Energetic Material Fast Cookoff Testing in a Propane-Fueled Burner

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Abstract

The liquid-fuel fire test consists of exposing a full-scale ordnance item in a liquid-fuel fire to assess the violence of reaction and susceptibility of the item to a fire that may result from an accident due to transportation, storage, and/or a mishap on the deck of an aircraft carrier. However, increasing environmental concerns with respect to air quality and 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 paper documents the initial demonstration and validation of 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. Different munitions with varying sensitivity of energetic materials were subjected to the propane burner fire. The time to reaction, reaction violence, and other quantifiable test results were compared with kerosene-based fuel fire tests with the same ordnance and test configuration. 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.

Introduction

All military munitions or energetic compounds must pass a liquid-fuel fire test. The test exposes full-scale ordnance in a liquid-fuel fire and assesses the violence of reaction and susceptibility of the item to fire that 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 (References 1 and 2). The STANAG designates the use of kerosene-based liquid-hydrocarbon fuels, such as JP-4, JP-5, Jet-A1, AVCAT, or commercial kerosene. The ordnance item is suspended or positioned 1 meter above the fuel. The fuel is ignited, and the fire must burn for at least 150% of the ordnance item's reaction time (Reference 3). The response of the item 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 fragment throw. 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.

Figure 1 shows a photograph of a fast cookoff test with a kerosene-based-fuel pool fire. One of the environmental concerns with the liquid-fuel fire test is the pollutant emissions. A single liquid-fuel fire test will emit over 400 pounds of CO, 70 pounds of NOx, 60 pounds of SOx, 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 (References 4 through 7).

Figure 1. Fast Cookoff Test with Kerosene Based Fuel**.**

Furthermore, contamination of the soil and water from the fuels used in the external fire and fast cookoff 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 to soils. Groundwater could be contaminated through this pathway. 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. In addition, PAHs may have long-term health effects, including changes in the liver as well as negative effects on the kidneys, heart, lungs, and nervous system (Reference 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. 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 (Reference 9). These increasing environmental concerns have led to considering propane as the alternative to liquid-kerosene fuels.

A cleaner, more controlled, and more reproducible option for the liquid-fuel pool fire is a propane burner. Propane is a well-studied and easily accessible fuel. Propane is stored as a pressurized liquid and offers greater energy-density and ease of transport compared to gaseous fuels. As the propane is vented to atmospheric pressure, it is vaporized creating a combustible vapor.

Propane is a gas at atmospheric pressure and temperature and will not pollute groundwater. It is cleaner burning than jet fuel. The propane burner will operate cleaner than kerosene-based fires with 75% less soot. 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. Propane also offers greater combustion efficiency compared to larger hydrocarbons. It is also easier to acquire compared to many kerosene-based fuels. A liquid-propane burner compared to a pool fire can be turned off after the ordnance item reacts, further reducing pollution emissions and saving thousands of dollars per test in fuel costs. With proper design, the test setup is inexpensive and easy to manufacture, making rebuilding of the burner easy after a violent reaction. Another possible option is to create a design that is scalable and can test small or large items.

Burner Description

The propane-fueled fast cookoff burner is a 12-foot by 12-foot square burner containing 26 burner tubes. An overview of the burner is shown in Figure 2. On each side of the burner, a manifold feeds 13 burner tubes from the center out. This arrangement, along with the fact that the burner tubes alternate the side from which they are fed, results in a uniform flow of fuel within the burner. Underneath the burner there exists a patio constructed from refractory bricks above a 1-inch-thick steel plate. The fire bricks insulate and protect the plate and prevent it from distorting during a test.

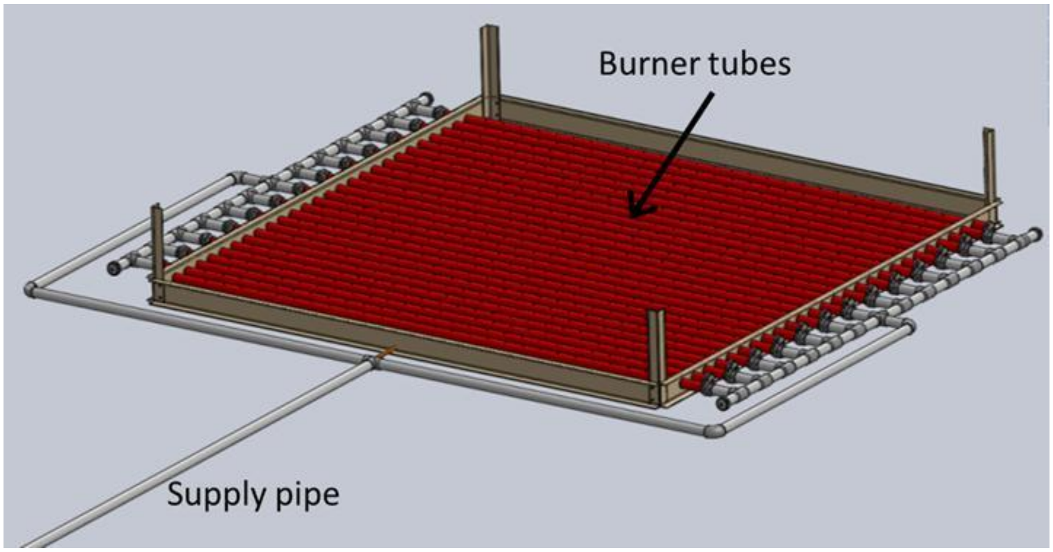


Figure 2. Overview of Propane Fast Cookoff Burner.

The burner is designed to be easily repaired in the event that it is damaged when testing energetic items. All the burner tubes are installed using unions that allow them to be removed individually without unnecessary disassembly. To remove a damaged burner tube, the top half of the burner tube mount is removed on both sides by removing two bolts. The union on the affected burner tube is then loosened, the burner tube is removed, and a new tube is installed in its place. The top halves of the two tube mounts are re-installed, and the burner is once again operational. For a more detailed description of the burner design, fuel delivery system, and characterization of the burner, the reader is referred to Reference 10.

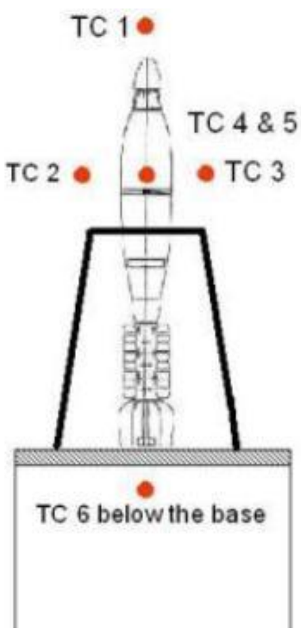
Testing

The propane burner was used to test the reaction of ordnance items in a fast cookoff situation. The desire of the testing was to show the following:

1) Reduction of fuel usage
2) Equal scoring of ordnance item tested
3) Ease of test setup and burner repair

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 second explosive fill was 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 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 (Reference 11). The schematic in Figure 3a is the test setup for the liquid pool fire test. The photograph in Figure 3b shows the test setup for the 81-mm mortar fast cookoff with the propane burner. The objective was to be as similar as possible.



(a)


(b)

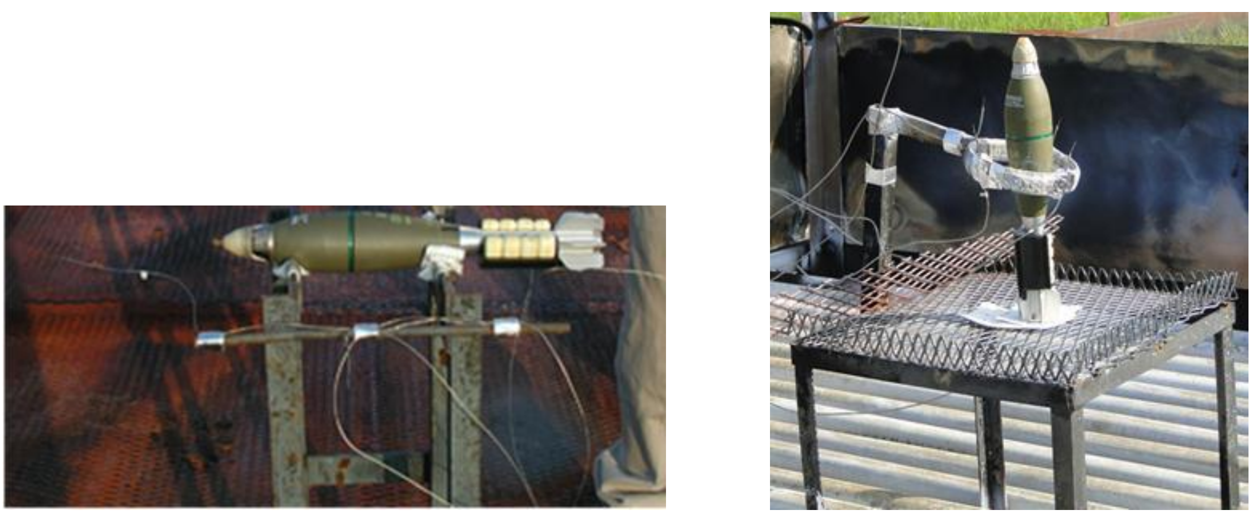
Figure 3. 81-mm Mortar With IMX-104 Explosive Fill Fast Cookoff Test Setup.
(a) Jet-A Pool Fire, (b) Propane Fire.

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 4. 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 4. 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 (Reference 12). The photograph in Figure 5a is the test setup for the liquid pool fire test. The photograph in Figure 5b 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.

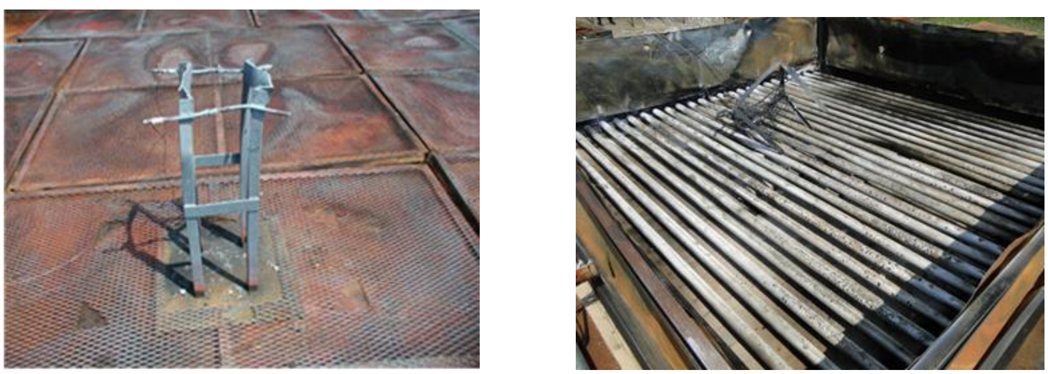


(a) (b)

Figure 5. 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 6. 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. Fragments from the item damaged three of the pipes in the propane burner by creating large holes. The burner still functioned for the rest of the test, and it took less than an hour to change out the damaged pipes for further testing.

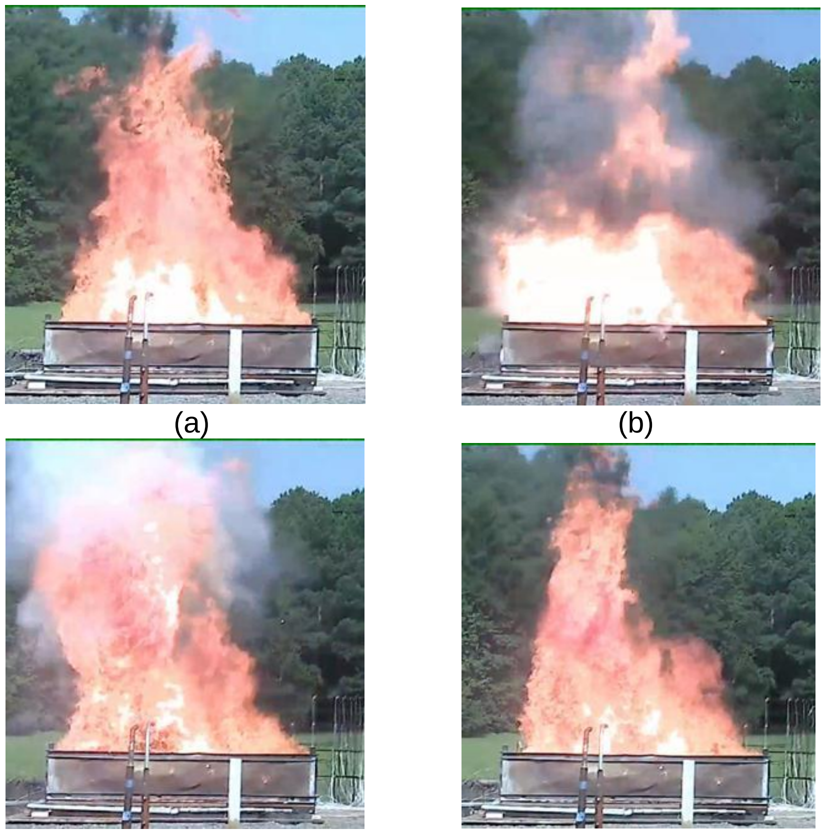


(a) (b)

Figure 6. Post-Test Photograph of 81-mm Mortar with CompB Explosive Fill Fast Cookoff Test. (a) Jet-A Pool Fire, (b) Propane Fire.

Figure 7 shows the propane fire during the test with the 81-mm mortar with CompB explosive fill. Figure 7 shows the propane burner just before the violent reaction. Comparing the photograph in Figure 7a to the photograph in Figure 1, 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, however, the flame is luminous and completely surrounds the test stand and item. The luminous flame will provide the necessary radiation to heat up the test article. In Figure 7b, the second reaction had just occurred leaving black smoke surrounding the flame. In Figure 7c, the smoke from the reaction is dissipating. In Figure 7d, the flame has returned to a pre-reaction state. The time between Figure 7a to Figure 7d is 3 seconds. The violent reaction had damaged three of the pipes, but the burner still had a consistent engulfing flame.

Figure 8 is a photograph from the same test as Figure 5. Figure 8 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 observe visually the reaction of the item.



(a) (b) (c) (d)

Figure 7. Photographs of Propane Fire Showing Sequence of Violent Event with 81-mm Mortar with CompB Explosive Fill.

Figure 8. 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. Figure 9 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 9 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.

(a)

(b)

Figure 9. Photographs Showing Ignition Process at 2 Seconds,
10 Seconds, 20 Seconds, and 40 Seconds after Ignition.
(a) Kerosene-Based Pool Fire, (b) Propane Fire.

Table 1 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. This occurred from the ability to turn off the fuel after a reaction. 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. 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 1. Summary of Results.

Test	Fuel type	Fuel quantity	Time to reaction	Average flame temperature	IM score
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*

Conclusions

Ordnance items were tested in both kerosene-based fuel pool fires and propane fires in the same configurations. The time to reaction, reaction violence, and other quantifiable test results of the test items in the propane fires were compared with kerosene-based fuel pool fire tests. The propane fuel fire used 7 to 15 times less fuel than the kerosene-based fuel pool fires. The times to reactions of the same item in the two types of fuel fires were comparable. The observed reaction violence appeared to be the same between the tests. After the violent reaction in the propane fire, the burner repair was minimal. The propane fuel fire burner established a steady-state consistent flame faster than the kerosene-based fuel pool fire, and the propane fuel fire visibly emitted almost no black soot while the kerosene-based fuel pool fire emitted large billowing clouds of black soot. 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.

Acknowledgments

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