fluxes and temperatures. 2) Mass density differences between the gases would not allow use of a burner with the different fuels without modification to the orifices and pressure regulation system. 3) With logistic and storage advantages and disadvantages to both, location will determine which fuel is best for price and convenience.

Table 5. Natural Gas and Liquid Propane Properties [23]

Property	Natural Gas	Liquid Propane
Chemical Structure	CH_4 (83-99%), C_2H_6 (1-13%)	C_3H_8 (majority) and C_4H_{10} (minority)
Ignition Point	813 K	743 K
Molecular Weight	16 gm/mol	44 gm/mol
Flammability Limits	5.3 vol%	2.2 vol%
	15 vol%	9.5 vol%
Latent heat of vaporization	509 kJ/kg	449 kJ/kg
Stoichiometric air/fuel, weight	17.2	15.7
Lower Heating Value BTU/lb	49544 kJ/kg	46055 kJ/kg
Adiabatic Flame Temperature	2226 K	2267 K
Laminar Flame Speed	See Figure 30	See Figure 31

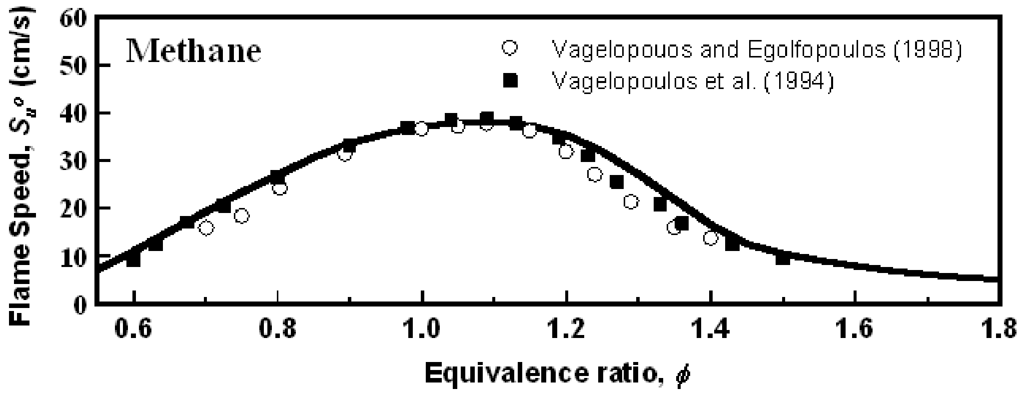


Figure 30. Measured Flame Speed of Methane and Air at 101 kPa and 300 K [24, 25]

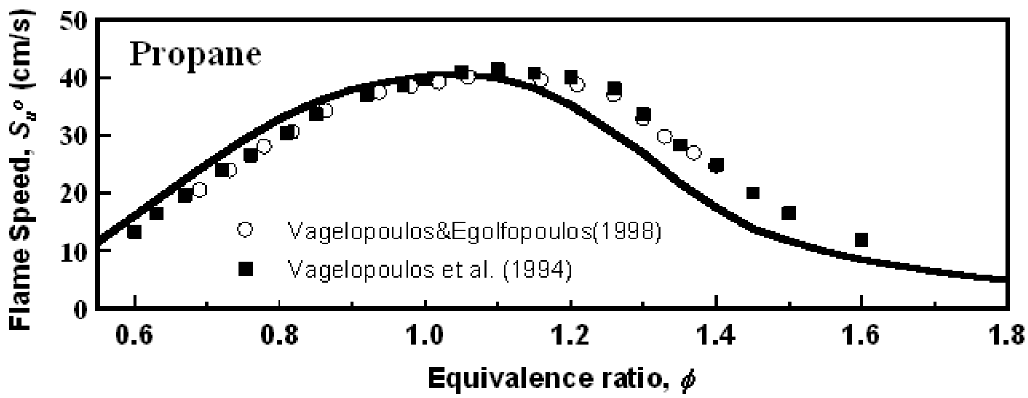


Figure 31. Measured Flame Speed of Propane and Air at 101 kPa and 300 K [24, 25]

3.0 PERFORMANCE OBJECTIVES

The performance objectives are shown in Table 6. The first objective was to reduce the fuel usage by greater than 50%. Less fuel usage will lead to lower costs and lower pollution. The fuel usage for the pool fires was determined by the amount of fuel added to the pool before ignition. The fuel usage for the propane fires was determined by recording the propane fuel in the tank before and after the tests. For the FCO propane tests with ordnance items compared to FCO tests with pool fires with the same ordnance items, the average reduction in fuel was 83%. The smallest reduction in fuel usage was 60% and the largest reduction in fuel usage was 93%.

The second performance objective was that the propane burner met all of the requirements of STANAG 4240. The test would not be accepted for use both nationally and internationally if the test did not meet the STANAG 4240 requirements. The average temperature must be greater than 800°C and reach 550°C within 30 seconds of ignition. The total absorbed heat flux, as measured by a device of specified dimensions, must be greater than 80 kW/m^2 when averaged over a minimum 30-second period after a minimum temperature of 800°C is achieved. This was determined by thermocouple and heat flux gauge measurements. All of the requirements of STANAG 4240 were met in the 8 ft (2.4 m) by 8 ft (2.4 m) burner, the 12 ft (3.7 m) by 12 ft (3.7 m) burner, and the 10 ft (3.0 m) by 20 ft (6.1 m) burner. This also demonstrates that this technology is scalable.

A suite of emissions' measurement hardware was flown above a propane 12 ft (3.7 m) square burner fire and a JP-5 pool fire to determine the difference in emissions between the two FCO test fires. This objective is important as it will facilitate testing as the environmental emissions regulations increase in stringency. The success criterion was that the emissions be reduced by greater than 50%. This criterion was met. The particulate matter emissions were reduced by 99.96%. The CO_2 emissions were reduced by 94%. The CO emissions were reduced by 99.3%. The polycyclic aromatic hydrocarbon (PAH) emissions were reduced by 99.6%. The volatile organic compounds were reduced by 99.1%. The elemental carbon (EC) emissions were reduced by 99.99%. The organic carbon (OC) emissions were reduced by 99.6%. The total carbon (TC) emissions were reduced by 99.97%.

The final quantitative performance objective was that an ordnance item tested in a propane burner FCO would receive the same assessment for violence of reaction as the same ordnance item in a pool fire FCO. This was an important objective as this was necessary to be able to compare future propane FCO data with past pool fire FCO data. The insensitive munitions community would not accept the propane FCO test if there were substantial differences in the reaction violence. All four ordnance items tested received the same engineering assessment reaction violence rating in both the 12 ft (3.7 m) square propane burner and pool fire FCO tests.

As far as the qualitative performance objectives, it was desirable that the propane burner be modular is design. Different test sites will test different sized ordnance items and having flexibility in the size of the burner will make it applicable to any site adopting the technology. Three burners were built and tested. They were the 8 ft (2.4 m) by 8 ft (2.4 m) burner, the 12 ft (3.7 m) by 12 ft (3.7 m) burner, and the 10 ft (3.0 m) by 20 ft (6.1 m) burner. All three burners performed as designed and met the STANAG 4240 requirements.

The success criterion for the reduced cost of the burner was greater than 50%. The initial calculated reduction in cost per test was 30%. The annual maintenance cost was reduced by 80%. Having a reduction in cost will make this technology more appealing to customers requesting the FCO testing. Related to cost is the convinence of replacement. Three pipes were damaged in a test in which the test item had a violent reaction and it took an hour to replace the pipes.

The final performance objective was that the flame above the propane burner would qualitatively appear similar to the flame produced during the liquid pool fire test. This was important as there is a long community history with the pool fires and there is an initial resistance to change. The fire above all the propane burners is luminous, turbulent, buoyant, and it fills the burner. All of these characteristics are qualitative characteristics of a pool fire. The temperature and heat flux measurements were important for community acceptance of the burner; however, the qualitative appearance of the flame greatly assisted the acceptance of the burner as well.

Table 6. Performance Objectives.

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Reduce fuel usage	Measure of fuel usage	Reduction in fuel usage by > 50%
Meet STANAG 4240 requirements	• Thermocouples • Heat flux gauges	Meet all specifications
Decrease air pollution	Emissions measurements	>50% reduction vs. baseline characterization
Same score for ordnance test items	Pressure gauges and recording of number of fragments	Same score
Qualitative Performance Objectives		
Modular design	Build multiple sizes	Applicable to all sizes tested
Inexpensive	Track total cost including labor	>50% reduction in cost compared to pool fire test
Easily replaced	Record total set up time	Less time to set up than current pool fire test
Similar structure to pool fire test	Compare visual flames between tests	Community accepts the test structure

4.0 SITE/PLATFORM DESCRIPTION.

4.1 TEST PLATFORMS/FACILITIES

The Explosive Experimental Area (EEA) facility at the Naval Surface Warfare Center Dahlgren Division (NSWCDD) was selected as the initial site for the propane liquid burners for this project. Dahlgren is located fairly close to Washington D.C., making it an easy location for the team to meet versus Eglin Air Force Base, Florida; China Lake, California; or Redstone Arsenal, Alabama. The EEA test facility is located in Virginia where burn permits are not required for testing. Specifically, the Virginia Department of Environmental quality (VDEQ) does not regulate open field fugitive emissions sources that cannot be practically controlled through an air permitting process. These types of RDT&E activities cannot be controlled during the test and therefore the operations do not require an air permit. In other states, such as California, sites can be in a non-attainment area for air quality. While open burns are still allowed, the emissions will be more tightly regulated and even tracked as part of a facility-wide emissions inventory. By selecting Dahlgren for the initial site, the added burden imposed by these tighter regulations was avoided which allowed the technology to be developed more easily.

As part of routine operations at EEA, explosive materials are thermally treated in a large propane fired enclosure. Therefore, the site was already explosively sited for both propane and energetic operations simultaneously and additional explosive siting was not required. Also, as a result of already using propane, no significant infrastructure improvements were required and the workforce was already comfortable with the use and storage of large quantities of propane. Dahlgren also has available magazine storage so that items can be staged prior to testing. Current energetic limits at the test site are 454 kg with a proposal awaiting review at DDESB to increase the energetic limit to 1361 kg. The 454 kg limit is sufficient for the majority of items that would be tested in a fast cook-off facility at Dahlgren. In most cases, it is the anticipated fragment distance of an item that limits testing at EEA, not the 454 kg explosive limit. Finally, the range was very eager to adopt/participate in the project.

EEA is currently used for kerosene based liquid-fuel fire tests. Therefore the facility has the personnel to analyze the violence of reaction of ordnance items in the same manner as will be used in the propane burner tests. Using a facility that already performs liquid fuel fire tests allows the testing group’s concerns to be addressed early in the development to allow for an easier transition in the future to other test facilities. The chair person for the munition review and evaluation board (MREB) for the Navy is also currently located at Dahlgren. The MREB provides the ordnance with the official IM score that will be presented to the Joint Services Insensitive Munitions Technical Panel (JSIMTP). The chairperson will be consulted along with members from China Lake to ease the transition of propane.

The CT-4 Test Site at the Naval Air Warfare Center Weapons Division (NAWCWD) was selected as the test site for the large scale liquid propane burner. This site is used to perform many types of Insensitive Munitions testing. The CT-4 Test Site was selected to implement the liquid propane burner because the site already has the equipment and instrumentation to support FCO testing and can be performed in conjunction the current liquid pool fire FCO testing.

4.2 PRESENT OPERATIONS

The liquid-fuel fire is setup slightly different depending on location. At China Lake, for example, the fuel-fire test pit is formed by a flat barren area surrounded by an earthen berm. This berm is approximately circular and is sized to form a pool that will create a fire that is large enough to engulf the test item and deep enough to contain sufficient fuel for the required fire duration. The pool formed by this berm is then lined with plastic to contain the fuel and prevent ground and water contamination as shown in Figure 32. There is also a bladder buried below the pool area which acts as a secondary containment to prevent ground contamination. The ordnance item is suspending approximately 3.3 ft (1 m) above the surface of the pool using the A-frame structure shown in Figure 32. The fuel is brought in from China Lake's flight line area early in the morning on the day of the test. The test is then initiated as early as possible, near dawn, when the wind velocity is the lowest. The fire usually burns for 30 to 45 minutes. Cleanup of the site then occurs once the area is cooled and the firing director has deemed the area safe.

The fast cook-off test pit at Dahlgren consists of a square metal pan within a secondary metal pan. Both of these pans are partially filled with water prior to testing. The water keeps the metal pans cool and prevents warping while also providing a level surface onto which the jet fuel is floated for testing. Fireproof brick is placed on the edge of the interior metal pan to block heat and prevent this extended vertical surface from overheating and warping. Dahlgren's double pan fast cook-off pit is also shown in Figure 32. The fuel is delivered from the Patuxent River Naval Air Station in Maryland, early in the morning and testing is also completed at dawn. The testing and cleanup is done very similar to China Lake.

Figure 32. The liquid pool fire pit at China Lake (left) and Dahlgren (right)

The propane fueled fast cook-off burner is designed to replicate the heating found in the liquid pool fires described above while eliminating the pollution and logistic issues with the current methodology. The propane burner utilizes a large propane tank in which propane is stored as a pressurized liquid. As long as there is liquid propane within the tank, the tank will remain pressurized at the saturation pressure of propane that corresponds to the current tank temperature. For ambient temperatures of -6.7 ^{o}C to 49 ^{o}C (the extremes at which testing is anticipated) the tank pressure will be from 410 kPa to 1700 kPa. Even at the lowest temperatures and pressures, the pressure is sufficient to provide propane flow to the burner site without the need for pumps. The tank is stored some distance from the test site and is located behind a shelter to prevent it from being hit by fragments during the test.

The 12 ft (3.7 m) square propane burner consists of a square enclosure made from steel plates. This enclosure is positioned on top of a patio made from fire bricks which rest on a steel plate. Within the enclosure a series of burner tubes, each containing a large number of fuel ports, are used to distribute the fuel evenly throughout the enclosure area. Each of these tubes is connected to a manifold which supplies the fuel from a single fuel line. The tubes are inexpensive and can easily be changed out if they are damaged during testing. Ignition is accomplished by using a 2 in (5.1 cm) torch that provides a pilot light. The pilot torch is ignited using a remotely actuated valve and high voltage spark ignitor.

Liquid propane is drawn from the bottom of the propane tank to fuel the propane burner. All the equipment from the tank to the burner is either buried or protected behind a shelter. The flow of liquid propane to the fast cook-off burner is controlled using remotely actuated ball valves and a flow control valve. The flow control valve maintains a constant flow rate regardless of tank pressure so that the same quantity of fuel is delivered whether testing in the summer or winter (as tank pressure changes). Each actuated ball valve is fail-safe and is designed to close automatically if connectivity or power is lost. Therefore, if a fragment or any other debris from a reaction severs any of the control lines, the burner will automatically shut down. Once the liquid propane enters the burner, the heat from the flames within the enclosure vaporizes the propane within the burner tubes where it exists as propane gas. In this way, the propane burner acts as its own vaporizer and no auxiliary vaporizer is required.

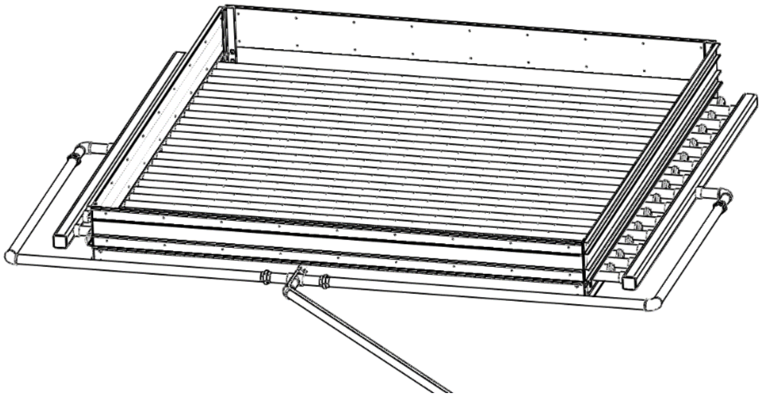



Figure 33. Propane Fueled Fast Cook-off Burner.

The large scale 10 ft (3.0 m) by 20 ft (6.1 m) liquid propane burner at China Lake rests directly on the ground. A small rectangular enclosure made from sheet steel surrounds the burner inside the earthen berm. Within the enclosure a series of burner tubes, each containing a large number of fuel ports, are used to distribute the fuel evenly throughout the enclosure area. Each of these tubes is alternated, connecting to opposing manifolds. A single fuel line supplies both manifolds.

The tubes are inexpensive and can be easily replaced if they are damaged during testing. The burner is ignited directly by a hot surface ignitor.

Figure 34. China Lake Liquid Propane Burner Set-up

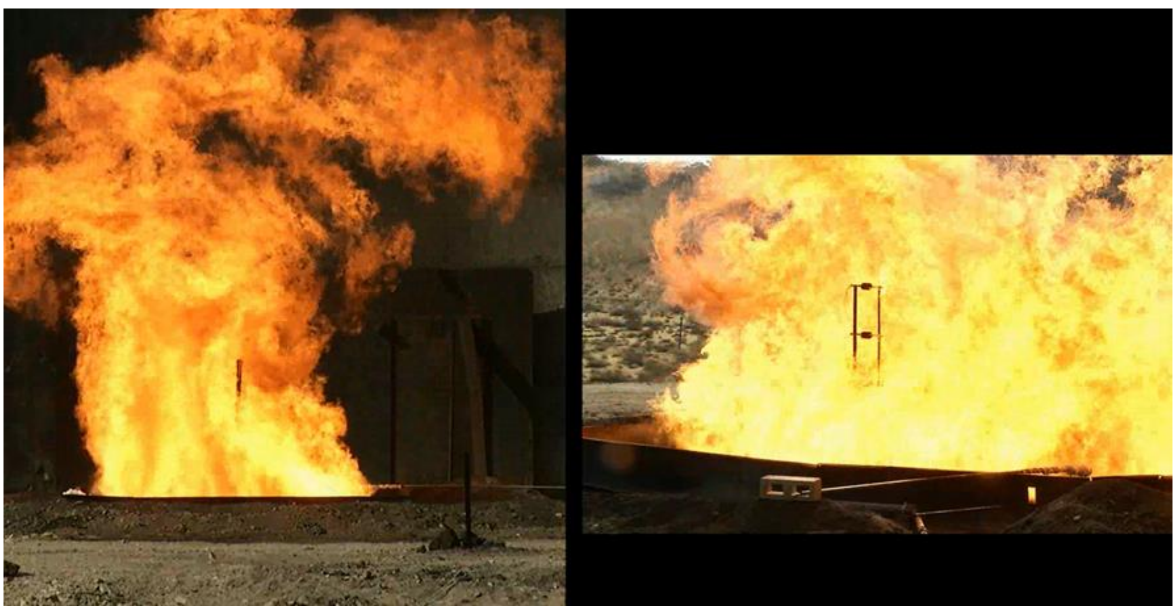


Figure 35. China Lake Liquid Propane Burner

4.3 SITE-RELATED PERMITS AND REGULATIONS

As a result of locating the propane 12 ft (3.7 m) square burner in Virginia, burn permits are not required for testing. In addition, the site already has explosive siting for both energetics and propane. An approved explosives' standard operating procedure (SOP) is needed to test as well. The current SOP allows testing an item with up to the fragment energy potential of a 105 mm howitzer round. An additional 10 ft (3.0 m) by 20 ft (6.1 m) propane burner was built in California at NAWCWD. It is located in the current area where kerosene-fuel fires are performed. The location is currently sited for use with both energetics and propane. There is already a San Bernardino County emissions permit that will allow this burner to function.

Current energetic limits at the CT-4 Test Site are 5896 kg during any calendar day. This 5896 kg limit is sufficient for the majority of large scale items that would be tested for fast cook-off at China Lake; therefore additional explosive siting is not required. China Lake also has available magazine storage so that items can be staged prior to testing. A burn permit is required for testing at this facility. Propane was previously used at this facility and allowed for up to 378 liters of propane used per day. A temporary experimental permit was obtained that allows for up to 13,250 liters of propane to be burned during any calendar day. This permit allows for no more than 757,000 liters of propane to be burned from March 1st 2016 to February 28th, 2018. After initial testing and characterization of the liquid propane burner, a permanent change will have to be made to the current burn permit at this site. The liquid propane burner was added to the current kerosene based liquid-fuel fire testing. Therefore the facility has the personnel and equipment to analyze the reaction of ordnance items in the similar manner required for the liquid propane burner testing. Infrastructure was added to the test site to support the controls and monitoring of the liquid propane burner.

5.0 TEST DESIGN

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 are analyzed.

One of the thermal requirements listed in STANAG 4240 is that the flame temperature must be at least 800°C surrounding the test item. It is not only important to see if the burner is able to reach this temperature but to also determine the size of the region that meets this temperature. Therefore, 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 12 ft (3.7 m) square burner on two orthogonal planes as shown in Figure 36. 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 121.9cm) from the center 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 test.

A heat flux requirement was also specified by the testing standards. Directional slug calorimeters (DSCs) were developed and used to collect total absorbed heat flux measurements within the burner volume. Slug calorimeters measure heat flux by measuring the temperature history of a known thermal mass then calculating the 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.

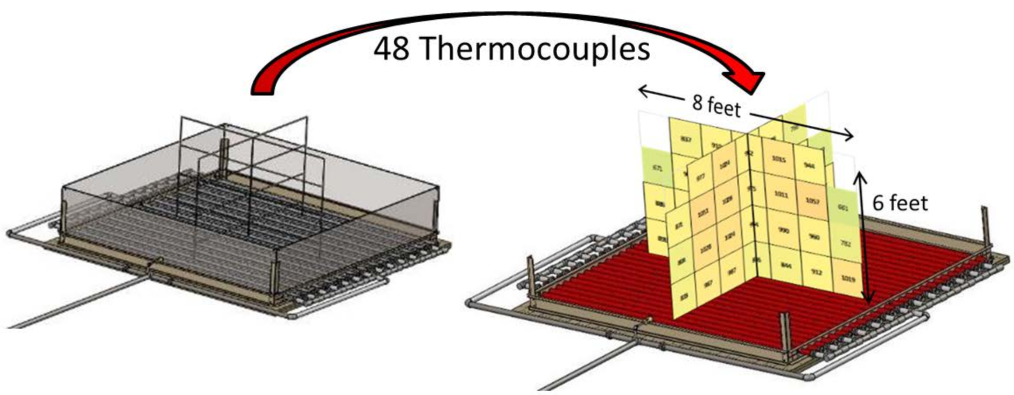
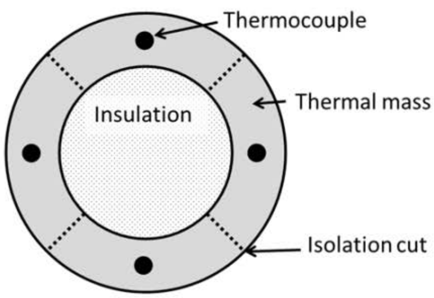


Figure 36: Thermocouple gird at left produces two orthogonal planes of temperature measurements as shown at right.

The DSC consists of a thick walled tube made from 304 stainless steel. The DSC is 3 inches (76.2mm) long, has an outside diameter of 2.70 inches (68.6mm), and a wall thickness of 0.425 inches (10.8mm). Four slots are cut every 90 degrees around the cylinder which thermally isolates the four quadrants of the cylinder as shown in Figure 37. Within each quadrant, a hole is drilled in the center that is 1.5 inches (38.1mm) 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. As part of the fabrication process, the DSC body is painted black using VHT® Flame Proof flat black paint. This paint's absorptivity has been well characterized and is known to have a total hemispherical absorptivity of 0.87.



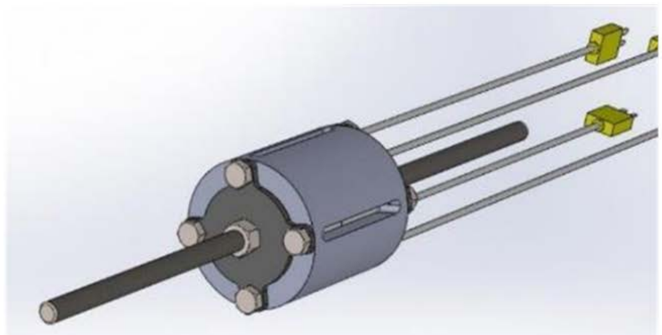


Figure 37: Directional slug calorimeters are used to measure heat flux within the fire. The calorimeter measures heat flux on top, bottom, left, and right of device.

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, equal to the absorptivity) times the Stefan-Boltzmann constant (σ) times the absolute temperature to the fourth power. Combining these gives the following equation.

$$q''_{in} \cdot A_s = A_s \varepsilon \sigma T^4 + mC(T)\frac{dT}{dt} \quad or \quad q''_{in} = \varepsilon \sigma T^4 + \frac{mC(T)}{A_s} \cdot \frac{dT}{dt}$$

For the DSC, the temperature (T) is measured and dT/dt can be calculated easily from the temperature history using a central difference scheme. The remaining properties for the DSC are given in Table 7. 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 7. Properties of the DSC.

Property	Value
A_s	36.19cm^2
ε	0.87 (measured using Surface Optic's ET-100 reflectometer)
σ	5.67e-8 (W/m^{2}K^4)
m	0.2576kg
C(T) (T in Kelvins)	131.08ln(T)-285.6 (J/kg K) curve fit to table in reference 28

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.

The emission measurement tests were conducted at the Explosives Experimental Area (EEA) at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) in Dahlgren, Virginia, USA. Six total tests were conducted, three using the 12 ft (3.7 m) square propane-fueled FCO burner and three using a liquid-pool fire. In each test, the EPA's instrumentation suite was positioned in the plume of the fire being tested.

5.1 Environmental Emissions Testing

The propane tests were performed with the 12 ft (3.7 m) square burner developed for this project. The liquid-pool fire tested was created in a burn pan that was the same size as the propane burner. A square pan was fabricated from 0.5 in (12.7 mm) thick steel plate that was 12 ft (3.66 m) square and 1 ft (305 mm) deep. Approximately 2 in (50 mm) of water was then pumped into the pan to provide a level surface for the fuel to float on and to keep the pan cool during testing. For each liquid-pool fire test, 1890 liters of JP5 jet fuel were pumped into the pan. To facilitate ignition, 19 liters of gasoline were added in each of two corners of the burn pan, for a total of 38 liters. This gasoline was ignited by two thermite grenades, which were remotely initiated using squibs. Figure 38 shows the burn pan containing water prior to transferring the fuel. In the lower left-hand corner of the burn pan, the thermite grenade and lead wires can be seen.

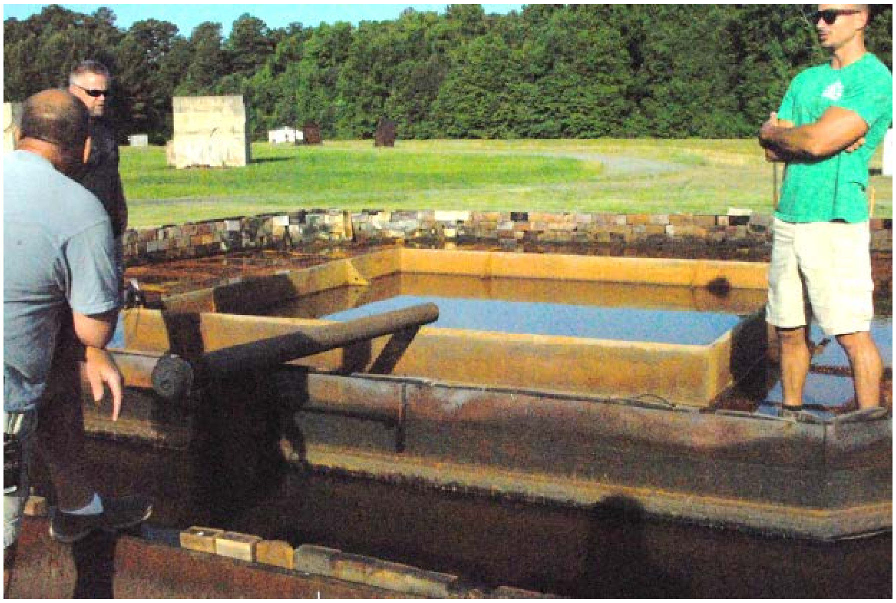


Figure 38. Photograph of the 12 ft (3.66 m) square pan containing water immediately prior to filling with fuel

The EPA instrumentation suite is shown in Figure 39 and is described in detail in the following references [26, 27]. This 22 kg system is a battery-powered, remotely controlled pollution sampler that was developed in EPA laboratories. The instrument measures CO_2 using a LICOR-820 (LIcor Biosciences, Lincoln, NE, USA) and temperature in real time, and then transmits the data back to the ground crew. This information is crucial for proper positioning of the instrument within the plume, especially in the case of the propane fire where the plume is nearly transparent. CO is measured continuously using a e2V EC4-500-CO electrochemical cell (SGX Sensortech, Buckinhamshire, U.K.).

Figure 39. Instrumentation suite that is positioned within the plume to sample emissions

In addition to CO_2 and carbon monoxide (CO), the instrumentation package also sampled atmospheric particulate matter (PM). These are the microscopic pieces of matter suspended in the air. Of particular interest are the very small particles smaller than 2.5 microns ($PM_{2.5}$), which can cause serious health problems. $PM_{2.5}$ samples were collected by SKC impactors using a Leland Legacy sample plump (SKC Inc., Eight Four, PA, USA) during each test and analyzed and weighed afterwards in a laboratory. PM emission factors are calculated from the mass of particles in ratio with the carbon mass of simultaneously collected CO_2 and CO, all scaled by the known amount of carbon in the fuel.

The instrumentation was also used to sample volatile organic compounds (VOCs). Specifically, sampling was done to detect the concentration of several particularly dangerous VOCs that exist on the EPA's list of hazardous air pollutants. VOC sampling is accomplished using vacuum canisters that are equipped with a solenoid valve. The onboard programming automatically opens the valve, when CO_2 levels exceed a user-set value, and closes the valve anytime CO_2 levels fall below the threshold value. This ensures that samples are only collected while the instruments are within the plume. VOC emission factors are calculated from the mass of the volatile compound in ratio with the mass of carbon from the simultaneously collected CO and CO_2, all scaled to the amount of carbon combusted in the fuel.

To accurately position the instrumentation within the plume for testing, it was suspended below an aerostat by an 800 ft (240 m) long cable. The aerostat used was a King Fisher model K18N-HC that was 18 ft (5.5 m) in diameter and contained 2,600 ft^3 (74 m^3) of helium, giving a sea-level lift capacity of 45 kg. The aerostat is shown in Figure 40. A trailer-mounted winch was used to control the altitude of the aerostat and the attached instrumentation. From the package, three tethers were used along with three line handlers to control the position of the instrumentation, as shown in Figure 40. By monitoring the CO_2 concentration and the air temperature, and then communicating with the line handlers and the winch operator, the instrumentation was able to be positioned within the plume.

Figure 40. EPA instrumentation suite with line handlers immediately after liftoff (left) and the aerostat (right)

6.0 PERFORMANCE ASSESSMENT

Thermal Characterization

The results from the temperature testing for the 12 ft (3.66 m) by 12 ft (3.66 m) burner are shown in Figure 41. 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 ft (1.37 m) above the burner and 4 ft (1.37 m) 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.

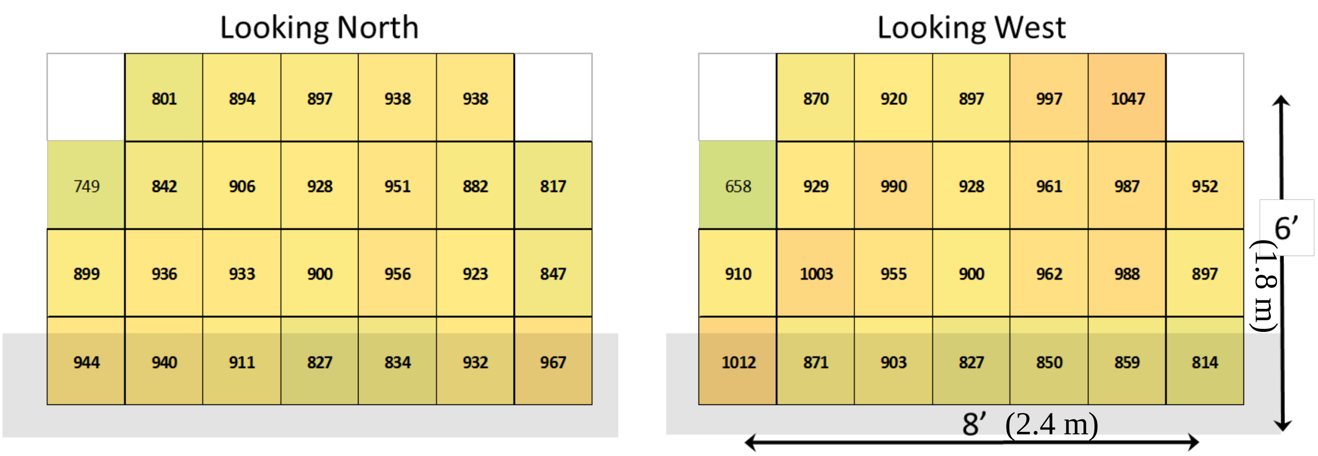


Figure 41: Results of temperature testing within 12 ft (3.7 m) square burner. Note that two diagrams are the two orthogonal planes produced by the temperature grids.

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 3) the flames look like those seen in a liquid fuel fire with the exception of the missing large black soot cloud above.

The heat flux in each of four directions at each DSC location was measured as a function of time in the 12 ft (3.66 m) by 12 ft (3.66 m) burner. The average value of each of these four signals is then calculated for the first 30 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 42. In 14 of the 16 measurement locations, the burner exceeds the goal of 80kW/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. Assuming that this symmetry holds true and the other quadrants have similar heating, then the volume produced that meets the heat flux requirement is over 5 ft (1.5 m) wide and 6 ft (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) at 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 42. 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 makes sense because of the fact that the fire has begun to neck-in at these locations 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 ft (1.5 m) wide and 6 ft (1.8 m) tall meets the directional uniformity requirement.

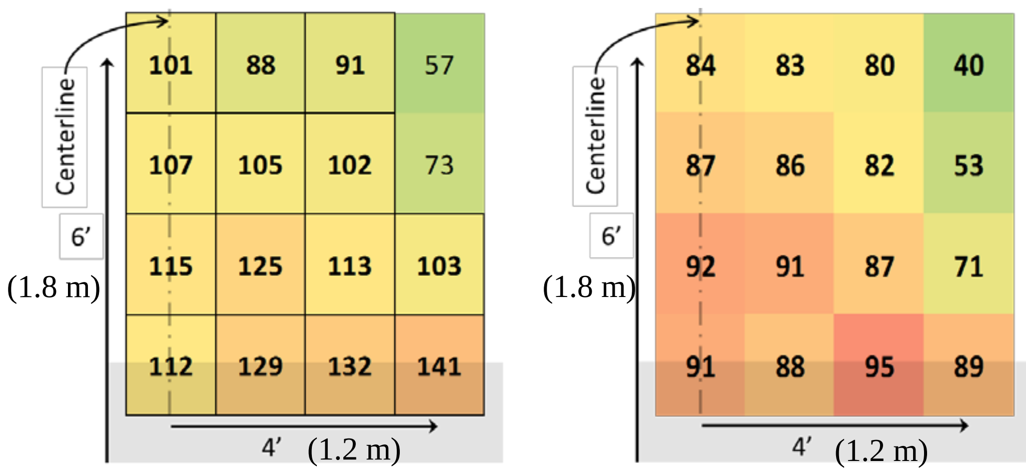


Figure 42: At left, average measured heat flux (kW/m^2) for one quadrant of the 12 ft (3.7 m) square burner. At right, the directional uniformity of the measured heat fluxes for the same data. In each graph, the left hand column is the center of the burner.

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 by 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 [28] the convective heat transfer coefficient (h) is approximately 27W/m^2/K. For the center of the fire 3.3 ft (1 m) above the burners the temperature is 900°C. This gives a convective flux of 24kW/m^2. The measured heat flux at this location was 115kW/m^2 which implies that the heating is at least 80% radiative. Therefore, the heating within the burner is mostly from radiation.

Initial operation of the 10 ft by 20 ft (3.0 m by 6.1 m) propane burner resulted in small inconsistent flames. With the 12 in. (0.3 m) spacing of the pipes, there was not enough heat feedback to evaporate the propane and provide the gaseous fuel for operation. The additional pipes were attached to the manifold to provide 6 in. (0.15 m) spacing of the pipes. The flames were more consistent, but it appeared that the fuel flow to the burner was not sufficient and the flames were small. After removing the strainers that were freezing and preventing flow, replacing the solenoid valves with electrically actuated ball valves, and replacing the pressure regulators with manually throttled ball valves, the flames were large and consistent. However, from a visual perspective, the flames were not as optically thick as desired. To decrease the initial mixing of the air and propane by decreasing the exiting velocity of the propane gas, the orifice diameter holes were drilled out to 0.125 in (3.2 mm) and the propane pressure was adjusted accordingly to provide an optimal flame. Additionally, a 1 ft (0.3 m) side shield was constructed around the propane burner to prevent early mixing of the propane and air and provide a more evenly dispersed radiant flame. Figure 43 provides a view of the burner in operation from both sides after all of the modifications were completed. The flames filled a large volume and had the characteristic dark orange color of an optically thick flame.

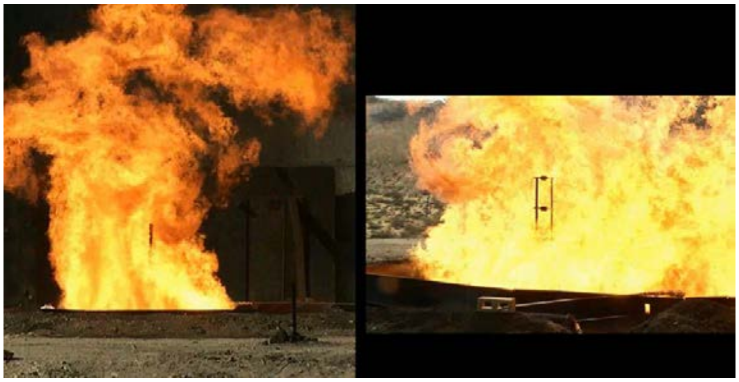


Figure 43. Operation of 10 ft by 20 ft (3.0 m by 6.1 m) Propane Burner with Heat Flux Gauges and Thermocouples.

Temperature and heat flux measurements were completed with the 10 ft by 20 ft (3.0 m by 6.1 m) propane burner. Nine sets of measurements will be reported in this paper. All of these measurements were collected with the burner tube spacing set at 6 in (0.15 m), 0.125 in (3.2 mm) orifice hole diameters, and 1 ft (0.3 m) side shields. The strainers and solenoid valves were removed as well as the pressure regulators. The manual ball valve was used to regulate the pressure and it was opened to provide a measured pressure of 1.65 bar on the burner side of the valve.

An instrumentation stand was built that was 6.0 ft (1.83 m) in height. Thermocouples and heat flux gauges were installed at the top and bottom of the stand. Two additional heat flux gauges and thermocouples were installed equally spaced throughout the stand. The four bare thermocouples were 0.0098 in (0.25 mm) type K thermocouples with silica insulation. DSCs were developed and used to collect total absorbed heat flux measurements within the burner volume. The burner was set up so that the 20 ft (6.1 m) dimension was in the north/south direction and the 10 ft (3.0 m) dimension was in the east/west direction.

Figure 44 – Figure 46 report the results of nine distinct tests over two days. A single test would measure the four bare thermocouples readings and the four heat flux gauge measurements at a particular burner location. The temperatures reported are the average temperature of a thermocouple over 30 seconds once the thermocouple reached 550°C. 550°C is used because the STANAG specifies that the flame temperature must reach 550°C within the first 30 seconds of the test. Historically, the time when the flame first reaches 550°C has been used as the starting point for the test. Specifically, when the average flame temperature is reported for a liquid pool fire test, that is the average temperature from when the flame first reaches 550°C up until the item reacts. To maintain consistency with the existing liquid pool fire test, the time when the flame first reaches 550°C is used as the starting point for all thermal characterization calculations. The DSCs have four thermocouples in four quadrants which can be used to calculate four directional heat flux values. For each DSC the heat flux for each quadrant was averaged for 30 seconds once the bare thermocouple reached 800°C and then those four values where averaged to give the reported heat flux. The figures show a compilation of measurements in different north/south planes through the fire. Each plane starts at the north/south centerline. In each figure there is a measurement at the north/south centerline, a measurement 3.5 ft (1.07 m) north of the north/south centerline and a measurement 7.0 ft (2.13) m north of this same centerline. The different measurements were compiled for ease of comparison. However, it is important to note that direct comparisons should take into account that there were changes in wind and atmospheric conditions between tests and large buoyant fires are variable and chaotic by nature.

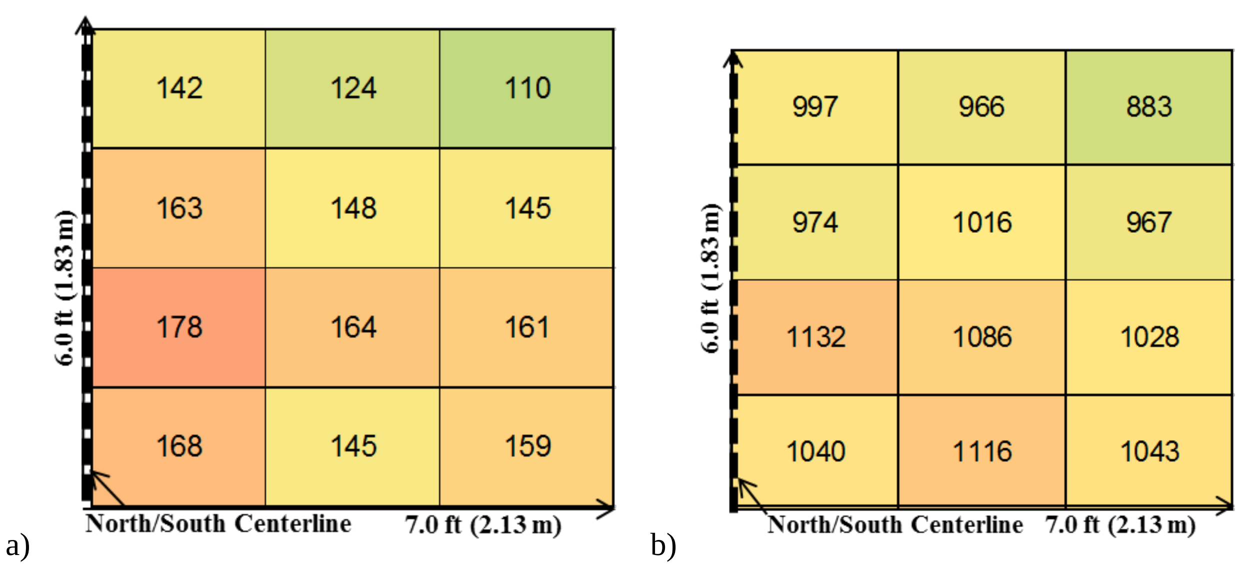


Figure 44. Measurement Plane at East/West Centerline a) Measured Heat Flux (kW/m^2) b) Measured Temperature (°C)

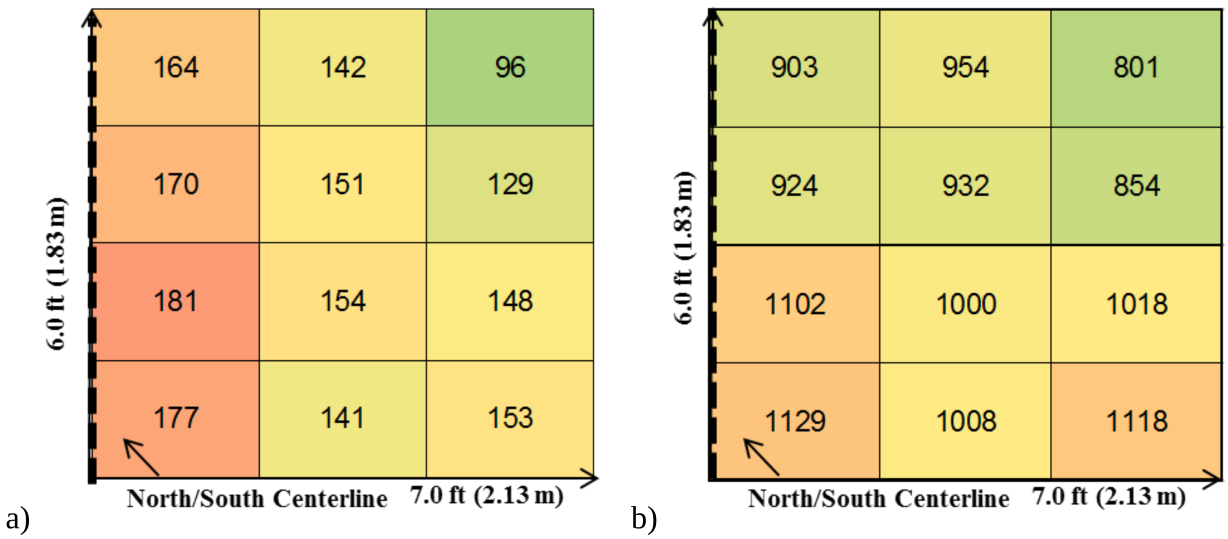


Figure 45. Measurement Plane 2 ft (0.61 m) West from East/West Centerline a) Measured Heat Flux (kW/m^2) b) Measured Temperature (°C)

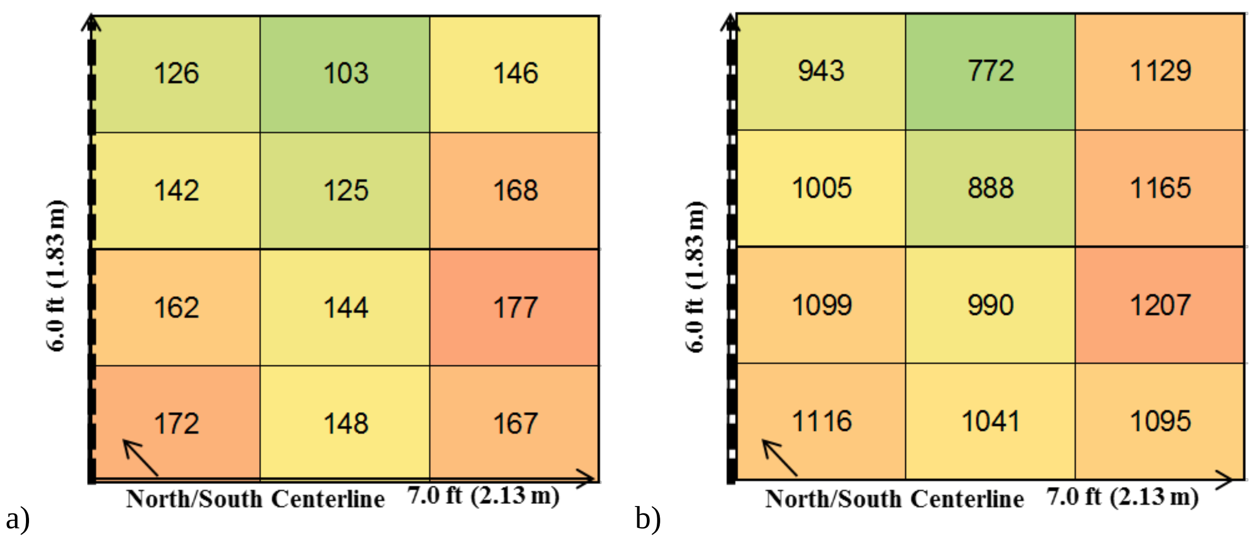


Figure 46. Measurement Plane 2 ft (0.61 m) East from East/West Centerline a) Measured Heat Flux (kW/m^2) b) Measured Temperature (°C)

All of the measured heat fluxes were greater than 80 kW/m^2. The measured heat fluxes were 20% – 30% greater than the measured heat fluxes in the 12 ft (3.7 m) by 12 ft (3.7 m) propane burner. However, this is to be expected as it is a larger burner and these values are similar to other heat flux values measured in large pool fires [29, 30]. The temperatures are all above 800 °C except one value. During this test, there were higher than desired winds that pushed the flame away from the gauges and it is suspected that in a test with less wind that this location would also meet the greater than 800 °C criterion.

The results of this study show that the 10 ft (3.0 m) by 20 ft (6.1 m) propane burner has a significant hearth in which to test ordnance items. If symmetry is assumed at the north/south centerline, the entire measured hearth would be 14.0 ft (4.26 m) long by 4.0 ft (1.21 m) wide by

6.0 ft (1.83 m) high. The temperatures and heat fluxes are higher than 80 kW/m^2 and 800 °C, especially for tests with calmer wind conditions and an even larger hearth is possible with a larger burner design. Some of the important results from this study are that the 12 ft (3.7 m) by 12 ft (3.7 m) propane burner system was adapted and built at a very different location. Also, both rectangular and square burners will meet the heat flux and temperature requirements. A large ordnance item could be tested in this burner and experience a thermal environment consistent with a large pool fire. This demonstrated the scaling of the propane burner design and the burner's ability to be used for fast heating testing for even the largest ordnance items.

Environmental Emissions Testing
Three liquid-pool fire tests were performed as part of the emissions testing campaign. In all tests, 1890 liters of JP5 were consumed. The wind was not consistent for the three tests and had a large impact. The wind was approximately 5-7 mph (2-3 m/s) for Test 1 and 3-6 mph (1.5-3 m/s) for Test 2. For Test 3, there was essentially no wind, and a calm condition was met. During Tests 1 and 2, the wind pushed the plume around and made it more challenging to keep the instrumentation properly positioned within the plume. The wind present during Test 2 caused the plume to move, which exposed the sensor suite from time to time, as shown by the red arrow in Figure 47. During Test 3, the calm conditions allowed the plume to rise vertically, and the instruments were within the plume for almost the entire test. Photographs from Tests 2 and 3 are shown in Figure 47. During the calm test, the sensor suite was obscured from sight throughout the test, as shown in the photograph of Test 3.

The wind also affected the rate at which the fuel burned. The fires in Tests 1 and 2 both lasted approximately 26 minutes before dying out. This gives a fuel burn rate of approximately 72 liters per minute. In terms of fuel recession rate, this translates to 0.2 in per minute (5 mm per minute). The general rule of thumb given in the STANAG is 7 mm per minute. However, for Test 3, where there was virtually no wind, the fire burned for 38 minutes. This equates to only 49 liters per minute or a fuel recession rate of less than 4 mm per minute. This demonstrates how strongly wind influences a liquid-pool fire. Coincidentally, the fuel consumption rate for the calm condition in Test 3 matches the fuel consumption rate of the propane burner of similar size.

Figure 47. Photographs taken during test 2 (left) and test 3 (right)

Since the 12 ft (3.7 m) square propane burner is remotely operated, no long delay is needed to allow the burner to cool between separate emission test events like in the liquid-pool fire, where personnel are needed at the site to set up the ignition and pour the fuel. This allows tests to be performed quickly and allowed all three propane fires for this test campaign to be conducted sequentially on the same day. There was approximately a 40 minute delay between each test that allowed the propane tank to be refilled and the EPA instrumentation to receive fresh batteries and sampling equipment. Therefore, wind conditions were very similar between the three tests and were steady at approximately 3 mph (1.5 m/s).

The same flow control valve was used for all three tests, and consequently the flow rate of propane to the burner was nearly constant. For all three tests, the average flow rate was 50.8 liters per minute. Also, in each test, the propane burner was operated until sufficient data was collected. The three tests lasted 26 minutes, 25 minutes, and 28 minutes, respectively.

A total of 35 different emission samples were collected from six burns during two test days. The background-corrected CO_2 and CO emission factors were higher for the JP-5 burns (20 g CO/kg $fuel_c$, 3,085 g CO_2/kg $fuel_c$) than the propane burns (2.4 g CO/kg $fuel_c$, 3,003 g CO_2/kg $fuel_c$) (Table 8). The literature reports 3,084 g CO_2/kg jet fuel [31] and 2,948-2,995 g CO_2/kg propane [31, 32], both values almost identical to those found in this study. The emission factors presented here also compare to surface oil burns at 58 g CO/kg oil_c and 3,023 CO_2/kg oil_c [33]. The MCE calculated with gas phase carbon showed almost complete combustion for propane burns (0.993 ± 0.001) and relatively high values for the JP-5 burns (0.959 ± 0.002). MCE is a measure of how well the fuel burns to final products. High MCE will mean efficient use of the fuel and reduced intermediate products that are pollutants. However, including the PM carbon mass ($C_{PM2.5}$) in the MCE calculations resulted in a large decrease in the MCE from 0.959 to 0.847 for the JP-5 but had virtually no effect for propane, 0.993 to 0.992. This differential effect is due to the large amount of carbon-containing soot emitted from the JP-5 fires and the lack of soot emitted by the propane burner. No CH_4 was detected from either JP-5 or propane burns.

The average $PM_{2.5}$ emission factor from JP-5 burns (129 ± 23 g/kg $Fuel_c$) was approximately 150 times higher than from propane burns (0.89 ± 0.21 g/kg $Fuel_c$) (Figure 48, Table 8), resulting in a statistically significant ($F/F_{crit} = 12$, $p = 0.0006$) difference between the fuels. Figure 48 shows an approximately 10% decrease in the $PM_{2.5}$ emission factor for the JP-5 burns when the PM carbon mass ($C_{PM2.5}$) is included in the emission factor calculations; the propane burn (Table 8) shows little such effect.

The $PM_{2.5}$ emission factor for propane is higher than the reported literature values combusting propane in boilers, 0.17 g Total PM/kg propane [32]. This was expected as the propane burner was designed to produce an optically thick flame to get similar radiative heat transfer in the flame as the jet fuel pool fire. Therefore, the burner was not optimized for combustion efficiency as a boiler would be. The JP-5 $PM_{2.5}$ emission factor is more than two times larger than emissions from surface burns of crude oil (58 ± 14 g/kg oil consumed)[33]. The PM size distribution showed that 82% and 97% of the PM from the JP-5 and propane burns, respectively, were PM_1 and less (Figure 49). Note that PM_x includes all particle sizes smaller than x microns in size. That is $PM_{2.5}$ includes all particulate matter smaller than 2.5 microns and is therefore the sum of PM_1 *plus* any particles that measure between 1 and 2.5 microns. This means that as you increase the size designation the percentages are cumulative and approach 100%. Emission factor results for PM_1, $PM_{2.5}$, PM_4, PM_{10} and Total PM as well as the accompanying MCE are summarized in Table 9. The JP-5 $PM_{2.5}$ emission factors from each burn were compared to their respective fuel consumption rate. The result showed a significant difference between JP-5 emissions and fuel consumption rate (F/F_{crit} 12.6, p = 0.00060), suggesting that faster JP-5 consumption rates produce less $PM_{2.5}$ emissions, albeit still significantly higher than with propane.

Table 8. Results[a]

Pollutant	Unit	JP-5		Propane	
		Average	Stand. Dev.	Average	Stand. Dev.
CO_2	g/kg $Fuel_c$	3,085	7.0	3,003	0.34
CO	g/kg $Fuel_c$	20	4.4	2.4	0.22
CO_2	g C/kg $Fuel_c$	841	1.9	819	0.10
CO	g C/kg $Fuel_c$	7.8	2.1	1.0	0.10
CH_4	g/kg $Fuel_c$	ND		ND	
MCE[b]	Ratio	0.959	0.029	0.993	0.0055
MCE $C_{PM2.5}$[b]	Ratio	0.847	0.015	0.992	0.0058
$PM_{2.5}$	g/kg $Fuel_c$	129	23	0.892	0.206
$PM_{2.5}$ $C_{PM2.5}$	g/kg $Fuel_c$	114	18	0.891	0.205
EC	g/kg $Fuel_c$	105	17	0.10	0.090
OC	g/kg $Fuel_c$	6.4	2.7	0.37	0.15
TC	g/kg $Fuel_c$	111	16	0.48	0.23
OC/EC	Ratio	0.063	0.031	9.4	10.5
EC/$PM_{2.5}$	Ratio	0.82	0.022	0.11	0.11
Σ VOCs[c]	mg/kg $Fuel_c$	1,764	568	236	167
Σ PAH_{16}	mg/kg $Fuel_c$	189	59	4.3	1.2
Σ PAH - TEQ	mg $B[a]P_{eq}$/kg $Fuel_c$	1.2	0.14	0.0010	0.00021
Fuel Consumption Rate	m^3/min	0.065	0.013	0.051	0

[a] Units in mass of pollutant per mass of fuel consumed ($Fuel_c$). NS = No sample. Stand. Dev. = Standard deviation. ND = not detected. [b] MCE = modified combustion efficiency from the entire burn. [c] Sum of 77 VOCs analyzed via U.S. EPA Method TO-15 [34] and TO-11A[35].

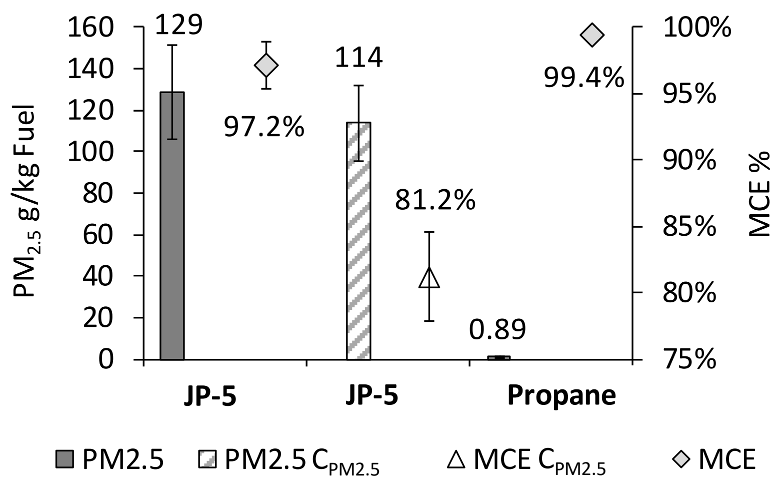


Figure 48. PM2.5 emission factors from JP-5 and propane burns. Modified combustion efficiency (MCE) was determined during collection of PM2.5 batch emissions. CPM2.5 values include PM-bound carbon in the calculation.

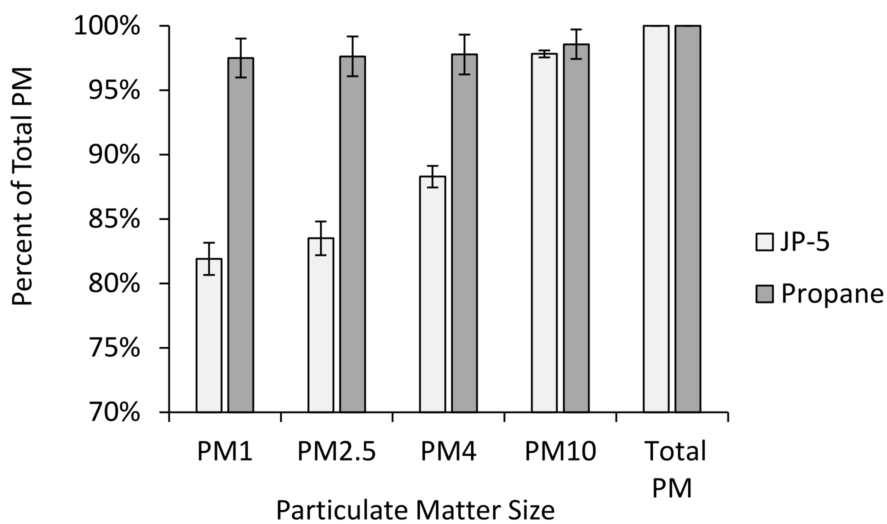


Figure 49. PM size distribution

Table 9. PM emission factors derived from optical measurements.

Size	Unit	JP-5	Propane
PM_1	g/kg Fuel	149 ± 9.6	1.51 ± 0.48
$PM_{2.5}$	g/kg Fuel	152 ± 9.7	1.51 ±0.48
PM_4	g/kg Fuel	161 ± 11.2	1.51 ±0.48
PM_{10}	g/kg Fuel	178 ± 14.5	1.52 ± 0.48
Total PM	g/kg Fuel	182 ± 14.3	1.54 ± 0.48
MCE	**Fraction**	**0.959 ± 0.029**	**0.993 ± 0.006**

The majority of the $PM_{2.5}$ was carbonaceous for both the JP-5 ($TC/PM_{2.5}$ = 0.86) and the propane burns (0.54). The carbonaceous $PM_{2.5}$ from the JP-5 burns was almost entirely EC ($EC/PM_{2.5}$ =

0.82 ± 0.022), unlike from the propane burns where EC accounted for only a minor fraction of the $PM_{2.5}$ ($EC/PM_{2.5}$ = 0.11 ± 0.11). The large EC fraction for the JP-5 and the $PM_{2.5}$ emission factors resulted in highly visible black smoke from the JP-5 burns. The $EC/PM_{2.5}$ of the JP-5 is the same as the $EC/PM_{2.5}$ from surface burns of crude oil ($EC/PM_{2.5}$ = 0.82 ± 0.062) [33]. The composition of $PM_{2.5}$ from the propane burns is similar to the composition of $PM_{2.5}$ from natural gas fired appliances ($EC/PM_{2.5}$ = 0.063 to 0.13) [36].

The most abundant VOCs in the plumes were benzene and propene for JP-5 and propane burns, respectively (Table 10). Figure 50 summarizes some of the most abundant VOCs, all of which are on EPA's list of hazardous air pollutants [37]. Benzene, formaldehyde, 1,3-butadiene, and acetaldehyde are known to be human carcinogens, and acrolein and toluene are considered toxic.

Table 10. VOC emission factors.[a]

	JP-5	Propane
	mg/kg Fuel[c]	
Benzene[b]	1,249 ± 629	2.5 ± 2.1
Formaldehyde[b, c]	322 ± 209	42 ± 12
Propene	98 ± 70	101 ± 77
Ethanol	96 ± 20	68
Acetaldehyde[b, c]	93 ± 82	17 ± 2.8
Acrolein[b]	82 ± 54	9.6 ± 6.9
Benzaldehyde[c]	81 ± 59	ND
Acetone[c]	77 ±124	4.8 ± 5.9
Toluene[b]	71 ± 20	5.1 ± 4.3[d]
1,3-Butadiene[b]	42 ± 28	ND
Styrene[b]	41 ± 25	ND
Ethyl Acetate	39 ± 35[d]	12
m-,*p*-Xylenes[b]	22 ± 12[d]	4.6
1,2,4-Trimethylbenzene	16 ±10	ND
Carbon Disulfide[b]	14 ± 22	5.5 ± 10[d]
n-Hexane	13 ± 14	4.5
2-Butanone (MEK)	13 ± 4.5	3.8 ± 1.4
o-Xylene[a]	9.7 ± 5.1	ND
Ethylbenzene	9.2 ± 5.7	ND

[a] Range of data one standard deviation if nothing else is mentioned. The VOCs shown here were selected based on the number of samples detectable above three times the detection limit and their relevance to the EPA's list of hazardous air pollutants list and their role as greenhouse gas/ozone precursors. Full list of the 87 analyzed VOCs and their emission factors are presented in SI Table S1. [b] On EPA's list of hazardous air pollutants (HAP list) [37]. [c] Sampled and analyzed by U.S. EPA Method 11A [35]. [d] Absolute difference.

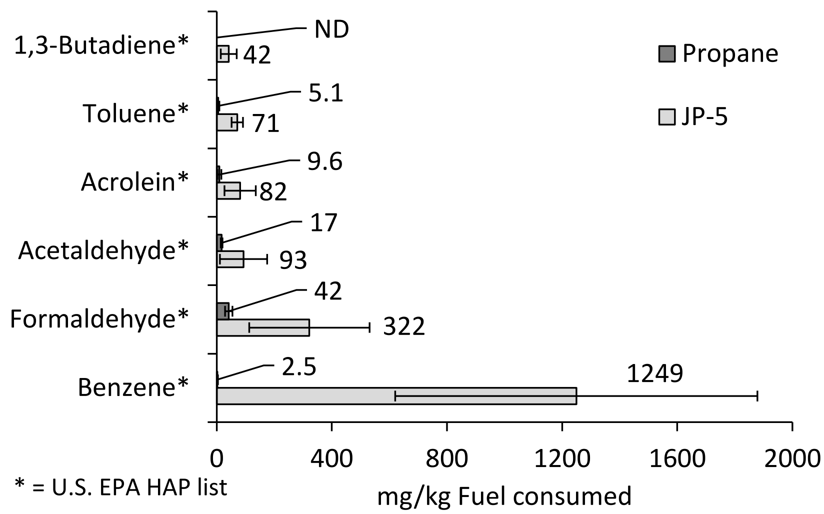


Figure 50. VOC emission factors. [37].

PAH compounds are products of incomplete combustion. The propane burns, which had a high MCE of 0.993, resulted in detectable levels of only five of the sixteen toxic PAHs. With a lower MCE for JP-5 (MCE 0.959 or MCE $C_{PM2.5}$ 0.847), PAH emissions were more than one hundred times higher than from the propane burns (Table 11). The PAH results showed a statistically significant difference (F/F_{crit} 4.0, $p = 0.0051$) between the propane (1.16 ± 0.14 mg/kg $Fuel_c$) and JP-5 (189 ± 59 mg/kg $Fuel_c$) emission factors. The most abundant PAHs varied slightly between the fuels with naphthalene, phenanthrene, fluoranthene, and pyrene having the highest concentrations for JP-5 and naphthalene, phenanthrene, and anthracene having the highest concentrations for propane.

Table 11. PAH Emission Factors.[a]

	JP-5		Propane	
PAHs	**mg/kg $Fuel_c$**	**mg $B[a]P_{eq}$/kg $Fuel_c$**	**mg/kg $Fuel_c$**	**mg $B[a]P_{eq}$/kg $Fuel_c$**
Naphthalene	9.31E+01 ± 2.6E+01	NA	8.58E-01 ± 8.4E-02	NA
Acenaphthylene	2.24E+01 ± 1.5E+01	NA	ND	NA
Acenaphthene	ND	NA	ND	NA
Fluorene	2.40E+00 ± 7.5E-01	NA	ND	NA
Phenanthrene	2.28E+01 ± 5.8E+00	1.14E-02 ± 2.9E-03	2.20E-01 ± 5.9E-02	1.10E-04 ± 2.9E-05
Anthracene	2.60E+00 ± 7.3E-01	1.30E-03 ± 3.6E-04	5.67E-02 ± 4.2E-02	2.84E-05 ± 2.1E-05
Fluoranthene	1.47E+01 ± 3.8E+00	7.36E-01 ± 1.9E-01	1.70E-02 ± 3.4E-03	8.48E-04 ± 1.7E-04
Pyrene	1.47E+01 ± 3.9E+00	1.47E-02 ± 3.9E-03	1.09E-02 ± 1.7E-03	1.09E-05 ± 1.7E-06
Benzo(a)anthracene	1.28E+00 ± 2.8E-01	6.40E-03 ± 1.1E-03	ND	ND
Chrysene	1.97E+00 ± 4.8E-01	5.92E-02 ± 1.2E-02	ND	ND
Benzo(b)fluoranthene	2.09E+00 ± 5.9E-01	2.09E-01 ± 5.9E-02	ND	ND
Benzo(k)fluoranthene	2.30E+00 ± 47E-01	1.15E-01 ± 2.3E-02	ND	ND
Benzo(a)pyrene	2.90E+00 ± 8.6E-01	2.90E+00 ± 8.6E-01	ND	ND
Indeno(1,2,3-cd)pyrene	2.19E+00 ± 4.6E-01	2.19E-01 ± 4.6E-02	ND	ND
Dibenz(a,h)anthracene	ND	ND	ND	ND
Benzo(ghi)perylene	3.61E+00 ± 9.6E-01	7.21E-02 ± 1.9E-02	ND	ND
SUM PAH_{16}	1.89E+02 ± 5.9E+01	4.34E+00 ± 1.2E+00	1.16E+00 ± 1.4E-01	9.97E-04 ± 2.1E-04

[a] NA – not applicable, compounds do not have assigned TEF values. Range of data represents 1 standard deviation. All PAHs are on EPA's list of hazardous pollutants [37].

Comparing the PAH emission factor from each burn with its fuel consumption rate showed that there was a significant difference between JP-5 emissions and fuel consumption rate (F/F_{crit} 4.0, $p = 0.0051$), suggesting that faster JP-5 consumption rates produce lower PAH emissions.

The environmental results that have been presented in terms of mass of pollute per mass of fuel burned. These results are based on three test burns in both the propane and liquid pool fire. in each of these six tests, the results are averages over approximately 20 minutes of data collection. It is assumed that the data collection window was sufficiently long for the data collected to be applicable to the entire burn period regardless of duration. Furthermore, since the emissions were measured per mass of fuel consumed, in order to understand the total emissions from the test, you must multiple these numbers by the total mass of fuel that is burned.

For a FCO test, it is not practical to insert additional fuel during the test. Therefore, an excess of liquid fuel is used during the FCO test to ensure sufficient duration of the simulation. Additionally, is it not practical to extinguish the pool fire once it has started, so there is always excess fuel that is burned. The propane burner is able to cease the flow of fuel to the burner once the item has reacted and therefore the excess of burnt fuel is prevented. This ability to shut off the propane flow during the test is one of the reasons that less fuel is used for a propane test compared to a liquid-fuel test. On average, approximately 280 kg of propane are used for a typical FCO test while approximately 4500 kg of JP-5 are used in an equivalent test. Multiplying these fuel mass numbers gives the total emissions per test as shown in Table 12 for both JP-5 and propane FCO tests. These data show that use of the propane burner instead of the traditional JP-5 FCO test could decrease the environmental impact substantially, e.g., the $PM_{2.5}$ emissions would be reduced 2000-fold per test.

Table 12. Total Amount Emissions Emitted per Test.

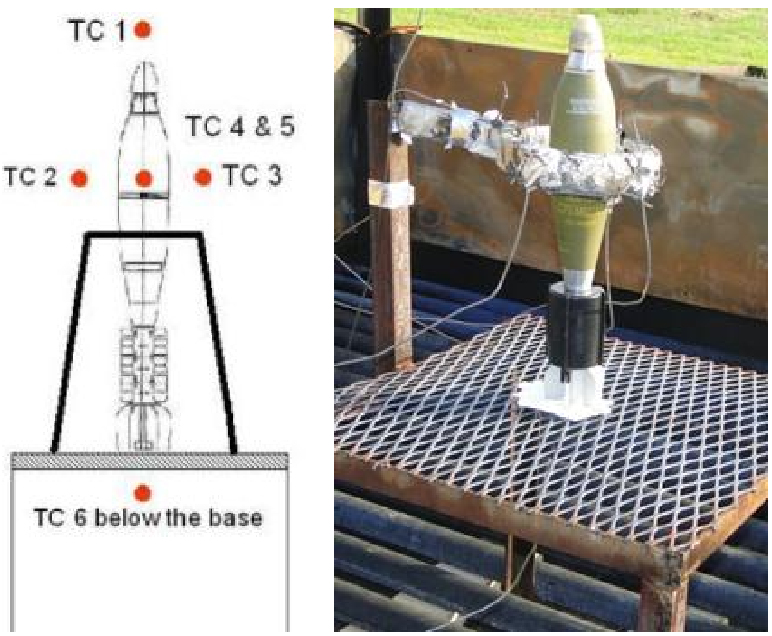
	JP-5 kg	Propane kg
$PM_{2.5}$	580	0.25
CO_2	13,882	841
CO	91	0.67
Sum PAH_{16}	0.85	0.0012
Sum VOCs[a]	7.9	0.066
EC	473	0.028
OC	29	0.10
TC	500	0.13

[a] Sum of 77 VOCs analyzed via U.S. EPA Method TO-15 [34] and TO-11A [35]

Energetic Item Testing

The propane burner was used to test the reaction of ordnance items in a fast cookoff situation. To date, all energetic items that have undergone a propane FCO tests have been tested in the 12 ft (3.7 m) square Dahlgren burner. The first ordnance chosen for testing was the M821A2 81-mm mortar. This item was chosen because there were two explosive fills available with this mortar body. The first explosive fill was IMX-104. IMX-104 is an insensitive explosive formulation designed to replace Composition B (CompB). IMX-104 is expected to have a mild reaction in the fast cookoff scenario. The legacy explosive fill for this item is CompB, which is a high-energy explosive fill. Items filled with CompB typically have a severe reaction in the fast cookoff test. While using the same ordnance body with two explosive fills should exhibit widely different results, it is possible to achieve the same test reaction score for the ordnance items in the propane burner and liquid-pool fire.

The fast cookoff testing of the IMX-104-filled 81-mm mortar using a kerosene-based fuel pool fire was conducted by the U.S. Army Research, Development, and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey [38]. The schematic in Figure 51a is the test setup for the liquid pool fire test. The photograph in Figure 51b shows the test setup for the 81-mm mortar fast cookoff with the propane burner. The objective was to be as similar as possible to the existing liquid-pool fire when performing the propane burner tests.



(a) (b)

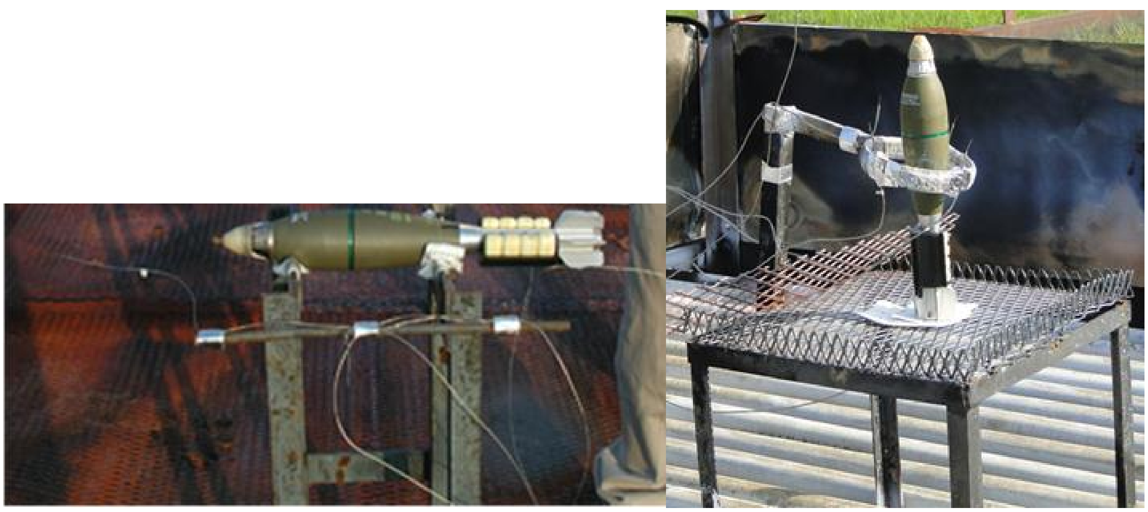
Figure 51. 81-mm Mortar With IMX-104 Explosive Fill Fast Cookoff Test Setup. (a) Jet-A Pool Fire, (b) Propane Fire.

In both tests, an audible pop occurred at ~40 seconds; the pop was assumed to be the propellant primer. The measured average liquid-pool fire flame temperature was 950°C. The measured average propane fire flame temperature was 830°C. Both were above the required 800°C. After the initial audible pop, there was no visible or audible reaction for either test. The post-test photographs for both tests are shown in Figure 52. The pool-fire test was scored a Type V reaction. The propane-fire test was not officially scored, but showed evidence of a Type V reaction. The liquid pool fire test used 3,785 liters of Jet-A fuel, and the propane fire test used 568 liters of liquid propane.

(a) (b)

Figure 52. Post-test Photograph of 81 mm Mortar with IMX-104 Explosive Fill-Fast Cookoff Test. (a) Jet-A Pool Fire, (b) Propane Fire.

The 81-mm mortar with CompB fill fast cookoff testing using a kerosene-based fuel pool fire was conducted by the Naval Surface Warfare Center (NSWC) at Dahlgren, Virginia [39]. The photograph in Figure 53a is the test setup for the liquid pool fire test. The photograph in Figure 53b shows the test setup for the 81-mm mortar fast cookoff with the propane burner. The orientations of the mortars with CompB explosive fill were different between the Jet-A pool fire and the propane fire as the same test stand was used throughout the propane burner testing.



(a) (b)

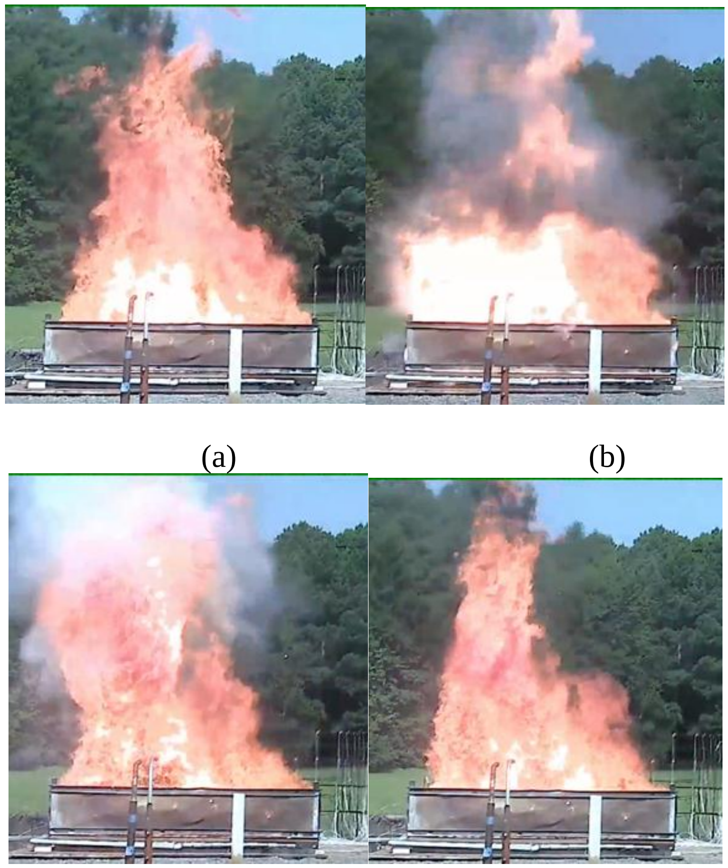
Figure 53. 81-mm Mortar with CompB Explosive Fill Fast Cookoff Test Setup. (a) Jet-A Pool Fire, (b) Propane Fire.

In both tests, there was first an audible pop. The test using a kerosene-based fuel had the pop occur at 29 seconds, and the test with propane as a fuel had the pop occur at 43 seconds. As the tests with IMX-104 explosive fill, this first reaction was assumed to be the propellant primer. Recognizing the inherent chaotic nature of the fuel fires, reaction times of the propellant primers in the four tests of 29 seconds, 43 seconds, 44 seconds and 43 seconds is considered to be very repeatable and shows a definite agreement between the kerosene-based fuel fire and propane fuel fire-heat input. Both tests with the CompB explosive fill had a second more violent reaction. With the kerosene-based fuel pool fire, the reaction occurred at 52 seconds, and with the propane fuel fire, the reaction occurred at 61 seconds. The 20% difference in time to reaction for the second event is acceptable and validates the assumption that the propane fire and kerosene-based fire produce similar heat loads into the test items. The measured average liquid pool fire flame temperature was 996^{o}C. The measured average propane fire flame temperature was 1,020^{o}C. Both flame temperatures were above the required 800^{o}C. The liquid-pool fire test used 3,180 liters of Jet-A fuel, and the propane fire test used 208 liters of liquid propane.

The post-test photographs for both tests are shown in Figure 54. The pool fire test was scored a Type II reaction. The propane fire test was not officially scored, but showed evidence of a Type II/III reaction. Both tests dented the items' restraints. The item restraint in the propane test was thrown but was not directly attached to the burner as in the pool fire. After the test, a visual inspection of the pipes showed that fragments from the item had created large holes in three of the burner pipes. No smaller holes were found and it is anticipated that holes small enough to be hard to detect during a visual inspection would not pose a concern. Even with the three large holes produced during the 81mm mortar test, the burner remained functional and no change in the fire was observed. After the test the burner was repaired by replacing the damaged pipes. This repair took less than an hour and immediately afterwards the burner was ready to be used for testing.

(a) (b)

Figure 54. Post-Test Photograph of 81-mm Mortar with CompB Explosive Fill Fast Cookoff Test. (a) Jet-A Pool Fire, (b) Propane Fire.



(a) (b)

(c) (d)

Figure 55. Photographs of Propane Fire Showing Sequence of Violent Event with 81-mm Mortar with CompB Explosive Fill.

Figure 55 shows the propane fire during the test with the 81-mm mortar with CompB explosive fill. Figure 55 shows the propane burner just before the violent reaction. Comparing the photograph in Figure 55a to the photograph in Figure 32, there are large billowing clouds of soot in the kerosene-based fuel fire and almost no visible soot outside of the luminous flame zone. In the propane burner the flame is luminous and completely surrounds the test stand and item. The luminous flame provides the necessary radiation to heat up the test article. In Figure 55b, the second reaction had just occurred leaving black smoke surrounding the flame. In Figure 55c, the smoke from the reaction is dissipating. In Figure 55d, the flame has returned to a pre-reaction state. The time between Figure 55a to Figure 55d is 3 seconds. The violent reaction had damaged three of the pipes, but the burner still had a consistent engulfing flame.

Figure 56 is a photograph from the same test as Figure 53. Figure 56 is from a safety camera taken from a tower looking down on the burner. The purpose of the safety camera is to see the state of the item after the test to determine the safety of approaching the burner. Photographs from the safety camera also showed that, at that angle, it is possible to see the test item and test stand. This photograph was taken after the propellant primer had reacted and before the violent reaction. The test item can be seen as still supported in the test stand but leaning to the right.

The lack of billowing black soot provides the opportunity to visually observe the reaction of the item.

Figure 56. Photograph of Propane Flame with 81-mm Mortar with CompB Explosive Fill Looking Down on Flame.

Additional tests were performed with 7.0-cm rocket IM-compliant warheads. The same type of warhead was tested in both a kerosene-based pool fire and a propane fire. The FCO test setups are shown in Figure 57.

(a) (b)

Figure 57. 7.0-cm Rocket IM-compliant Warheads Fill Fast Cookoff Test Setup. (a) Kerosene-Based Fuel Pool Fire, (b) Propane Fire.

Figure 58 shows the ignition process for both tests. Going from left to right, the photographs were taken 2 seconds, 10 seconds, 20 seconds, and 40 seconds after the ignition process started. The kerosene-based pool fires took about 40 seconds to establish a steady-state fire. The process was gradual. Within 2 seconds, the propane fire had established a steady-state consistent flame. The consistent and quick ignition process will make more repeatable tests. Comparing the final flames in Figure 58 for the kerosene-based pool fire and the propane fire, they are both luminous and will provide substantial heat transfer from radiation. However, the kerosene-based pool fire has billowing clouds of polluting black soot. The average temperature of the propane fire was 1,170°C and used 833 liters of fuel, and the average temperature of the kerosene-based pool fire was 900°C and used 7,570 liters of fuel. An audible reaction occurred in the kerosene-based fuel fire at 118 seconds, while an audible reaction occurred in the propane fire at 400 seconds. With both kerosene-based fuel and propane, 7.0-cm rocket IM-compliant warheads did not generate overpressure or throw fragments when they reacted. It appeared that the explosive burned away.

Neither test was officially scored, but both tests showed evidence of a Type V reaction. The post-test photographs for both tests are shown in Figure 59.

(a)

(b)

Figure 58. Photographs Showing Ignition Process at 2 Seconds, 10 Seconds, 20 Seconds, and 40 Seconds after Ignition. (a) Kerosene-Based Pool Fire, (b) Propane Fire.

(a) (b)

Figure 59. Post-Test Photograph of 7.0-cm Rocket IM-compliant Warheads Fill Fast Cookoff Test. (a) JP-5 Pool Fire, (b) Propane Fire.

FCO testing was performed on 105mm M1 Cartridges that were packed in a PA190 vented shipping container. The test consisted of an inert warhead and a live propulsion system. As in the previous testing, two similar items were tested in the same configuration in both a liquid fuel pool fire and the 12 ft (3.66 m) by 12 ft (3.66 m) propane burner. The FCO test setups are shown in Figure 60.

(a) (b)

Figure 60. 105mm M1 Cartridge Fast Cookoff Test Setup. (a) Kerosene-Based Fuel Pool Fire, (b) Propane Fire.

The liquid pool fire FCO test used 7,570 liters of JP-5. The average temperature was 719 °C. There was an audible pop at 12:05 and nothing thrown from the pool fire area. This test was given a reaction violence engineering assessment of (V). The average temperature of the test was below the STANAG standard of 800 °C. By talking to the owners of the items, additional past testing was discovered that met the STANAG standard of 800 °C. All tests used 7,570 liters of JP-5. In one test the average temperature was 1002 °C with a reaction time of 11:37 and a reaction violence engineering assessment of (V). The other past test had an average temperature of 974 °C with a reaction time of 9:34. However this test had a reaction violence engineering assessment of (IV) as the shipping container lid was thrown outside the pit as the cartridge was ejected. This testing shows that there can be inherent variability in FCO testing. The owners of the items said that in multiple tests, the cartridge was ejected about half the time.

The FCO test performed with the 12 ft (3.66 m) by 12 ft (3.66 m) burner used 833 liters of propane. The average temperature was 979 °C with a time to reaction of 9:51. The 5.8 lb cartridge case was thrown 41 ft to receive a reaction violence engineering assessment of (IV). This reaction violence engineering assessment corresponded to one of the past test performed with a liquid fuel pool fire FCO test. Within the variability of the liquid pool fire test, the propane burner test of the 105mm M1 cartridge had the same reaction violence. The post-test photographs for both tests are shown in Figure 61.

(a) (b)

Figure 61. Post-Test Photograph of 105mm M1 Cartridge Fast Cookoff Test. (a) JP-5 Pool Fire, (b) Propane Fire.

A M72 light anti-armor weapon (LAW) round with an inert warhead was tested in the 12 ft (3.66 m) by 12 ft (3.66 m) propane burner. The test setup is shown in Figure 62. 757 liters of propane were used for the test. The average temperature was 873 °C with an audible popping sound as the reaction at 0:44. The item pitched down during the reaction and the projectile melted and dripped into the burner. The item's reaction violence received an engineering assessment of (V) (see Figure 62).

(a) (b)

Figure 62. M72 LAW Propane Burner Fast Cookoff (a) Test Setup, (b) Post-Test Photograph.

A M72 LAW round was tested with a live warhead in a liquid fuel FCO test. The test used 1893 liters of Jet-A fuel. It had an average temperature of 900 °C. With the live warhead, the reaction violence engineering assessment was a (I) because of the violent reaction. However, the propellant reacted around 0:53 and had a similar reaction as the M72 LAW with the inert warhead.

Table 13 provides a summary of results from the different tests using kerosene-based fuel pool fires and propane fires. Some observations to note are the propane tests used 7 to 15 times less fuel than the kerosene-based fuel fires. With the ability to turn off the fuel, the tests themselves were shorter. All the propane tests were less than 10 minutes while the tests with the kerosene-based fuel fires lasted more than 30 minutes. However, if an ordnance item had a reaction that is longer than 10 minutes, the propane burners could be used for those tests. The maximum duration of the propane burner FCO test is determined by the size of the tank. This could lead to faster test turn around and depending on the test item, multiple tests per day. The time to reactions between the same items in different fuel fires were comparable and within the expected variability of a fast cookoff test. Some variation in the average flame temperature was noted, but the variation was seen in fires with both propane and kerosene-based fuels, and all tests had temperatures above 800°C. Most importantly, even though the reactions of the items in the propane fire tests were not officially scored, they showed evidence of the same reaction type as the items in the kerosene-based fuel fires. These results indicate that the propane burner used in the study reported is an acceptable alternative to liquid-hydrocarbon fueled burners for fast cookoff testing.

Table 13. Summary of FCO of Ordnance Items Results.

Test	Fuel type	Fuel quantity	Time to reaction	Average flame temperature	IM score[a]
81-mm IMX	Kerosene-based	3,785 liters	43 seconds	950 °C	V
81-mm IMX	Propane	568 liters	44 seconds	830 °C	(V)
81-mm CompB	Kerosene-based	3,180 liters	29/61 seconds (first/second)	996 °C	II
81-mm CompB	Propane	208 liters	43/52 seconds (first/second)	1,020 °C	(II) or (III)
7-cm rocket warhead	Kerosene-based	7,570 liters	118 seconds	900 °C	(V)
7-cm rocket warhead	Propane	833 liters	400 seconds	1,170 °C	(V)
105mm M1	Kerosene-based	7,570 liters	725 sec	719 °C	(V)
105mm M1	Kerosene-based	7,570 liters	697 sec	1002 °C	(V)
105mm M1	Kerosene-based	7,570 liters	574 sec	974 °C	(IV)
105mm M1	Propane	833 liters	591 sec	979 °C	(IV)
M72 LAW (HE)	Kerosene-based	1893 liters	53 sec	901 °C	(I)
M72 LAW (INERT)	Propane	757 liters	43 sec	873 °C	(V)

[a]IM score in parentheses means that it was an engineering assessment and not an official IM score.

Additional testing was performed with an inert large aluminum container in the 12 ft (3.66 m) by 12 ft (3.66 m) burner. The aluminum case will melt in the burner and the test was completed to determine if there would be any degradation to the burner performance by the melting aluminum. This was the largest item tested in the 12 ft (3.66 m) by 12 ft (3.66 m) burner. The propane burner ignited without difficulty and the flames completely surrounded container. The average temperature of the 12 thermocouples surrounding the aluminum container was 863°C. The aluminum container was completely melted after 3.5 minutes. After the aluminum container melted, the burner continued to function and the flames were consistent and the same size as the flame without the melted aluminum. The small flames from the residual propane in the pipes post test shown in Figure 64, demonstrate that the holes in the tubes were not blocked by molten aluminum. Figure 64 also shows the posttest once all the residual propane was expended. A thin layer of sand was place on the bottom of the burner prior to performing the test to prevent the aluminum from adhering to the bottom of the burner make cleanup easier.

(a) (b) (c)

Figure 63. Large Aluminum Container in Propane Burner Test (a) Pre-Test Setup (b) During Test with Aluminum Container Present (c) During Test with Aluminum Container Melted.

(a) (b)

Figure 64. Large Aluminum Container in Propane Burner Test (a) Post-Test Residual Propane Flame (b) Post Test

The burner was built with light gage galvanized steel side shields. The original height of the side shields were 27 in (69 cm) as this was a standard width of the fabricating material. The purpose of the side shields was to inhibit air entrainment. By inhibiting air entrainment, the flame should fill the edges of the burner better. Also, they lead to a more fuel rich mixture within the burner and lead to a more luminous radiative flame. The side shield was developed to minimize any effect on a fragment from the test. A pristine 27 in (69 cm) side shield is shown in Figure 65.

Figure 65. Pristine 27 in (69 cm) Side Shield.

To observe the effect of side shields, tests were performed without the side shields. The structure of the flame can be observed in the photograph of Figure 66. The flame still has a luminous radiative portion. However the width of the flame narrows above the burner compared to the burner with side shields. Quantitatively, this can be seen in the measured heat fluxes of Figure 66 and the measured temperatures of Figure 67 compared to Figure 41 and Figure 42. With the quicker entrainment of air without side shields, the outside edges of the burner have lower temperature and heat flux values than the burner with side shields. Without the side shields, the fuel is concentrated more at the center of the burner where there are higher temperatures and heat fluxes than the burner with side shields.

Symmetry | Measured

62	68	88	115	88	68	62
74	84	114	133	114	84	74
82	118	134	140	134	118	82
138	153	146	149	146	153	138

6'

8'

(a) (b)

Figure 66. Testing without Side Shields on 12 ft (3.66 m) by 12 ft (3.66 m) Propane Burner (a) Photograph of Burner in Operation (b) Measured Heat Flux

	349	689	1032	1135	833	
282	432	893	1009	1199	988	425
299	638	1094	1023	1223	1113	418
932	1248	1010	1055	1150	1158	1159

8'

	1066	1121	1032	1058	1148	
406	1054	1147	1009	1054	1217	668
200	1297	1208	1023	1018	1179	792
850	1014	1160	1055	1110	1056	989

6'

Figure 67. Figure 62. Testing without Side Shields on 12 ft (3.66 m) by 12 ft (3.66 m) Propane Burner Measured Temperatures.

The testing without side shields showed that side shields are necessary. Additional testing was completed with shorter side shields. The advantages of shorter side shields are that there would be less interference to a fragment thrown from the test and moving personnel and test items in and out of the burner is easier. Tests were completed with 18 in (46 cm) and 9 in (23 cm) side shields. A photograph from a test with 9 in (23 cm) side shields is shown in Figure 68. A temperature grid was used to measure ‘fullness’ of flame. Results of the temperature grid with 9 in (23 cm) side shields are shown in Figure 69. The flame was nearly as full as with 27 in (69 cm) shields. After the side shield testing, 12 in (30 cm) side shields were used as this was another standard width of the side shield material making it readily available and inexpensive.

Figure 68. Test with 9 in (23 cm) Side Shields for 12 ft (3.66 m) by 12 ft (3.66 m) Burner.

8’

	640	1057	1172	1119	952			1163	1187	1172	1105	1160	
444	772	1113	1192	1190	1080	535	996	1144	1207	1192	1141	1137	910
522	1060	1096	954	1223	1221	850	1200	1210	1193	954	1127	1099	1020
1196	1108	1214	1170	1232	1277	1206	1236	1181	1141	1170	1199	1128	1157

6’

Figure 69. Temperature measurements from Temperature Grid for 12 ft (3.66 m) by 12 ft (3.66 m) Propane Burner with 9 in (23 cm) Side Shields.

7.0 COST ASSESSMENT

A cost assessment was performed to compare the total operating costs associated with performing fast cook-off testing. Both the propane fast cook-off burner and the traditional JP-5 pool fire were analyzed.

The total operating cost of the propane burner is based on data from two burners that were developed and operated at Dahlgren (the 8 ft (2.44 m) by 8 ft (2.44 m) and 12 ft (3.66 m) by 12 ft (3.66 m) square burners) and a 10 ft (3.05 m) by 20 ft (6.10 m) rectangular burner that is operating at China Lake. There was also a cost projection made to install a burner at U.S. Army Armament Research, Development and Engineering Center which is located at Picatinny Arsenal, NJ and a burner now under construction at Bofor's Test Center, Karlskoga, Sweden. Annualized recurring cost data are more limited, as the Dahlgren burners are the only ones that have been operational long enough to obtain data. The regulatory compliance costs are very site specific, as regulations vary from state-to-state in the US, and by country internationally. The per-test costs vary according to the test site's labor rates and safety rules, but the hours of work required should be accurate anywhere.

Costs are compared to liquid fuel fire testing. Standard test cost estimating templates are used by test ranges. The cost of conducting liquid fuel fire tests and propane fire tests can be accurately obtained with the templates. However, cost is only one element of the decision as to what type of burner to use or build. Liquid fuel burners have a large environmental liability, which can make them impractical no matter what the cost. Propane burners have a very small environmental impact and should be able to be used almost anywhere.

The following sections detail the cost assessment methodology and results. The analysis shows that the propane burner offers a per test cost savings of $10,905 ($25,886 vs $36,791) and an annualized recurring cost savings of $36,598 ($8,784 vs $45,382). Over the last five years, Dahlgren has averaged 15 FCO tests per year which results in a total annual savings of just over $200,000.

7.1 COST MODEL

The cost assessment was performed by breaking the costs down into three categories:

1. Nonrecurring costs of engineering, manufacturing, construction, and calibration
2. Per-test cost of daily operations
3. Annualized recurring costs of maintenance and regulatory compliance

The nonrecurring costs are the one-time costs associated with obtaining a burner. The nonrecurring costs include the engineering costs to design the burner, the manufacturing and construction cost to fabricate and build the burner, and the costs associated with calibrating and certifying the burner. The majority of the nonrecurring cost is the labor required to fabricate and assemble the facility. Dahlgren's labor rate of $149/hour was used throughout the cost assessment whenever labor hours were involved.

The per-test costs include all the recurring costs that are repeated for each additional test performed. The per-test costs include the requirements and documentation, all pre-test preparations and fabrication, the labor involved in test execution, all post-test activities (i.e. clean up), material surcharges (i.e. fuel), and non-labor costs (i.e. test stand material). Significant savings in the per-test costs are due to the lower cost of propane per gallon as well as the need for less total fuel per test. Additionally, there are savings from not requiring a commercial driver to deliver the fuel truck on the day of the test. Instead, the propane tank is filled as a routine operation when all other tanks are filled at the test site and the delivery fee is factored into the fuel cost. Finally, per-test savings are realized with the propane burner by requiring fewer weather call man hours. The weather call is factored into the cost of the test because, historically, a certain percentage of tests are cancelled due to high wind. It is anticipated that the shorter time required to setup for a propane test (no delay for fuel to be pumped) will decrease the likelihood of a weather related cancellation.

Finally, the annualized recurring costs include all recurring costs that are not specifically tied to test execution. These recurring costs would include regular maintenance to the system and the costs associated with maintaining regulatory and safety compliance. It is assumed here that the truck used to transport jet fuel is owned by the test site while propane will be delivered by a truck owned by the propane supply company. There are significant costs associated with maintaining fuel delivery capability as will be presented in the following section

7.2 COST ANALYSIS AND COMPARISON

Nonrecurring Costs

Engineering Costs. Drawings of the 12 ft (3.66 m) by 12 ft (3.66 m) burner at Dahlgren are included in the appendix of this report. This burner has been carefully developed and calibrated and is made from readily available materials that are inexpensive and easy to assemble. The cost of constructing a burner is summarized in Table 14. Labor represents the majority of the cost in constructing the burner. The engineering has been done and is not a cost item should this burner be selected by a test facility.

Manufacturing and Construction Costs. The manufacturing and construction costs are included in the labor costs provided in Table 14. The burner at Dahlgren sits on a one-inch thick steel plate that is covered with hand placed bricks without mortar. The bricks serve to protect the plate from the heat produced during the test which would warp an unprotected steel plate. Some tests spill molten aluminum onto the bricks, which are easily cleaned or replaced. The plate and bricks were already available at the test site and are not included in the cost analysis. Options at other sites would be an existing concrete slab, a fabricated slab, or a bed of tamped crushed rock. The burner at Dahlgren uses a 500 gallon propane tank. It is rented from a propane supplier and not considered to be a part of constructing the system.

There are several options for controlling a gas burner. The first and least expensive is manual control. Dahlgren burners were operated manually while under development. Manual operation consists of opening valves to start the gas flow, operating a switch to start the igniter, and turning the valves off after the test. The operations have to be performed in a shelter when energetic materials are being tested. The fuel supply tank must also be sheltered. With a manually operated system the shelters need to be close enough to the burner to allow reasonably short runs of pipe or hose, but still provide safety for the operators. Pipe runs on the order of 30 ft worked fine and were used for all of the developmental testing. With the passive evaporation burner design, only liquid flows through most of the pipe and the pressure drops are small. The Dahlgren liquid and gas fuel fast cook-off tests are only part of the testing going on at the range. Other tests such as bullet impact, fragmentation arenas, and rocket motor restrained firings are conducted there as well. There are central, collocated shelters for test control and data acquisition. Pipe runs from these shelters would be on the order of 1000 ft, making manual operation impractical. Therefore a personal computer (PC) based electrical system was developed which could control the burner remotely over an existing network using LabVIEW software. PCs and the software are available at most large test centers and laboratories, and are not included in the cost estimate. A second system based on a programmable logic (PLC) controller was built to control a gas fuel fast cook-off burner at China Lake.

The cost of materials for constructing a propane burner is $20,297. The labor cost (at $149/hour) at Dahlgren was $44,700. The cost of a fully operational burner is $64,997.

Table 14. Cost of a Propane Fast Cook-off Burner

	Burner	Controls	Fuel System	Total
Material	**$ 4,317.00**	**$ 3,098.00**	**$ 12,882.00**	**$ 20,297.00**
Labor	**$ 11,920.00**	**$ 14,900.00**	**$ 17,880.00**	**$ 44,700.00**
				$ 64,997.00

Calibration Costs. The cost of calibration of the burner as required in the STANAG depends on the skills and equipment available at the test center. Calibration testing requires collection of thermocouple and heat flux data during a number of tests. Many test centers have personnel and equipment suitable for the testing. Dahlgren personnel have calibrated burners at NSWC Dahlgren, NAWC China Lake, the Artillerie Schietkamp in the Netherlands, and Bofors Test Center in Sweden. Should they be asked to calibrate a burner in another location, Table 15 can be used to estimate the cost. If Dahlgren personnel are asked to perform the calibration for the test site, the calibration cost is $30,784.

Table 15. Cost of Calibrating a Propane Fast Cook-off Burner

Item	No. persons	Duration (hrs)	Rate ($/hr)	Total
Checkout and pack	1	40	$ 149.00	$ 5,960.00
Conduct tests	2	40	$ 149.00	$ 11,920.00
Return, clean equipment	1	20	$ 149.00	$ 2,980.00
Analyze & report	1	40	$ 149.00	$ 5,960.00
			Total Labor	**$ 26,820.00**
Materials				$ 1,000.00
Travel				$ 2,964.00
			Total Cost	**$ 30,784.00**

Per-test Cost of Burner Operations. The liquid fire costs are well characterized and form the basis for estimating the costs of conducting tests with the propane burner. A standard template is used to plan a STANAG 4240 liquid fuel test and calculate the cost as shown in Table 16. The table is organized into sections for producing and organizing documents, test site preparations, conducting the test, analyzing and reporting the data, instrumentation expenses, and materials and surcharges. The elements of the table in the context of the liquid fuel fire are discussed below. Following the liquid fuel fire discussion, the differences in costs for a propane fueled test are explained. The final costs for each type of test are then compared.

Requirements and Documentation. The first block of data is for meeting with the customer, determining their requirements, learning about the test item, handling the test item, any special safety requirements, preparing the test plan, preparing other safety documents such as the threat hazard analysis, and designing the test stand. This requires 29 man hours at a cost of $4,321 and is the same for both the liquid pool test and the propane test.

Pre-test Preparations. This section covers fabrication of the test fixtures, installing the fixtures into the burner, and setting up the thermocouples, blast overpressure gauges, and video cameras. For a liquid pool fire, the pan is inspected and any required repairs are made and fuel is delivered to the test site. For the liquid pool test, this requires 50 man hours for a cost of $7,450.

Test Execution. The test requires calm or very low wind speeds, as the test item must be engulfed in the flame until it reacts, and the fire is very susceptible to wind. The wind is usually at its lowest speed in the early hours of the morning before sunrise, and then builds as the sun rises which requires an early start time for the test. The instrumentation team makes final checks of the blast overpressure gauges, videos, and thermocouples. The test engineer and the test director monitor the wind speed and decide whether or not to conduct the test. The test item is brought out to the test site and put on the test stand. Thermocouples are installed two inches from the front, back, left, and right sides of the test item. (the new STANAG 4240 will require thermocouples also at the top and bottom). The only persons allowed to touch the test item on Dahlgren ranges are ones who have special qualifications and certifications for handling explosive items. There must also be a certified firing director and a certified lookout (safety observer) present. For tests in a liquid fuel fire, the ordnance handlers also install thermite grenades in the corner of the pit (required to ignite the liquid fuel). For liquid fuel fires, fuel must be transferred from a pumper truck into the pit. Once fuel transfer is complete, gasoline is poured in the corners as an accelerator to achieve the required rise rate of temperature on the test item. The test personnel retire to a shelter, and once instrumentation is confirmed to be ready, the test is conducted. After the test item reacts and the fire is completely out, test personnel must remain in shelter for an additional 30 minutes as a safety precaution. After the hold time has elapsed, the firing director and ordnance handlers go to the pit and confirm it will be safe for the others to come out to begin the post-test operations. This requires 63 man hours for a total cost of $9,387.

Post-test Activities. Fragments and debris from the test are located, collected, and catalogued as to range and bearing from the test stand. Their appearance and mass are also recorded and used in determining the violence of the reaction. The data collected by the instrumentation is analyzed and compiled as desired by the customer. The videos are also edited and exported to the test engineer. These materials are then further analyzed into a set of deliverables, including a final report that is supplied to the customer. These post-test costs are the same for both the propane and liquid pool test. These activities require 36 hours for a cost of $5,364.

Materials and Surcharges. There are fixed charges for fuel, technical writers, and the range control console operators that are billed to the test. Fuel makes up the bulk of the material cost of a liquid pool fire. Total costs for this section are $9,275.

Non-labor Costs. The cost of expendable items such as the firing leads, thermocouples, and test stand are billed to the test. The total is $995 per liquid pool test.

Total liquid fuel fire cost. The total cost of the example liquid fuel fire test in Table 16 is $36,791.

Propane Fire Costs. The pre-test requirements and documentation costs for the two types of fires are the same. The post-test activities are the same. However, there are significant differences in the pre-test preparation, test execution, and materials.

Changes in Pre-test Preparations. Part of the cost of the liquid fuel fire test is inspecting and repairing the water tight pit that holds the fuel. The pit is required to be water tight to ensure that fuel does not escape onto the ground. For the propane burner, pre-test preparations include moving the propane tank to the test site and connecting it to the burner supply lines, cleaning the burner tube ports, checking the pipe fittings for leaks, flowing propane through the system, and depending on how much time has lapsed since the previous test, a short checkout burn may also be conducted. The inspection and checkout of the propane burner requires half the labor of inspecting and repairing the liquid fuel pit, which saves $745 per test. A fuel delivery cost (8 hours of labor to deliver the fuel from Pax River) of $1,192 is also avoided resulting in a total pre-test savings of $1,937.

Changes in Test Execution. When testing with the propane burner, tests are less likely to be canceled due to weather since the test can be conducted very quickly once the test item is in place on the stand. This will save, on average, 6 man hours ($894) per test due to fewer test cancellations due to weather call. An additional 6 man-hours is saved by eliminating the time required to pump the fuel and wire and place the thermite grenades. Finally, 4 additional hours of labor are saved by eliminating the public works fuel truck driver to bring the liquid fuel to the test site on the day of the test. In total, this results in a savings of an additional 16 man hours per test for a total of $2,384.

Changes in Materials and Surcharges. For the liquid fuel fire, the test requires a quantity of fuel that will burn for 150% of the expected reaction time. Fuel quantities in the range of 2000 to 3000 gallons are normal with 2000 being used in this analysis. With the propane fuel fire, the burner can be shut off at any time. Therefore, once the test item reacts, the burner can be shut off, which saves a significant quantity of fuel per test. Liquid JP-5 fuel costs $3.50/gallon. This leads to a normal fuel expense of $7,000. A typical propane fast cook-off test can be performed using a single 500 gallon fuel tank. The current price delivered for the last test that was conducted was $0.99/gallon. One full tank would cost $500. This results in a fuel savings of $6,500 per test. As a final item, the firing leads used to initiate the thermite grenades are eliminated which saves $84 per test.

Table 16. Comparison of Per-test Costs of a Liquid Pool Fire vs the Propane Burner

Requirements & Documentation	People	hr/Day	Days	Labor Hours	Labor Cost($)	Propane	Savings
Customer interface & Requirements	1	4	1	4	$ 596.00	$ 596.00	$ -
Preparation of test plan(s)	1	4	1	4	$ 596.00	$ 596.00	$ -
Preparation of safety documents	1	8	1	8	$ 1,192.00	$ 1,192.00	$ -
Schedule coordination	1	4	1	4	$ 596.00	$ 596.00	$ -
Fixture design & procuremnt	1	2	1	2	$ 298.00	$ 298.00	$ -
Planning meeting(s) support	2	2	1	4	$ 596.00	$ 596.00	$ -
Review Test Plan	2	1	1	2	$ 298.00	$ 298.00	$ -
Review Test Plan	1	1	1	1	$ 149.00	$ 149.00	$ -
Subtotal				29	**$ 4,321.00**	$ 4,321.00	$ -
Pre-Test Preparations							
	People	hr/Day	Days	Labor Hours	Labor Cost($)		
On-site technical direction (range coordination)	1	4	1	4	$ 596.00	$ 596.00	$ -
Fabrication of fixtures/targets (range crew)	2	4	1	8	$ 1,192.00	$ 1,192.00	$ -
Pan Checkout and Setup	2	5	1	10	$ 1,490.00	$ 745.00	$ 745.00
Build up Thermocouples (4)	1	4	1	4	$ 596.00	$ 596.00	$ -
Set up gauges, cameras, and TCs	2	8	1	16	$ 2,384.00	$ 2,384.00	$ -
Fuel Delivery	1	8	1	8	$ 1,192.00	$ -	$ 1,192.00
Subtotal				50	**$ 7,450.00**	$ 5,513.00	$ 1,937.00
Test Execution							
	People	hr/Day	Days	Labor Hours	Labor Cost($)		
On-site technical direction	1	5	1	5	$ 745.00	$ 745.00	$ -
Weather Call	1	2	1	2	$ 298.00	$ 298.00	$ -
Lookout / firing director	2	4	1	8	$ 1,192.00	$ 1,192.00	$ -
Weather Call	7	2	1	14	$ 2,086.00	$ 1,192.00	$ 894.00
Test Setup (leaving during test)	5	2	1	10	$ 1,490.00	$ 596.00	$ 894.00
Ordnance Support during test	2	2	1	4	$ 596.00	$ 596.00	$ -
Weather Call	2	2	1	4	$ 596.00	$ 596.00	$ -
Instrumentation Setup	4	2	1	8	$ 1,192.00	$ 1,192.00	$ -
Instrumentation Support during test	2	2	1	4	$ 596.00	$ 596.00	$ -
Public works support	1	4	1	4	$ 596.00	$ -	$ 596.00
Subtotal				63	**$ 9,387.00**	$ 7,003.00	$ 2,384.00
Post Execution Activities							
	People	hr/Day	Days	Labor Hours	Labor Cost ($)		
Test Engineering							$ -
On-site technical direction	1	3	1	3	$ 447.00	$ 447.00	$ -
Quick-Look Report(s)	1	4	1	4	$ 596.00	$ 596.00	$ -
Engineer meeting with I.E.	1	2	1	2	$ 298.00	$ 298.00	$ -
Site/ mount cleanup (range personnel)	3	2	1	6	$ 894.00	$ 894.00	$ -
Equipment breakdown/storage	2	2	1	4	$ 596.00	$ 596.00	$ -
Film/video editing	1	4	1	4	$ 596.00	$ 596.00	$ -
CD/DVD reproduction (labor)	1	1	1	1	$ 149.00	$ 149.00	$ -
Data Analysis	1	6	1	6	$ 894.00	$ 894.00	$ -
I.E. Meeting with Test Engineer	1	2	1	2	$ 298.00	$ 298.00	$ -
Post-test ammo expenditure documentation	2	1	1	2	$ 298.00	$ 298.00	$ -
Test Engineer generates deliverables for I.E.	1	2	1	2	$ 298.00	$ 298.00	$ -
Subtotal				36	**$ 5,364.00**	$ 5,364.00	$ -
Materials and Surcharges							
Item			Unit Cost($	Qty	Cost ($)		
JP-5 fuel			3.5	2000	$ 7,000.00	$ 500.00	$ 6,500.00
Tech Writer (per document- TP, OPS, RHA)			605	3	$ 1,815.00	$ 1,815.00	$ -
Range Control (per range day)			460	1	$ 460.00	$ 460.00	$ -
					$ 9,275.00	$ 2,775.00	$ 6,500.00
Burdened Non-Labor Costs							
Item			Unit Cost ($)	Qty	Cost ($)		
Firing lead			60	1	$ 84.00	$ -	$ 84.00
Thermocouples (4)			100	4	$ 560.00	$ 560.00	$ -
Table Materials			250	1	$ 350.00	$ 350.00	$ -
					$ 994.00	$ 910.00	$ 84.00
				Total	**Liquid** $ 36,791.00	**Propane** $ 25,886.00	**Savings** $ 10,905.00

Total cost and Savings. The total cost of the example propane fast cook-off test depicted in Table 16 is $25,886 compared to $36,791 for a total per-test savings of $10,905.

Annualized Recurring Costs

The recurring costs of maintenance and regulatory compliance for the liquid fuel fast cook-off and the propane gas fuel fire are presented in Table 17. The annualized recurring cost for liquid fuel fire testing is $45,334 while the annualized recurring cost for testing with the propane burner is $8,784. Many costs are identical between the two systems such as anticipated repair costs per year and the cost to update and maintain safety documentation but the liquid pool fire does have some significant yearly costs that the propane burner does not. Environmental requirements to collect and analyze the containment area as well as the environmental reporting required total $5,483 per year. Maintaining the fuel delivery truck is also expensive, costing the test site $19,380 per year. Finally, the thermite grenades required to ignite the liquid pool fire and the associated ammo transfer fees that go along with them total $14,213 per year. This results in a total annualized recurring savings of $36,598.

Table 17. Annualized Recurring Costs

Item	Frequency	Liquid Fire	Cost/year	Gas Fire	Cost/year
Repair and replace expanded	1/per year	2 man days	$ 2,384	n.a.	$ -
metal grates		materials	$ 500		
Burner tube replacement	1/year	n.a.	$ -	2 man days	$ 2,384
				materials	$ 2,250
Repair wind screens	1/year	n.a.	$ -	2 man days	$ 2,384
				materials	$ 176
Propane tank rental	1/year	n.a	$ -	2- 500 gallon	$ 100
Liquid waste pump and haul	5 years			n.a.	$ -
Collect samples		4 man days	$ 954		
Labortory analysis		3 man days	$ 715		
Vendor contract		2 man days	$ 477		
Award contact		1 man day	$ 238		
Meet vender, transfer liquid		5 man days	$ 715		
Fuel Truck with Pump	1/year				$ -
Inspections		1 man day	$ 1,192		
NavFac CDL w Certs		8 man days	$ 9,536		
Minor Maintenance		6 man days	$ 7,152		
Parts			$ 1,500		
Maintenace of SOPs-Inert	4 years	2 man days	$ 596	2 man days	$ 596
Maintenace of SOPs-Energetic	4 years	3 man days	$ 894	3 man days	$ 894
Post test clean up w/hazmat	1/year	4 man days	$ 4,768	n.a.	$ -
Environmental reporting	1/year	2 man days	$ 2,384	n.a.	
Thermite grenades				n.a.	$ -
receive shipment	1/yr	$1250 ea	$ 1,250		
ammo transfer to EEA	2/year	$2500 ea	$ 5,000		
grenade unit cost	72/year	$34 ea	$ 2,448		
squib unit cost	72/year	$29 ea	$ 2,088		
requisitions(alocate, expend)	1/year	.5 man days	$ 745		
expenditure forms	1/test	1 man hr/test	$ 2,682		
	Total		**$ 45,334**	**Total**	**$ 8,784**

8.0 IMPLEMENTATION ISSUES

There is a temptation to use the gas output from the propane tank. This is the usual output for applications using propane tanks and it avoids multi-phase flow through the plumbing. Except for small burners (less than 1 m^2 (10 ft^2) of burner area), the flow through the gas outlet does not provide enough mass flow to produce the heat necessary for the required temperatures and heat fluxes. Also, the vaporization of the liquid propane within the tank causes a rapid decrease in the temperature of the tank. As the tank temperature decreases, the saturation pressure of the propane within the tank also decreases which further limits the mass flow rate of fuel leaving the tank. The liquid propane burner avoids this problem by using the heat of the flames to vaporize the propane within the burner tubes.

Liquid propane is a wonderful refrigerant. The temperature of saturated propane liquid at atmospheric pressure is -43 ^{o}C. Frost will form on the pipes where the propane is expanding, even in desert climates. Valves, screens, and other blockages can freeze and inhibit flow as the liquid propane expands and vaporizes.

If the burner is stored outside in-between tests and the test site experiences rain it is possible for the burner tubes to fill with water. Holes can be drilled on the bottom of the burner tubes at their ends to provide drainage of the rainwater.

The propane burner FCO technology has been implemented in two independent locations (Dahlgren, VA and China Lake, CA) with a large variation in climate. Currently STANAG 4240 is going through the international approval process for a revised version that approves and defines the necessary requirements of a propane burner. Connected to STANAG-4240 is AOP 4240, which will have a section on calibrating and qualifying a propane burner for use in the FCO test. Even before the complete NATO approval of STANAG-4240, the use of propane for FCO tests will be approved in the US once the US approves STANAG-4240. This approval is expected in FY2018.

Discussions with Eglin Air Force Base, Redstone Arsenal, and Picatinny Arsenal have occurred to discuss the building of a propane burner at those facilities. Initial contact has been made with Edwards Air Force Base and Tooele Army Depot. A DoD contractor, has already transitioned the technology for small-scale FCO testing. Bofors test range in Sweden used the test procedure in the draft AOP-4240 to calibrate and qualify their propane burner [40]. They were successful in their use of the AOP-4240 procedures and have a functional propane FCO burner. Discussions have also occurred with representatives of the UK and the Netherlands Ministry of Defense to transition this technology.

Early in the design phase of the project it was decided to utilize COTS parts wherever possible. The burner tubes are standard 2 inch galvanized steel pipe and the enclosure is made from galvanized steel flashing used in roofing. All of the controls are made from COTS parts as well with standard valves and fittings. For this reason, procurement and production was accomplished without issue. Drilling the holes into the pipes can be tedious if there is no automated method to do so. Water-jet drilling of the holes was an effective and fast method to produce the holes. Care needs to be found to choose valves that can handle the refrigerant nature of the propane liquid. However, there are COTS valves available that will work. Also, the valve at the bottom of the propane tank for the liquid feed often has a maximum flow regulator. This maximum flow regulator is often too restrictive to provide the needed mass rate and will need to be removed from the valve or a valve without a regulator will need to be installed. A US patent application has been filed for the propane burner developed.

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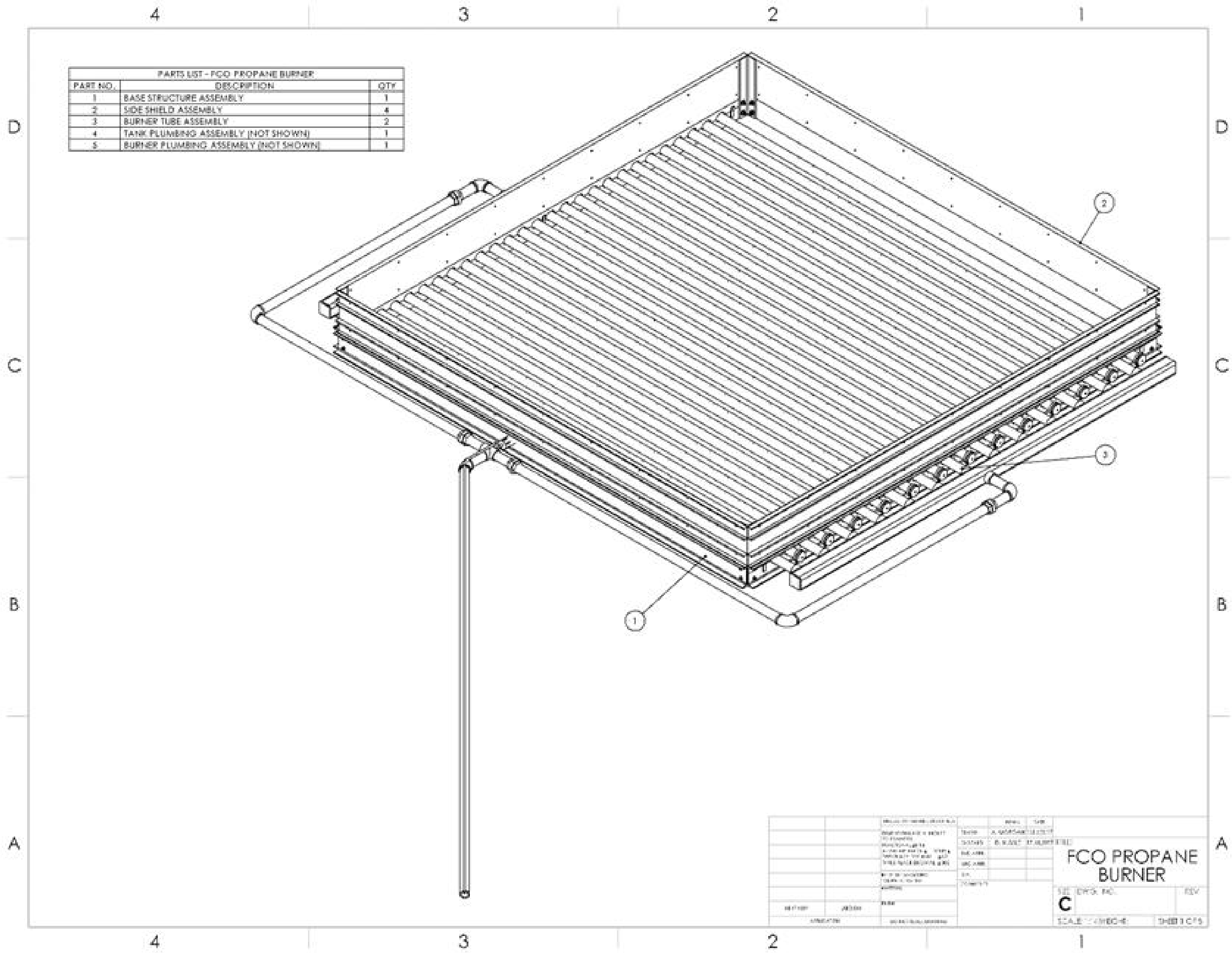
APPENDICES

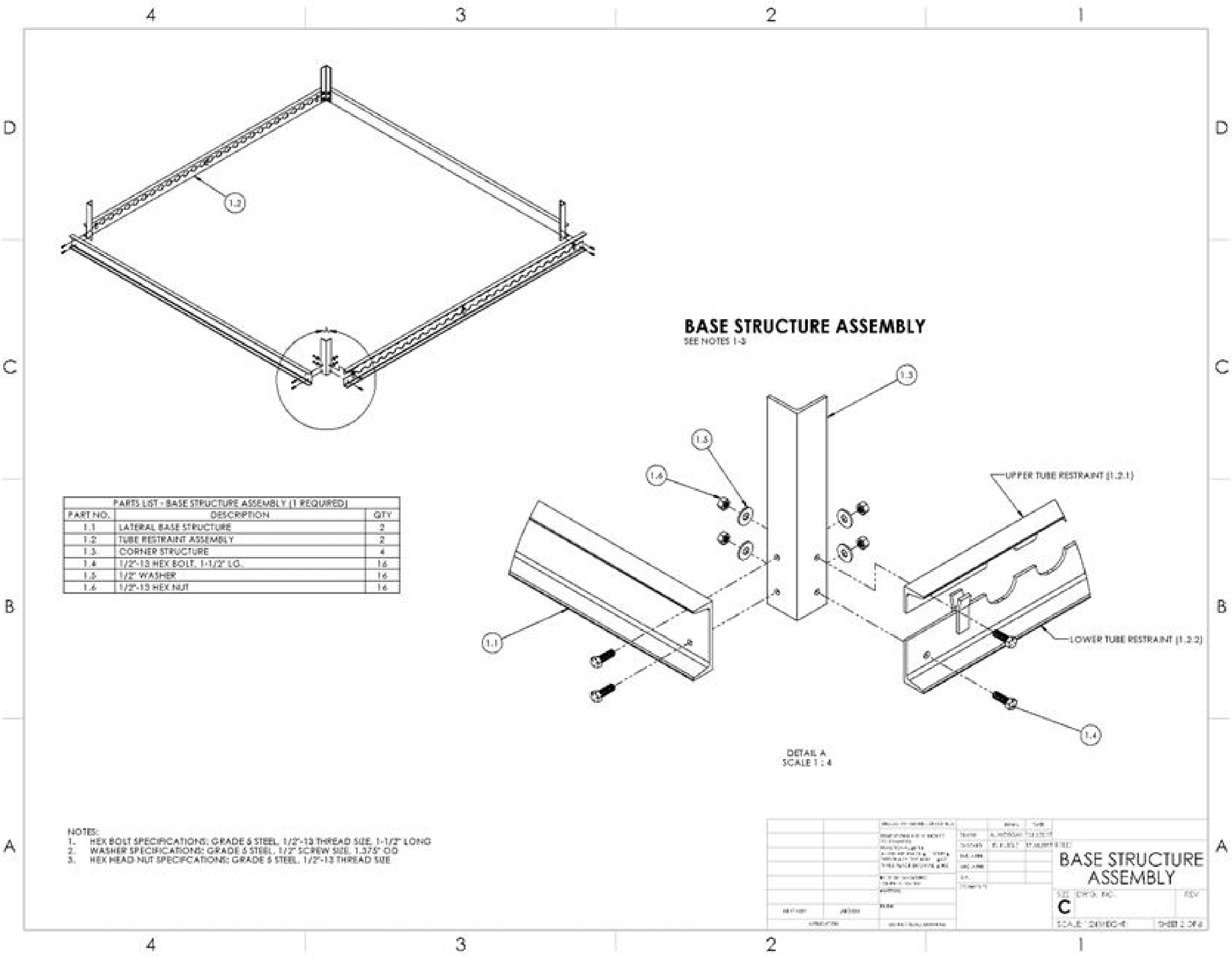
Appendix A: Points of Contact

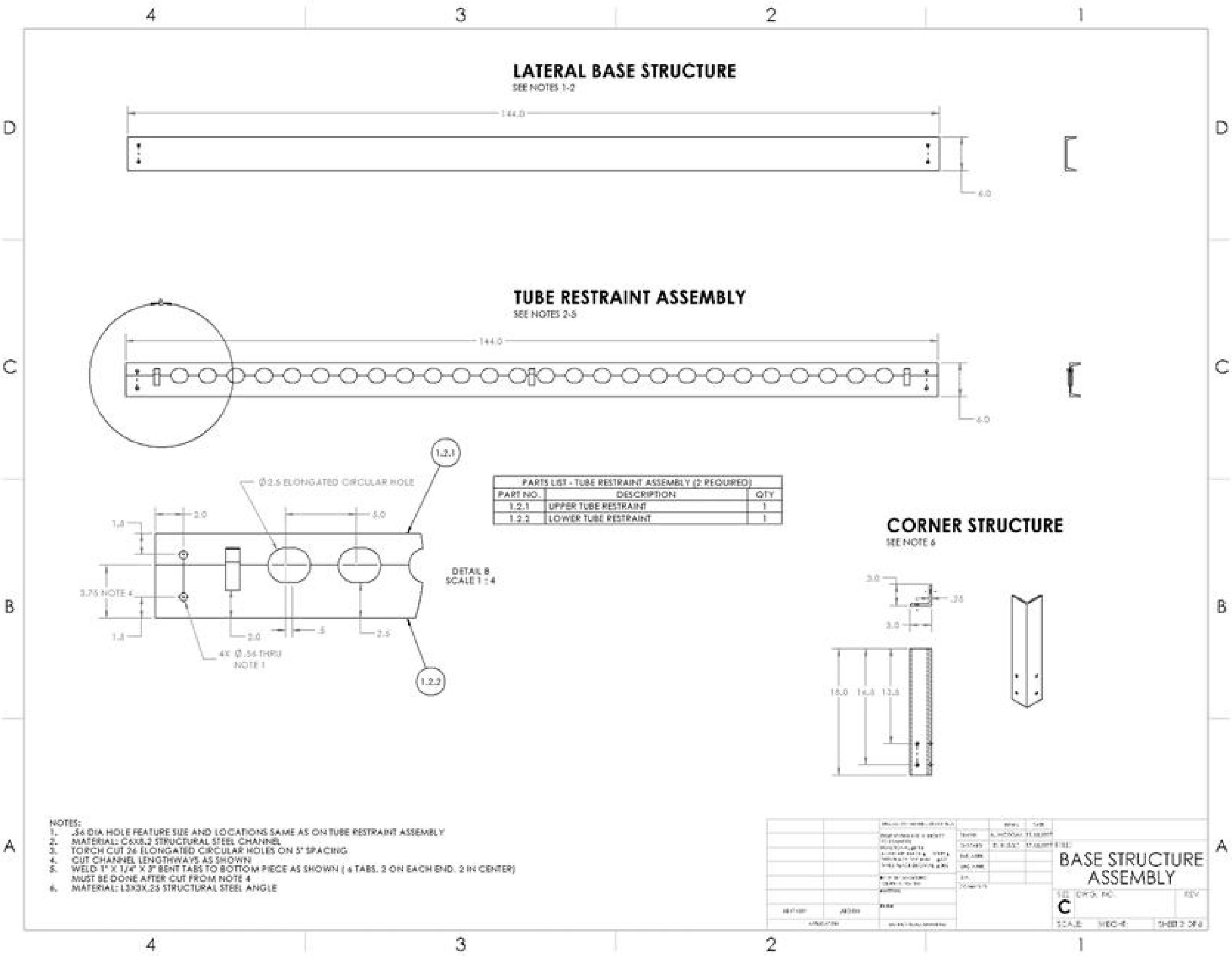
POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Ephraim Washburn	NAWCWD 1 Administrative Cir MS 6204 China Lake CA 93555	Phone: (760) 939-0684 Fax: (760) 939-2597 Ephraim.Washburn@navy.mil	Co-PI
David Hubble	NSWCDD 18236 Thompson Rd., Suite 230 Dahlgren VA 22448-5116	Phone: (540) 653-6450 David.O.Hubble@navy.mil	Co-PI
Jon Yagla	Bowhead Technical Services 18236 Thompson Rd., Suite 230 Dahlgren VA 22448-5178	Phone: (540) 653-7748 Jon.Yagla.ctr@navy.mil	Co-Investigator
Jeff Prevost	NAWCWD 1 Administrative Cir MS 5101 China Lake CA 93555	Phone: (760) 939-7218 Fax (760) 939-7621 jeffrey.prevost@navy.mil	Co-Investigator
Ross Falen	NAWCWD 1 Administrative Cir MS 5101 China Lake CA 93555	Phone: (760) 939-7562 Fax (760) 939-7621 ross.falen@navy.mil	Co-Investigator
Brian Gullett	U.S. Environmental Protection Agency Office of Research and Development National Risk Management Research Laboratory E343-04 Research Triangle Park, NC 27711	Phone: (919) 541-1534 gullett.brian@epa.gov	Co-Investigator
Jamie Fisher	AMRDEC Missile Sustainment Function WDI Directorate RDMR-WDP-M 2208 Britain Ave SW Redstone Arsenal, AL 35803-2039	Phone: (256) 876-5115 jamie.m.fisher2.civ@mail.mil	Army Advisor
Scott Allred	Marine Corps Systems Command 2200 Lester St Quantico VA 22134-5050	Phone: (703) 432-8756 scott.allred@usmc.mil	Marine Advisor
Stephen Struck	AFRL-Eglin Munition Directorate Air Force Research Laboratory Eglin AFB, FL 32542	Phone: (850) 882-3911 stephen.struck@us.af.mil	Air Force Advisor
Josephine Covino	DDESB Policy Development Division	Phone: (571) 372-6685 Fax: (571)372-6752	DDESB Advisor

	DoD Explosives Safety Board SUITE 16E12 4800 MARK Center Drive Alexandria, VA 22350-3606	Josephine.Covino.civ@mail.mil	
Greg Little	NSWCDD Navy IMAD Ordnance Technology Coordinator 6138 Norc Ave, Suite 314 Dahlgren VA 22448-5157	Phone: (540) 653-0187 greg.little@navy.mil	IMAD Rep
Daniel Zaloga	U.S. Army Armament Research, Development and Engineering Center Picatinny Arsenal, NJ	Phone: (973) 724-2980 Fax: (973) 724-7117 daniel.l.zaloga.civ@mail.mil	Contact For Donated Test Ordnance Items

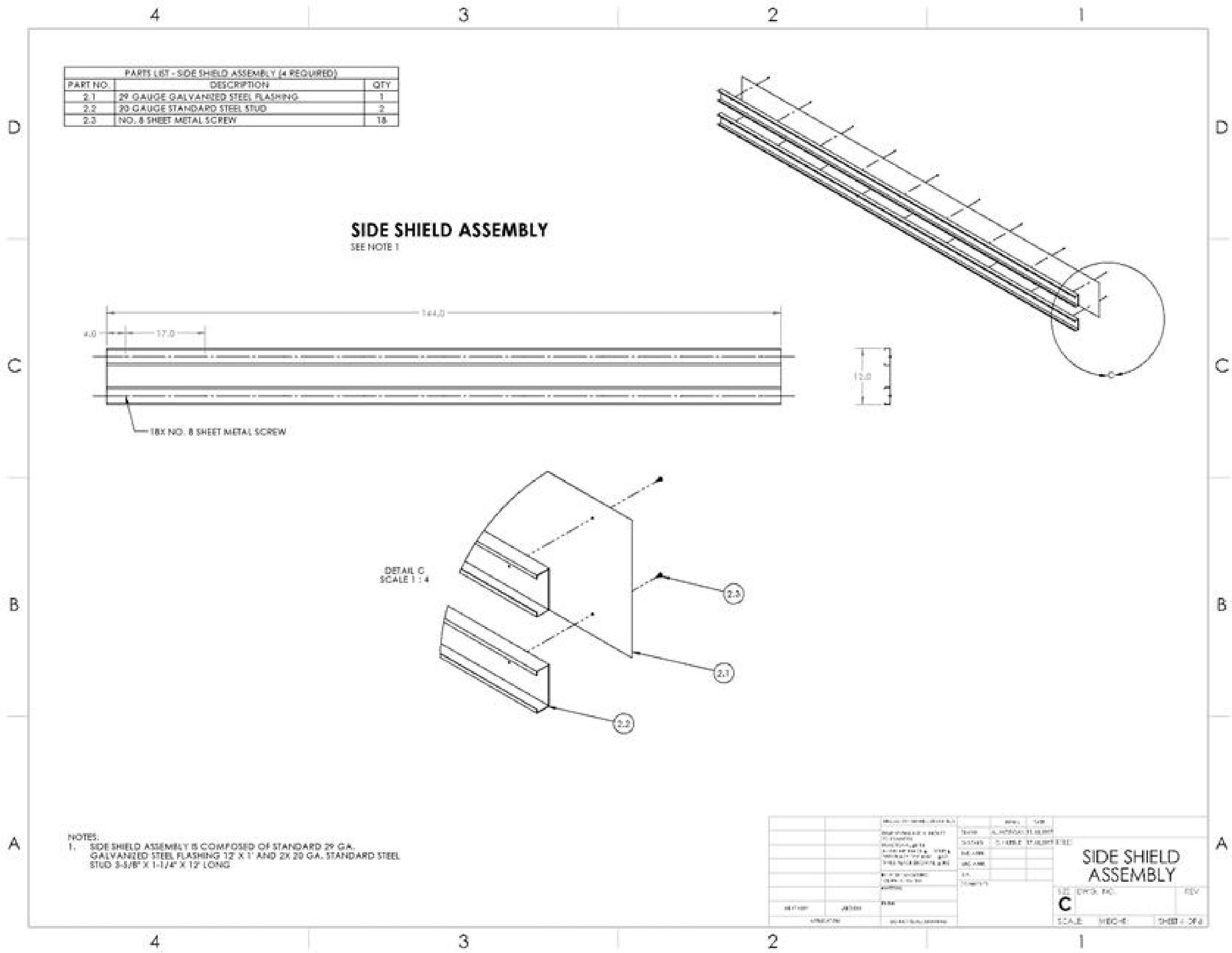
Appendix B: Technical Drawings



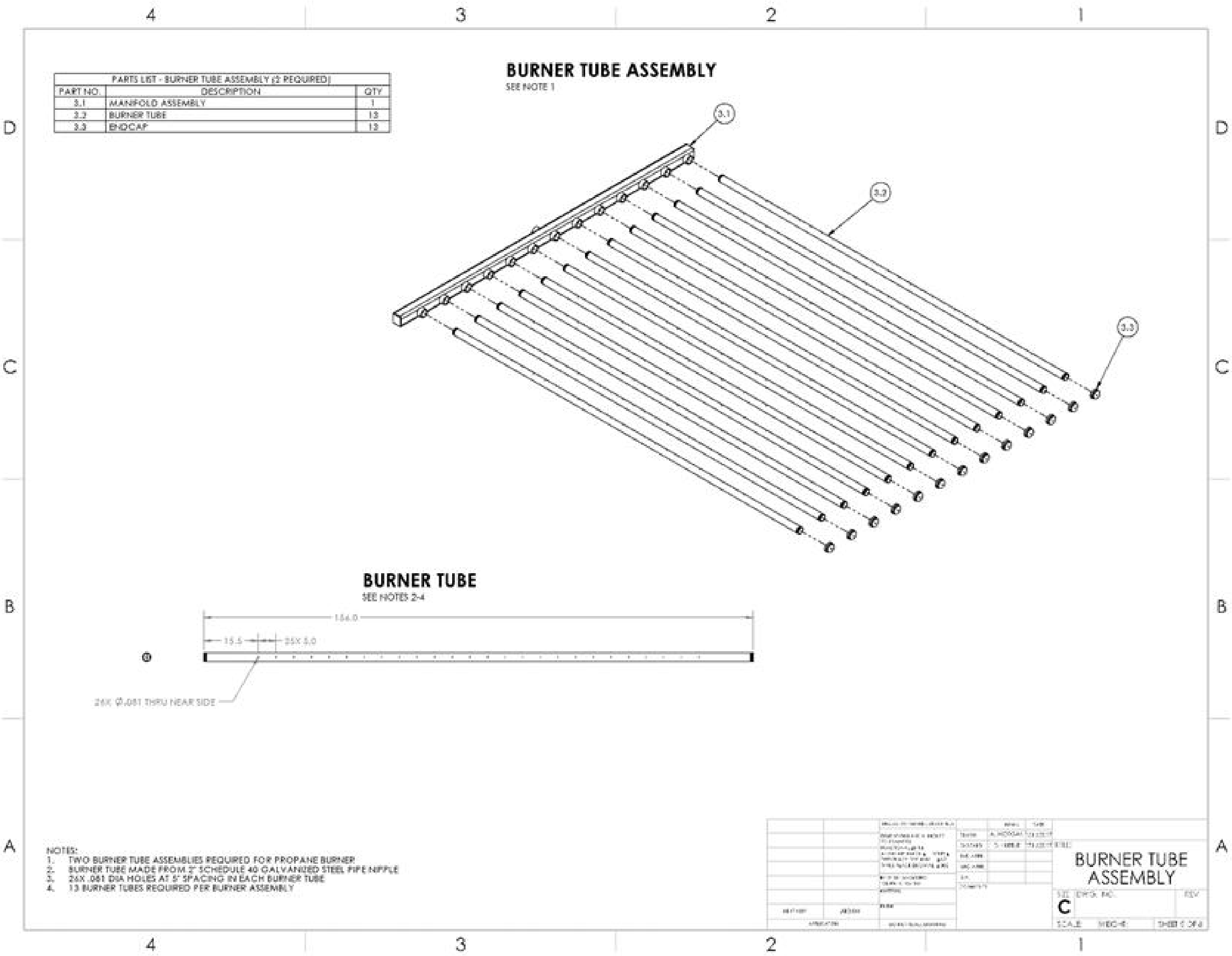

BASE STRUCTURE ASSEMBLY
SEE NOTES 1-3
1.1
1.2
1.3
1.4
1.5
1.6
UPPER TUBE RESTRAINT (1.2.1)
LOWER TUBE RESTRAINT (1.2.2)
DETAIL A
SCALE 1 : 4
PARTS LIST - BASE STRUCTURE ASSEMBLY (1 REQUIRED)
PART NO. | DESCRIPTION | QTY
1.1 | LATERAL BASE STRUCTURE | 2
1.2 | TUBE RESTRAINT ASSEMBLY | 2
1.3 | CORNER STRUCTURE | 4
1.4 | 1/2"-13 HEX BOLT, 1-1/2" LG. | 16
1.5 | 1/2" WASHER | 16
1.6 | 1/2"-13 HEX NUT | 16
NOTES:
1. HEX BOLT SPECIFICATIONS: GRADE 5 STEEL, 1/2"-13 THREAD SIZE, 1-1/2" LONG
2. WASHER SPECIFICATIONS: GRADE 5 STEEL, 1/2" SCREW SIZE, 1.375" OD
3. HEX HEAD NUT SPECIFCATIONS: GRADE 5 STEEL, 1/2"-13 THREAD SIZE
BASE STRUCTURE
ASSEMBLY
C

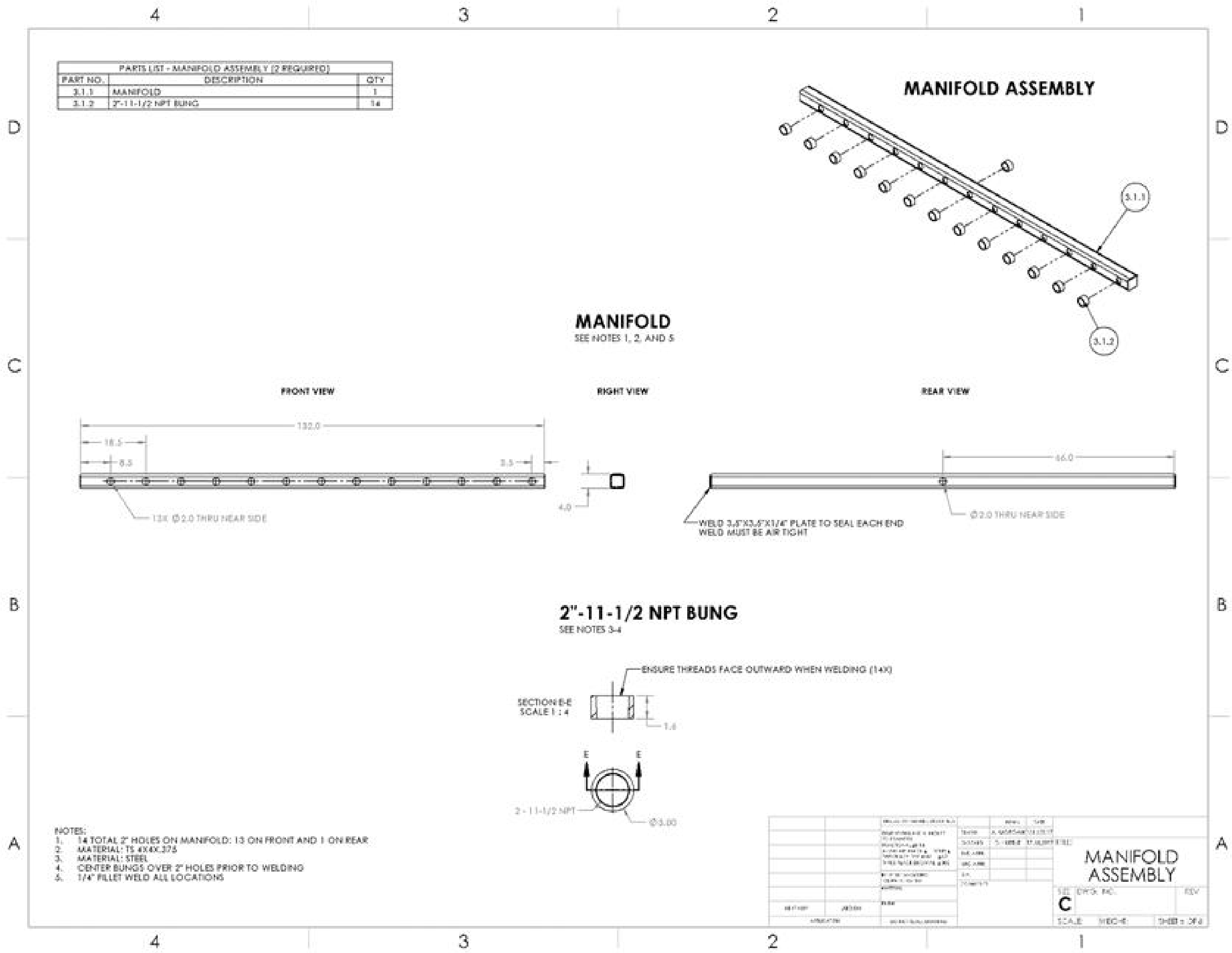


PARTS LIST - TUBE RESTRAINT ASSEMBLY (2 REQUIRED)		
PART NO.	DESCRIPTION	QTY
1.2.1	UPPER TUBE RESTRAINT	1
1.2.2	LOWER TUBE RESTRAINT	1

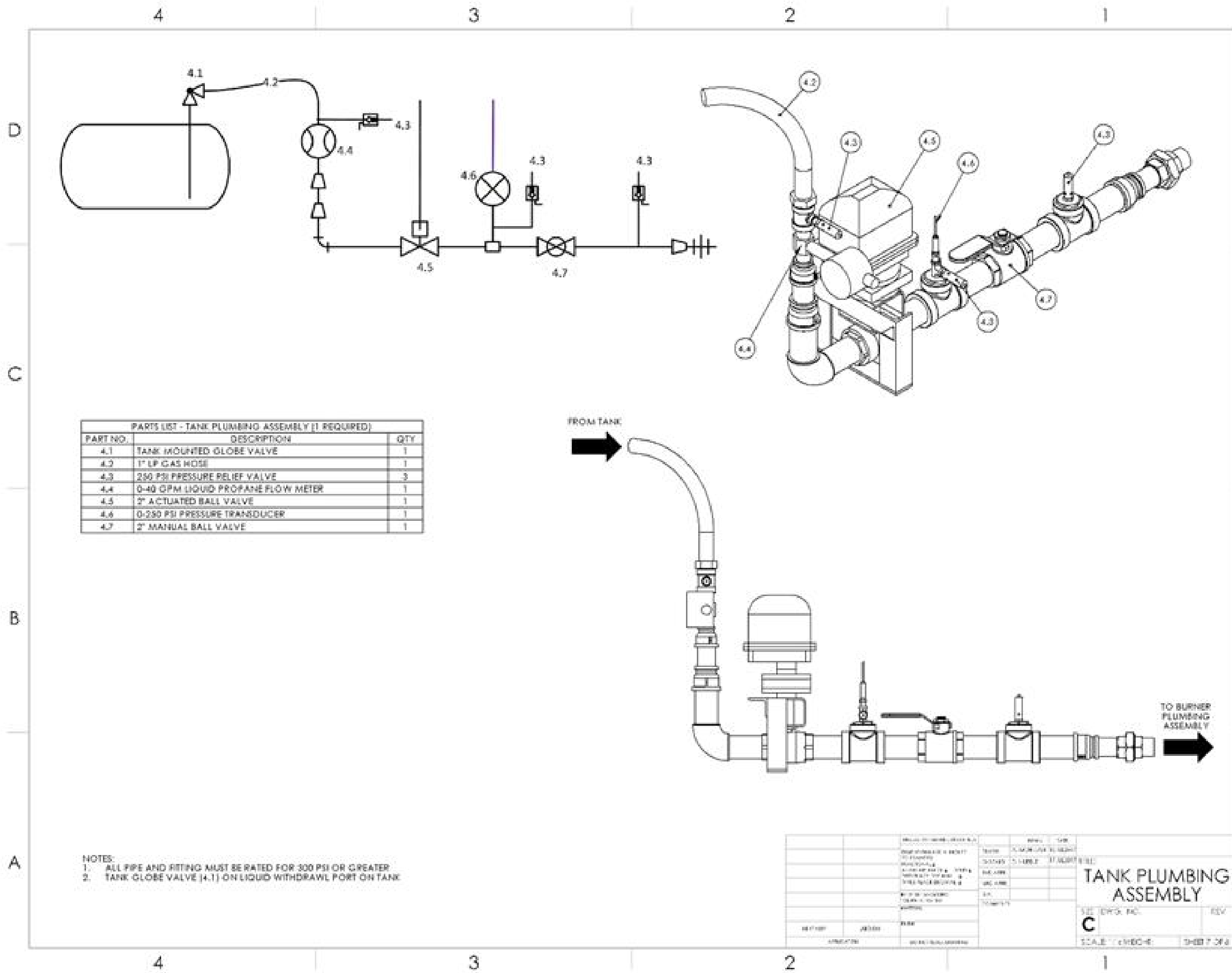


PARTS LIST - SIDE SHIELD ASSEMBLY (4 REQUIRED)
PART NO. | DESCRIPTION | QTY
2.1 | 29 GAUGE GALVANIZED STEEL FLASHING | 1
2.2 | 20 GAUGE STANDARD STEEL STUD | 2
2.3 | NO. 8 SHEET METAL SCREW | 18
SIDE SHIELD ASSEMBLY
SEE NOTE 1
144.0
4.0
17.0
12.0
18X NO. 8 SHEET METAL SCREW
C
DETAIL C
SCALE 1 : 4
2.1
2.2
2.3
NOTES:
1. SIDE SHIELD ASSEMBLY IS COMPOSED OF STANDARD 29 GA. GALVANIZED STEEL FLASHING 12' X 1' AND 2X 20 GA. STANDARD STEEL STUD 3-5/8" X 1-1/4" X 12' LONG
SIDE SHIELD ASSEMBLY
C

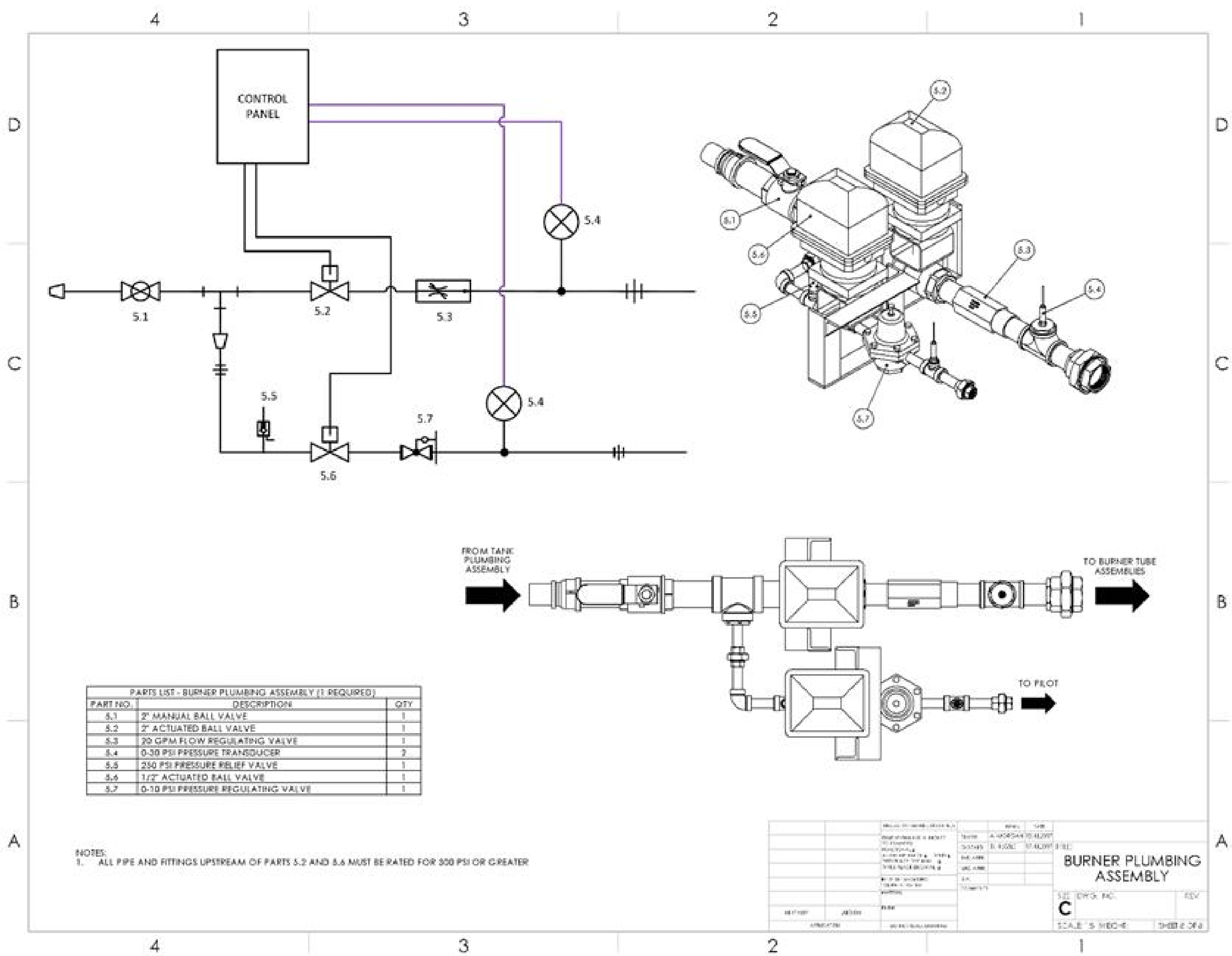

PARTS LIST - BURNER TUBE ASSEMBLY (2 REQUIRED)
PART NO.
DESCRIPTION
QTY
3.1
MANIFOLD ASSEMBLY
1
3.2
BURNER TUBE
13
3.3
ENDCAP
13
BURNER TUBE ASSEMBLY
SEE NOTE 1
3.1
3.2
3.3
BURNER TUBE
SEE NOTES 2-4
156.0
15.5
25X 5.0
26X Ø.081 THRU NEAR SIDE
NOTES:
1. TWO BURNER TUBE ASSEMBLIES REQUIRED FOR PROPANE BURNER
2. BURNER TUBE MADE FROM 2" SCHEDULE 40 GALVANIZED STEEL PIPE NIPPLE
3. 26X .081 DIA HOLES AT 5" SPACING IN EACH BURNER TUBE
4. 13 BURNER TUBES REQUIRED PER BURNER ASSEMBLY
BURNER TUBE
ASSEMBLY
C



PARTS LIST - MANIFOLD ASSEMBLY (2 REQUIRED)
PART NO. | DESCRIPTION | QTY
3.1.1 | MANIFOLD | 1
3.1.2 | 2"-11-1/2 NPT BUNG | 14
MANIFOLD ASSEMBLY
3.1.1
3.1.2
MANIFOLD
SEE NOTES 1, 2, AND 5
FRONT VIEW
RIGHT VIEW
REAR VIEW
132.0
18.5
8.5
8.5
4.0
66.0
13X Ø2.0 THRU NEAR SIDE
Ø2.0 THRU NEAR SIDE
WELD 3.5"X3.5"X1/4" PLATE TO SEAL EACH END
WELD MUST BE AIR TIGHT
2"-11-1/2 NPT BUNG
SEE NOTES 3-4
ENSURE THREADS FACE OUTWARD WHEN WELDING (14X)
SECTION E-E
SCALE 1 : 4
1.6
E
E
2 - 11-1/2 NPT
Ø3.00
NOTES:
1. 14 TOTAL 2" HOLES ON MANIFOLD: 13 ON FRONT AND 1 ON REAR
2. MATERIAL: TS 4X4X.375
3. MATERIAL: STEEL
4. CENTER BUNGS OVER 2" HOLES PRIOR TO WELDING
5. 1/4" FILLET WELD ALL LOCATIONS
MANIFOLD
ASSEMBLY
C



PARTS LIST - TANK PLUMBING ASSEMBLY (1 REQUIRED)		
PART NO.	DESCRIPTION	QTY
4.1	TANK MOUNTED GLOBE VALVE	1
4.2	1" LP GAS HOSE	1
4.3	250 PSI PRESSURE RELIEF VALVE	3
4.4	0-40 GPM LIQUID PROPANE FLOW METER	1
4.5	2" ACTUATED BALL VALVE	1
4.6	0-250 PSI PRESSURE TRANSDUCER	1
4.7	2" MANUAL BALL VALVE	1



PARTS LIST - BURNER PLUMBING ASSEMBLY (1 REQUIRED)		
PART NO.	DESCRIPTION	QTY
5.1	2" MANUAL BALL VALVE	1
5.2	2" ACTUATED BALL VALVE	1
5.3	20 GPM FLOW REGULATING VALVE	1
5.4	0-30 PSI PRESSURE TRANSDUCER	2
5.5	250 PSI PRESSURE RELIEF VALVE	1
5.6	1/2" ACTUATED BALL VALVE	1
5.7	0-10 PSI PRESSURE REGULATING VALVE	1

NOTES:
1. ALL PIPE AND FITTINGS UPSTREAM OF PARTS 5.2 AND 5.6 MUST BE RATED FOR 300 PSI OR GREATER