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CORRELATION OF LABORATORY FLAME PROPAGATION TESTING RESULTS WITH BALLISTIC TESTING UTILIZING SEVERAL THREATS WITH VARYING EXPLOSIVE

INTERIM REPORT
TFLRF No. 410

by
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U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Allen S. Comfort
Luis A. Villahermosa

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. DAAE-07-99-C-L053 (WD38)

September 2011

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14. ABSTRACT

Typical results obtained from ballistic impacts on vehicular fuel tanks are an instantaneous fireball, lasting approximately 5 seconds followed by a quickly spreading pool fire consuming the balance of the fuel and causing catastrophic damage to personnel and vehicle. This report discusses the results obtained when attempts were made to correlate a laboratory procedure with full scale ballistic testing. Laboratory testing was conducted at fuel temperature of 150°F which corresponds to similar ballistic test temperature. The laboratory procedure determined only flame propagation rates and was not designed to address the fireball issue.

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EXECUTIVE SUMMARY

During an Army research program in the Mid-1980's, Southwest Research Institute (SwRI) developed a fire-resistant diesel fuel that would self extinguish when ignited by an explosive projectile. This fire resistant fuel (FRF) was composed of a stable mixture of diesel fuel, 10% water, and an emulsifier. The research program ended in 1987 without the FRF blend being fielded due to several reasons, including some technical problems. Recently, due to the conflicts in Iraq and Afghanistan, there has been a renewed interest in FRF development. The Army research program was restarted to continue development of FRF, with a redefined scope to include the development of FRF using JP-8, known as the "One Fuel Forward", which was Jet-A with several additives to enhance diesel engine performance.

This research was conducted to evaluate a previously developed laboratory procedure with ballistic testing currently being conducted. Controlling factors included flashpoint of test fuels with test temperature of ballistic testing. The results obtained indicated a reasonably good correlation between flame propagation of the fuels used in this series of test.

The controlling factor was, as expected, the flash point of the test fuels and fuel test temperature. There was a clear indication of the effects of ignition energy since the flame trough ignition source was the fuel wetted wick and the ballistic impact included not only, the ballistic ignition fragments but also the instantaneous fireball that developed over the spilled fuel.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period January 2008 through September 2011 under Contract No. DAAE-07-99-C-L053. The U.S. Army Tank-Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Luis Villahermosa (AMSTA-RBFF) served as the TARDEC contracting officer's technical representative.

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ACRONYMS AND ABBREVIATIONS

AMA	anti-mist agent
FRF	fire resistant fuel
HC	hydrocarbon
NOx	oxides of nitrogen
ppm	parts per million
SwRI®	Southwest Research Institute
TARDEC	Tank Automotive Research and Development Command
TFLRF	U.S. Army TARDEC Fuels and Lubricants Research Facility

1.0 INTRODUCTION

The loss of life and equipment as a result of hostilities in Iraq and Afghanistan from a series of threats has escalated the research to develop methods to reduce or eliminate these hazards from fuel fires. Approaches being pursued include up-armoring of combat vehicles, development of personal armor and reduction of fuel-fed fires. Among the areas of research is a program to eliminate the fires that occur when fuel systems are penetrated by some explosive or projectile. Research has been conducted in recent years to develop a fuel with reduced vulnerability. Several approaches were investigated including fuel thickness and fuel comprised of water/surfactant forming a fuel emulsion. The scope of this report is to present the results obtained when using a laboratory test fixture to predict the fuel response when struck by a ballistic round.

This report presents results of essentially two different approaches to understanding/predicting fuel flammability hazards. The results of flame propagation studies of three separate fuels whose flashpoints (FP) are related to fuel classification: Jet-A/JP-8; JP-5, and diesel fuels. The second series of flame propagation studies were conducted of 12 different, randomly selected fuels with varying chemistry and flashpoints. This series also reports the propagation results of fuels blended and used as fire resistant fuels in ballistic testing.

2.0 DISCUSSION

2.1 PHYSICAL PROPERTIES OF FUELS AND THEIR RELATIONSHIP TO FLAME PROPAGATION

2.1.1 Hydrocarbon

Fuels are rather complex blends of a variety of hydrocarbons, i.e.; paraffins, olefins, aromatics, and naphthenics. Because of the chemical complexity of fuels, they are classified on the basis of their physical properties. Turbine engine and diesel fuels are placed in two broad categories, which are based on their distillation temperature ranges. Primarily, the differences between any of these fuels are due to the relative proportions of the hydrocarbon constituents.

2.1.2 Fuel Volatility Flammability

Fuel volatility flammability is primarily a process involving vapors. For example, in the burning of a fuel droplet, three distinct phases occur. In the first stage the droplet is preheated to a point where sufficient vapors are evolved to support a flame. In the second stage, the heat from the enveloping flame causes fuel vapors to evolve continuously and feed the flame. In the final stage, the combustion of a cokelike residue may occur. Fuel volatility is one of the primary characteristics that relate to fuel flammability. Those specification properties which are a measure of volatility are: flashpoint, distillation range, and vapor pressure. These are the primary properties that are inferred when differences in flammability are determined for one fuel in comparison with another.

2.1.3 Flash Point

The flashpoint is an estimate of the minimum temperature at which sufficient vapor is released by the fuel to form a flammable vapor-air environment at one atmosphere pressure. For pure hydrocarbons, such as n-alkanes, flashpoint data have been successfully correlated with lean flammability limits as well as vapor pressures. However, because of experimental errors, apparatus effects and fuel fractionation, flashpoint data for fuels lose a good deal of their fundamental significance. The usefulness of flashpoints with respect to fuels may be limited to establishing relatively large flammability differences between fuels.

2.1.4 Vapor Pressures

Vapor pressure affects flammability by controlling the amount of fuel in the vapor space. In a fuel tank which is only partially filled with fuel, the fuel molecules escape from the liquid into the space above it. If it is a closed vessel, the space is limited and the molecules will steadily accumulate in the vapor space. As the number of molecules increase in the space, the number of molecules returning to the liquid increases accordingly. If the temperature is maintained constant, a condition of equilibrium becomes established when the number of molecules leaving the liquid equals the number of molecules returning. The pressure which the liquid molecules exert in the vapor space is the vapor pressure.

2.1.5 Incendiary Ignitions

Fuel tank ignitions by incendiary particles are of particular concern wherever gun firing may be encountered, such as in a hostile environment. The energy flux provided by this type of heat source is far greater than that of most hot surface sources. The burning incendiary particles can produce temperatures of the order of 4000°F or more. Thus, incendiary ignitions of optimum fuel vapor-air mixtures would usually be expected to have extremely short ignition delays, e.g., a few milliseconds or even less. Furthermore, the ignitions can occur at multiple sites in a fuel tank, depending upon the extent that the incendiary particles are dispersed.

2.2 FLAME TROUGH PROPAGATION RATES BASED ON FLASHPOINT

2.2.1 Base Fuels Only

Results of flame propagation tests, reported in Table 1 indicate that the flame, at fuel temperature either ambient or heated above their flashpoints, spreads across a liquid surface faster for the lower flashpoint fuel. This procedure, illustrated in Figure 1, was developed at U.S. Army TARDEC, and utilizes a temperature-controlled fluid trough 3 in. x 36 in. x 0.5 in. deep (76 mm x 914 mm x 13 mm). The ignition source is a fuel soaked lighted wick positioned approximately 0.5 inch (13 mm) from one end of the trough. Following wick ignition with a match, a period of time is generally required for the ignition source to heat the fuel prior to flame propagation. The wick in this procedure is thought to provide a low heat flux and is therefore effective in demonstrating small differences in flammability characteristics between two fuels. The results are reported in: (a) time for flame propagation to begin after the ignition source is lit and, (b) time for the flame to propagate across the surface (propagation rate).

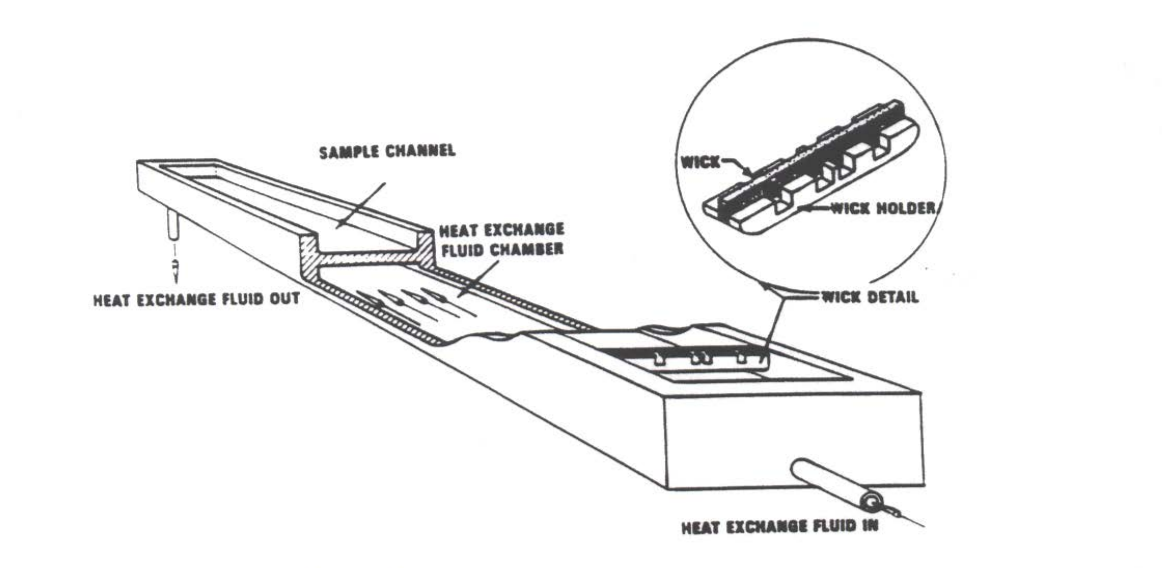


Figure 1. Illustration of Controlled-Temperature Horizontal Flame Propagation Channel

The JP-5 and DF-2 at 75°F (24°C) were not heated sufficiently by the wick to initiate flame propagation, as shown in Table 1. The test was conducted for a maximum of five (5) minutes; if propagation had not begun, the test was terminated. Under these same conditions, JetA-1 began propagation after approximately three (3) minutes, and the flame propagated at the rate of 1.3 inches (3.3 cm) per second. When the fuels were evaluated at 125°F (52°C) essentially the same results were obtained, however, the propagation rate of Jet A-1 increased. When the fuel temperature was held at 170°F (77 °C), JP-5 and DF-2 did propagate a flame as shown in Table 1, however, Jet A-1 showed instantaneous flame propagation after wick ignition as this fuel temperature was 57°F above its flashpoint. These results show that JP-5 more closely matches DF-2 than Jet A-1, as might be expected since their flash points are similar. These results also show that at 57°F above the flashpoint of DF-2 (i.e., fuel test temperature of 205°F), the propagation rate is still much slower than with Jet A-1 at 57°F above its flashpoint (170°F). However, the propagation rate of JP-5 was 16 in/second, which was considerably faster than DF-2 even though there is only 2 deg. F difference in flashpoints.

Table 1. Flame Trough Propagation Test Results

Fuel	D 93 Flash Point, °F (°C)	Fuel Test Temp. °F (°C)	Time to Propagation	Propagation Rate In/Second
Jet A-1	113 (45)	75 (24)	3 Min.	1.3
JP-5	146 (63)	75 (24)	>5 Min.	Did Not Propagate
DF-2	148 (64)	75 (24)	>5 Min.	Did Not Propagate
Jet A-1		125 (51)	11 Sec.	2.5
JP-5		125 (51)	>5 Min.	Did Not Propagate
DF-2		125 (51)	>5 Min.	Did Not Propagate
Jet A-1		170 (77)	Instantaneous	Instantaneous
JP-5		170 (77)	18.5 Sec.	2.5
DF-2		170 (77)	1 Min. 53 Sec.	1.02
Jet A-1		--	--	--
JP-5		205 (96)	1 Sec.	1.6
DF-2		205 (96)	41 Sec.	1.0

2.2.2 Discussion of Results

Purpose of Testing:

Develop correlation between laboratory test procedure and full scale ballistic testing of typical fuels used by the military.

Table 2 is a random selection of base fuels and FRF blends using the same base fuels. The plan was to investigate the relationship between flame propagation rates of base fuels and fuel blends with results of ballistic testing using a variety of threats. The first twelve (12) fuel samples were selected for propagation testing only and the second phase are actual blends that were subjected to both ballistic testing and laboratory flame propagation testing.

Table 2. Flame Propagation of Reference Fuels at 66°C (150°F) Test Temperature in Laboratory Fixture

CAN #	REF	FLASH PT. °C	CL#	AROMATICS Volume %	FBP °C	TIME TO PROPAGATE IN SECONDS	PROPAGATION TIME IN SECONDS	PROPAGATION RATE INCH/SECONDS
1		56.5	900207	16.8	272	10.62	11.45	3.06
4		59.5	900210	18.7	287	4.8	10.5	3.33
5		48.5	900211	20.1	304	2.34	6.61	5.3
2		50.5	900208	8.6	289	<1	1.1	31.82
3		67.5	900209	21.4	382	120	21.8	1.61
6		82	900212	35.7	398	>600	DNP	N/A
7		39	900213	16.6	292	<.1	<1	>35.0
8		56	900214	20.5	303	7.4	10.98	3.19
9		65	900215	19.5	418	>600	DNP	N/A
10		40	900216	18.30	345	0.62	1.49	23.49
11		91	900217	20.8	412	N/A	DNP	N/A
12		46	900218	15	270	0.39	0.3	116.67
JP-8	1	41	--	17.9	280	<1	1	>35
JP-8	2	--	--	--	--	<1	1.9	18.4
JP-8	3	--	--	--	--	<1	<1	>35
Jet-A	4	56	--	18.6	278	7	11	3.2
Jet-A	5	--	--	--	--	10	39	.89
Jet-A	6	--	--	--	--	44	21	1.6
DF-2	7	66	--	19.7	394	>600	DNP	N/A
DF-2	8	--	--	--	--	>600	DNP	N/A
DF-2	9	--	--	--	--	>600	DNP	N/A

1 – Base Fuel

2 – Base Fuel-FRF

3 – Base Fuel-FRF+125PPM Anti-Mist

DNP - Did Not Propagate

FBP – Final Boiling Point

3.0 RESULTS AND DISCUSSION

The results of the chemical analysis shown for the fuels selected at random did not show a tight correlation with flame propagation results.

3.1 AROMATIC CONTENT

While aromatic concentration may be a factor in distillation and flashpoint (FP), our data indicated that higher aromatics did not always correlate with flashpoint and therefore flame propagation. For example, one sample had an aromatic content of 20.1%, F.P. 48.5, and had higher propagation rate than another sample with 50.5 F.P. and aromatic content of 8.6%. However, as a general rule, flashpoint seemed to be the controlling factor in flame propagation.

3.2 FRF BLENDS – LABORATORY TESTING

The chemical analysis, i.e., aromatics and final boiling point were similar, however, there was a variation in flashpoint between the JP-8, Jet-A, and diesel fuel. In this case the flame propagation testing correlated very well with flame trough test temperatures. The flame propagation with the Jet-A (higher F.P.) was slower developing than the JP-8, but neither fuel self-extinguished. However the diesel fuel ignited but showed no flame propagation in the laboratory.

3.3 FRF BLENDS – BALLISTIC (THREAT-C) FIELD TESTING

Full-scale ballistic tests (Threat-C) were conducted on the same blends of fuel as those tested in the laboratory procedures and shown in Table 3 as a general rule. The fuel blends tested are listed below:

- JP-8 Base Fuel (Fuel #1), JP-8 FRF (Fuel #2), and JP-8 FRF+125 AM (Fuel #3). Figure 2 depicts each of these tests.
- Jet-A Base Fuel (Fuel #4), Jet-A FRF (Fuel #5), and Jet-A FRF+125 AM (Fuel #6). Figure 3 depicts each of these tests.
- Diesel Base Fuel (Fuel #7), Diesel Fuel FRF (Fuel #8), and Diesel Fuel FRF+125 AM (Fuel #9). Figure 4 depicts each of these tests.

Table 3. Flame Propagation of Blended Fuels at 66°C (150°F) Test Temperature using Threat-C VS Laboratory Fixture

Test Sample	Ref. Fuel	Flash Point °C	Aromatics Volume %	Test Fixture Propagation, Sec	Test Fixture Rate, In/Sec	Threat-C Propagation/Sec	Threat-C Propagation, In/Sec, (*Approx**)
JP-8	1	41	17.9	1	>35	<2.5	60*
JP-8	2			1.9	18.4	<2.5	60
JP-8	3			<1	>35	<2.5	60
Jet-A	4	49	18.6	11	3.2	<2.5	60
Jet-A	5			39	.89	<2.5	60
Jet-A	6			21	1.6	<2.5	60
Diesel Fuel-2	7	66	19.7	DNP	N/A	<2.5	N/A
Diesel Fuel-2	8			DNP	N/A	<2.5	N/A
Diesel Fuel-2	9			DNP	N/A	<2.5	N/A

- ***DNP -*** ***Did Not Propagate***
- **** -*** ***Approximate***

Ballistic Testing, Threat-C, Test Temperature 150°F
Fuel #1 - JP-8 Base Fuel, Fuel #2 - JP-8 FRF, Fuel #3 - JP-8 FRF + 125 AM

Fuel 1 Frame .00.08.bmp

Fuel 1 Frame .05.00.bmp

Fuel 2 Frame .00.08.bmp

Fuel 2 Frame .05.00.bmp

Fuel 3 Frame .00.08.bmp

Fuel 3 Frame .05.00.bmp

Figure 2. JP-8 Base Fuel, JP-8 FRF, and JP-8 FRF+125 AM

Ballistic Testing, Threat-C, Test Temperature 150°F
Fuel #4 - Jet-A Base Fuel, Fuel #5 - Jet-A FRF, Fuel #6 - Jet-A FRF + 125 AM

Fuel 4 Frame .00.08.bmp

Fuel 4 Frame .05.00.bmp

Fuel 5 Frame .00.08.bmp

Fuel 5 Frame .05.00.bmp

Fuel 6 Frame .00.08.bmp

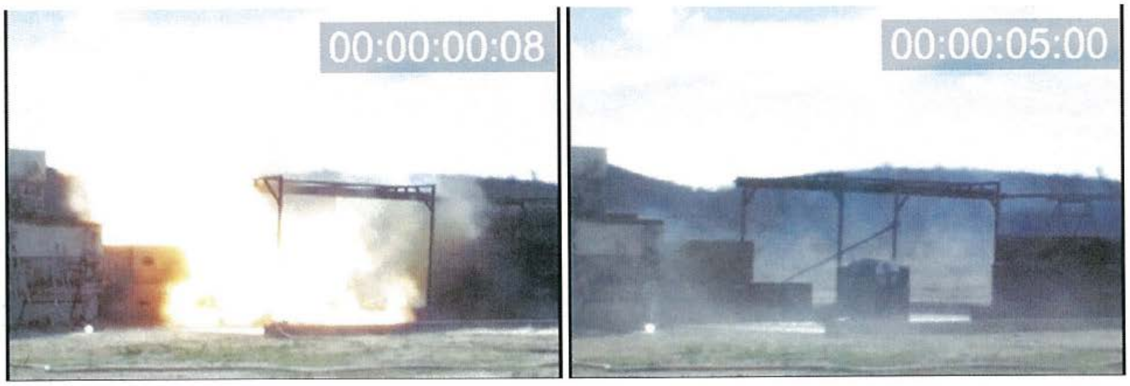
Fuel 6 Frame .05.00.bmp

Figure 3. Jet-A Base Fuel, Jet A FRF, and Jet-A FRF+125 AM

Ballistic Testing, Threat-C, Test Temperature 150°F
Fuel #7 - Diesel Base Fuel, Fuel #8 - Diesel Fuel FRF, Fuel #9 - Diesel Fuel FRF + 125 AM

Fuel 7 Frame .00.08.bmp

Fuel 7 Frame .05.00.bmp



Fuel 8 Frame .00.08.bmp

Fuel 8 Frame .05.00.bmp

Fuel 9 Frame .00.08.bmp

Fuel 9 Frame .04.14.bmp

Figure 4. Diesel Base Fuel, Diesel Fuel FRF, and Diesel Fuel FRF+125 AM

The results in the field correlated with the laboratory testing of the same blends. There was some variation in time due to the energy ratio of wick ignition vs. ballistic ignition and the residual burning (rate of flame spread) varied, based on flashpoint. There was no perceived marangoni effect (enhancement of flame propagation due to heat transfer to fluid surface ahead of flame.) That was expected due to changes in propagation rate of fuels containing the viscoelastic polymer effects. Since it is known that flashpoint is a major factor affecting ignition and flame propagation, perhaps, a series of tests should be conducted at various temperatures above flashpoint on specific fluids. It appears that the laboratory procedure is worthwhile in providing a measure of flame propagation at various fuel temperatures.

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