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TECHNICAL REPORT BRL-TR-2875

PREDICTIONS OF PROBABILITIES OF SUSTAINED FIRES FOR COMBAT DAMAGED VEHICLES

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A simple model was used to predict combat induced fires of flammable components (except ammunition) carried on combat vehicles. Five U.S. Army ground vehicles were examined. Eight attacking weapons were considered. Fuel temperatures from 8°C to 53°C were included. The model was based as much as possible on existing data which simply did not cover all situations of interest. Considerable personal judgment was required. Nevertheless, the importance of certain vehicle properties was quite evident. These properties include engine design, fuel cell location, vehicle material and the presence of an automatic fire suppression system.

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PREFACE

It is an obvious fact that large quantities of fuel (and other flammable fluids) are carried on combat vehicles. These materials can pose a severe threat to any vehicle which suffers combat damage.[1] If a hit in combat causes ignition and sustained combustion of the fuel, the vehicle will be destroyed.

Since the early 1950's, the U.S. Army has been engaged in controlled testing to determine under what attack conditions fuel will be ignited and undergo sustained combustion. A large data base has been generated.[2-21] A second objective of this testing has been to determine what countermeasures would be effective so that suitable means could be employed to prevent fire losses due to combat damage. Several methods of preventing fire losses have been identified.[22-34] Less success has been achieved in actually quantifying the probability of a sustained fire, given the fact of a hit by a particular weapon on a particular combat vehicle.

The objective of this task was to use the available data base in order to predict the probabilities of sustained fires in different vehicles struck by a variety of weapons.

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1. INTRODUCTION

Both basic and applied research efforts on methods of rendering fuels fire-safe[29 30] or fire-resistant[31 32] have been pursued by the U.S. Army since the late 1960's. The approaches have focused on the use of additives which will allow the fuel to perform satisfactorily in an engine combustion chamber environment while preventing sustained pool fires of spilled fuel.[35] Limited attempts were made to demonstrate the benefits to the Army if such fuel formulations were fielded for combat.[30 36] However, no attempt was made to quantify the overall benefit of changing the status of potentially fire-lost vehicles to repairable (not burned out) loses.

The Southwest Research Institute (SWRI), working under a contract with the Army, has developed a fire-resistant fuel (FRF) formulation.[31 32] Work on the development of this FRF has reached a stage where a decision to go ahead and field it, or to stop work, has to be made. As input to that decision, LABCOM tasked AMSAA to evaluate the military worth of fire resistant fuel (FRF).[37] As part of that project, it was necessary to develop a method of predicting the probability of a sustained fire in a vehicle subjected to combat damage. The BRL was tasked to perform this part of the study.

Many vehicle related fuel fire tests have been carried out over the years. Only one useful model of sustained fuel fires caused by munition attacks has emerged. This is the Dehn Model.[38] It is presented in both a descriptive form and a mathematical form. The descriptive part of the model explains in detail the process through which a destructive fire can occur when a munition attacks a fuel component in a vehicle. The probability of a destructive fire in a vehicle is the product of several probabilities, namely, the probability of fuel spray formation leading to the probability of a sustained fire and the probability of failure of any extinguishing system. Unfortunately, at this time we cannot use the mathematical form of the Dehn Model. We simply do not know the correct values of the parameters and variables which go into the model.

Wright and Slack present a simplified form of the Dehn Model.[18] This allows one to predict the probability of a sustained fire given a particular fuel temperature using an equation which requires only two experimentally determined temperatures and one constant. However, the equation into which these are inserted will apply only to a specific type of vehicle and attacking munition. For example, a particular temperature and constant set will apply only to a steel type vehicle, containing an interior steel splash surface, with an aluminum fuel cell containing diesel fuel attached by a 90mm shaped charge. If any of these conditions change, the equation must be changed to give the correct probability of a sustained fuel fire. Even with the simplified equation, a large number of tests must be carried out at low temperatures, and a large number of tests carried out at high temperature to determine the two limiting temperatures required for the equation. In addition, more tests are required at intermediate temperatures to determine the constant of the equation.

It is apparent that a large number of tests must be performed on each type of vehicle and munition to get equations which can be used to predict accurately the probabilities of sustained fires in diverse vehicles attacked by several munitions at different fuel temperatures. At this point in time, we do not have sufficient data to implement even the simplified form of the Dehn Model.

Therefore it is necessary to use an even simpler model to predict the probability of a sustained fire in a vehicle subjected to munition attack. An extensive literature search was conducted to identify available data which would be useable to predict fuel fires from hits in combat. It is also necessary to use personal judgment as to the applicability of much of the data, since the configuration used for the tests varied from "fairly close to" to "very far from" the configuration expected in real combat vehicles. In many cases, only a portion of the data in which we are interested was actually recorded. It is also a real problem to define "sustained fire". Some researchers categorize any fuel fire which lasts a minute or more as a "sustained fuel fire," even if it involves only wick burning of fuel on some accumulated dirt or debris. For our purposes, such a fire is not considered to be a sustained fire. Other researchers categorize only medium and large fires as "sustained fires," on the theory that crew members would extinguish small fires. Other researchers claim that conditions inside a crew compartment, after a hit on the fuel cell, are such that the crew would not be able to extinguish even a small fire. For our purposes, even a small fire will be considered a sustained fire. The automatic fire suppression system, if present, will be required to extinguish any fire more severe than a wick type fire.

2. AVAILABLE DATA

Test data on the initiation of fuel fires by weapons were examined back to the early 1950's. At that time, comparisons were made of the probabilities of ignition and sustained fire when gasoline and diesel fuel were attacked by both shaped-charge weapons and kinetic energy penetrators. Previous experience with gasoline indicated that there would be a very high probability of fire if a fuel cell should be perforated by an attacking weapon. The fuel temperature was of little, if any, importance. Therefore, the personnel who carried out the early tests with diesel fuel did not anticipate the fact that fuel temperature would be an important factor in the probability of sustained fires. When results of different series of tests, using the same attacking weapons on diesel fuel, did not agree, it was realized that tests carried out during the summer were more likely to produce sustained fires than were tests done in the winter.

Most of the subsequent testing with diesel fuel has involved measurements of the fuel temperature. To this day, it appears that only a limited number of investigators realize that the flash point (or even better, the fire point) of the fuel plays an important role in its propensity to undergo sustained combustion, given a weapon hit on the fuel container. Much of the data that does involve carefully measured fuel temperatures and flash points was obtained with 81mm precision shaped charge and 3.5-inch shaped-charge firings at "steel type" and "aluminum type" personnel carriers.

Due to the high cost, relatively few fuel fire tests have been conducted using real combat vehicles with running engines. A notable exception is the CARDE trials which used M47 and M48 tanks with running gasoline engines. The fuel tanks contained cold diesel fuel for the fuel fire tests.[6]

Most of the test data generated over the years involved fuel containers inside tank hulls or personnel carrier hulls. Replaceable steel or aluminum target panels made the hulls "steel like" or "aluminum like". Usually the fuel container split open due to hydrodynamic ram pressures which were generated when the shaped-charge jet passed through the fuel. The amount of spilled fuel was an important factor in determining whether or not a sustained fire occurred. Standard military issue fuel cells could not be obtained for these tests. Therefore, locally fabricated cells were used. This introduced a difficulty in applying the test results to actual Army vehicles.

A point which must be made is that most of the fuel fire data involve shaped-charge jet attack on the fuel container, usually behind some type of armor protection. Shaped charges are used because it is relatively easy to set up the devices for static firings. The devices are usually only inches away from the targets. Therefore, it is easy to hit the target where desired. Very few (although some) results are available on dynamic firings of shaped charges at fuel targets. To do those tests, an actual gun range is required, and it is difficult to strike the target in the desired spot. Similar problems are encountered using kinetic energy penetrators against fuel targets. Therefore, the available data for kinetic energy penetrator attack on fuel targets is not nearly as extensive as for statically fired shaped-charge jet attack.

Table 1 reports the number of firings of shaped charges and kinetic energy penetrators at the fuel targets. Not included in these data are the large number of tests in which additives were added to the fuel or some other means were used to inhibit sustained burning of the diesel fuel. Tables 2, 3, and 4 give further breakdowns of the data which were used in this project.

TABLE 1. Available Data on Weapon Firings at Neat Diesel Fuel

Most Data	- 81mm (3.2-inch) shaped charges against aluminum APC's and steel tanks - 90mm (3.5-inch) shaped charges against steel tanks and containers of diesel fuel and aluminum APC's - 105mm shaped charges against steel tanks - 127mm (5-inch) shaped charges against simulated tank engine compartments - 152mm (6-inch) shaped charges against simulated tank engine compartments - 178mm (7-inch) shaped charges against simulated tank engine compartments - 203mm (8-inch) shaped charges against simulated tank engine compartments
Some Data	- 120mm HEAT and 120mm KE rounds against steel tanks - 75mm shaped charges against a steel tank - 90/40 steel arrow rounds against steel tanks - 11mm depleted uranium KE rounds against steel APC's - 13mm tungsten carbide KE rounds against steel APC's - ICM's against aluminum APC's - M601 (20mm) KE and 11mm depleted uranium KE rounds against drums of fuel and pans of fuel. - 40mm KE rounds against a steel tank
Lack Data	- 30mm APDS against steel and aluminum targets containing fuel - 12.7mm rounds against any target with diesel fuel - large HEAT and KE rounds against light targets
Totals	- Shaped-charge firings - 342 Kinetic energy penetrator firings - 75 All firings - 417

TABLE 2. Number of Useable Firings at APC's Containing Neat Diesel Fuel

	No. of Shots
Aluminum APC's	
81mm shaped charges	27
75mm shaped charges	2
90mm shaped charges	5
Steel APC's (1" RHA)	
Tungsten Carbide 13mm KE	8
Depleted Uranium 11mm KE	11

TABLE 3. Number of Useable Firings at Tanks Containing Neat Diesel Fuel

	No. of Shots
M47 Tanks	
120mm AP T116	1 shot
120mm HEAT T153	2 shots
5-inch shaped charge	2 shots
6-inch shaped charge	1 shot
7-inch shaped charge	2 shots
8-inch shaped charge	2 shots
M48 Tanks	
3.2-inch shaped charge	22 shots
40mm AP-T, M-81	1 shot
75mm shaped charge	1 shots
5-inch shaped charge	2 shots
6-inch shaped charge	2 shots
7-inch shaped charge	2 shots
8-inch shaped charge	2 shots
Tiger Tank Hulls	
3.5-inch shaped charge	60 shots
105mm HEAT	7 shots
Steel Boxes (Simulated Tank Engine Compartments)	
3.5-inch shaped charge	15 shots
5-inch shaped charge	16 shots
6-inch shaped charge	16 shots
7-inch shaped charge	16 shots
8-inch shaped charge	16 shots
120mm HEAT	5 shots
90/40 APDSFS T320 Arrow	5 shots
120mm AP T116	8 shots

TABLE 4. Number of Useable Firings at Containers of Neat Diesel Fuel

	No. of Shots
55-Gallon Drums Protected by RHA	
3.5-inch shaped charge	38 shots
5-inch shaped charge	1 shot
90mm APT 33	6 shots
90mm HVAP M304	5 shots
5-Gallon Drum Protected by RHA	
3.5-inch shaped charge	8 shots
5-inch shaped charge	10 shots
90mm APT 33	5 shots
70mm HVAP M704	5 shots
Other Fuel Containers Protected by RHA	
3.5-inch shaped charge	60 shots
Unprotected Drums	
Tungsten Carbide 20mm KE	10 shots
Depleted Uranium 11mm KE	10 shots

Most of the tests took into account only the flammability of the fuel. The role of air was usually ignored. Most tests simply had a more than adequate supply of air. A notable exception is some tests of the CARDE, trials, where grills were placed over steel boxes containing fuel cells.[6] The grills were used to simulate the grills which can restrict air flow into the engine compartments of vehicles. However, the forced convection always found in vehicle engine compartments was ignored. It is interesting to find that, in almost all cases where the attacking shaped charge blew the grill off the box, there was a sustained fire. When the grill stayed on the box there was usually no sustained fire. There are also several tests of aluminum vehicles with diesel fuel up to 77°C which do not show sustained fire when attacked by shaped charges. These tests involved completely sealed vehicles. Upon opening the vehicles after the tests, investigators found blackened interiors, indicating combustion occurring with an insufficient amount of air. These tests indicate that the requirement of a sufficient air supply should not be overlooked.

Figure 1 shows a curve relating the probability of a sustained fire versus fuel temperature for an 81mm precision shaped charge attacking diesel fuel in an aluminum test setup. The tests which were used to generate this curve all involved an adequate supply of air. The actual numbers which can be taken off the curve should be modified by personal judgment when they are applied to a specific situation. The data for the curve

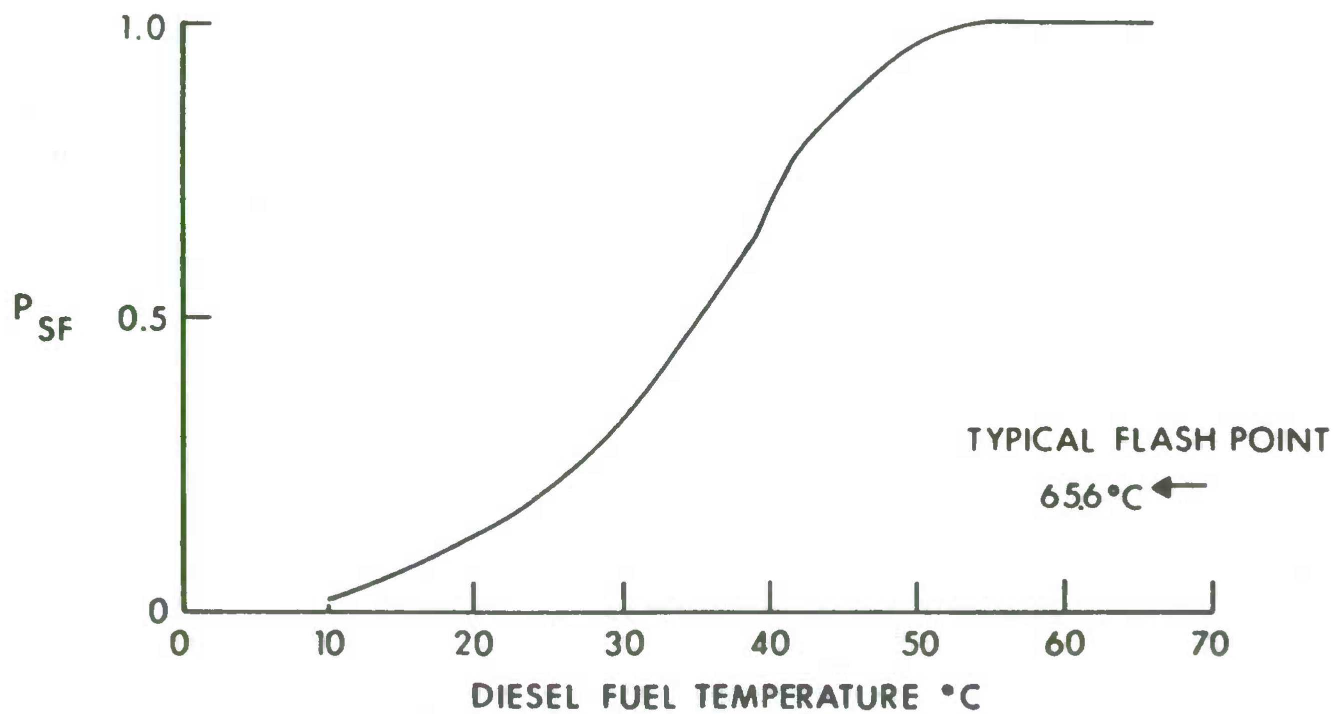

Figure 1. Probability of a Sustained Fire When an 81 mm (3.2 inch) Precision Shaped Charge is used to Attack Diesel Fuel in an Aluminum Test Fixture with Adequate Ventilation.

involved normal (90^{o}) attack on aluminum armor by static charges. Effects of obliquity were not included. The reverse shotline, where the shaped-charge jet entered the test vehicle through armor opposite the fuel cell, was rarely investigated. The test setups were "clean", in that none of the materials which normally are found in a real vehicle was present. Locally fabricated fuel cells were used, not the cells expected to be found in actual combat vehicles. While fuel temperatures were recorded, the temperatures of the aluminum surfaces onto which fuel would spill were not recorded. Conditions of actual vehicle fuel systems should be taken into account and used to modify the curves given in Figures 1-3. A curve generated from data involving aluminum test setups with limited air supplies (closed vehicles) is given in Figure 2. It should be noted that even if there is not sustained fire for an actual combat case at 75^{o}C fuel temperature, the crew members would be in an atmosphere essentially devoid of oxygen.

The curve relating probability of a sustained fire versus diesel fuel temperature for a steel setup is given in Figure 3. It should be noted that the fuel must be heated to its flash point before the probability of a sustained fire approaches unity.

3. THE MODEL

Taking advantage of the available data base, we will construct a model which will allow us to predict probabilities of sustained fires in various vehicles. The data, however, do not include firings at undamaged examples of vehicles that are of concern to us. The data are most conveniently used to predict probability of a sustained fire if the fuel cell of a generic steel or generic aluminum vehicle is struck by a shaped-charge jet or a kinetic energy penetrator. Therefore, we will use the data to determine the probability of a sustained fire given a hit on a fuel component by a particular weapon under the conditions in question. This probability is given the symbol $P_{SF/H}$. It is dependent on the type of armor and thickness, attacking weapon and fuel condition (temperature).

We must take other factors into account before we can estimate the probability of a sustained fire (P_{SF}) for a particular vehicle. Thus, we must take into account the fact that many vehicles have automatic fire suppression systems (AFSS). If these work correctly, they can extinguish hydrocarbon type fires and prevent the sustained fire which would lead to loss of the vehicle.[22 23 25 27] There must be a failure of the AFSS in order to have a sustained fire. The probability of this failure is given the symbol $P_{F/AFSS}$.

It is also necessary to take into account whether or not the fuel component is in a state which can lead to a sustained fire. Thus, in the case of a vehicle with several fuel cells, some may be empty at the time of attack. It is also possible that, given a second hit on a vehicle, the fuel component might have been damaged by the initial hit and thus be empty. In the case of fuel cells connected by pipes, a hole in one cell

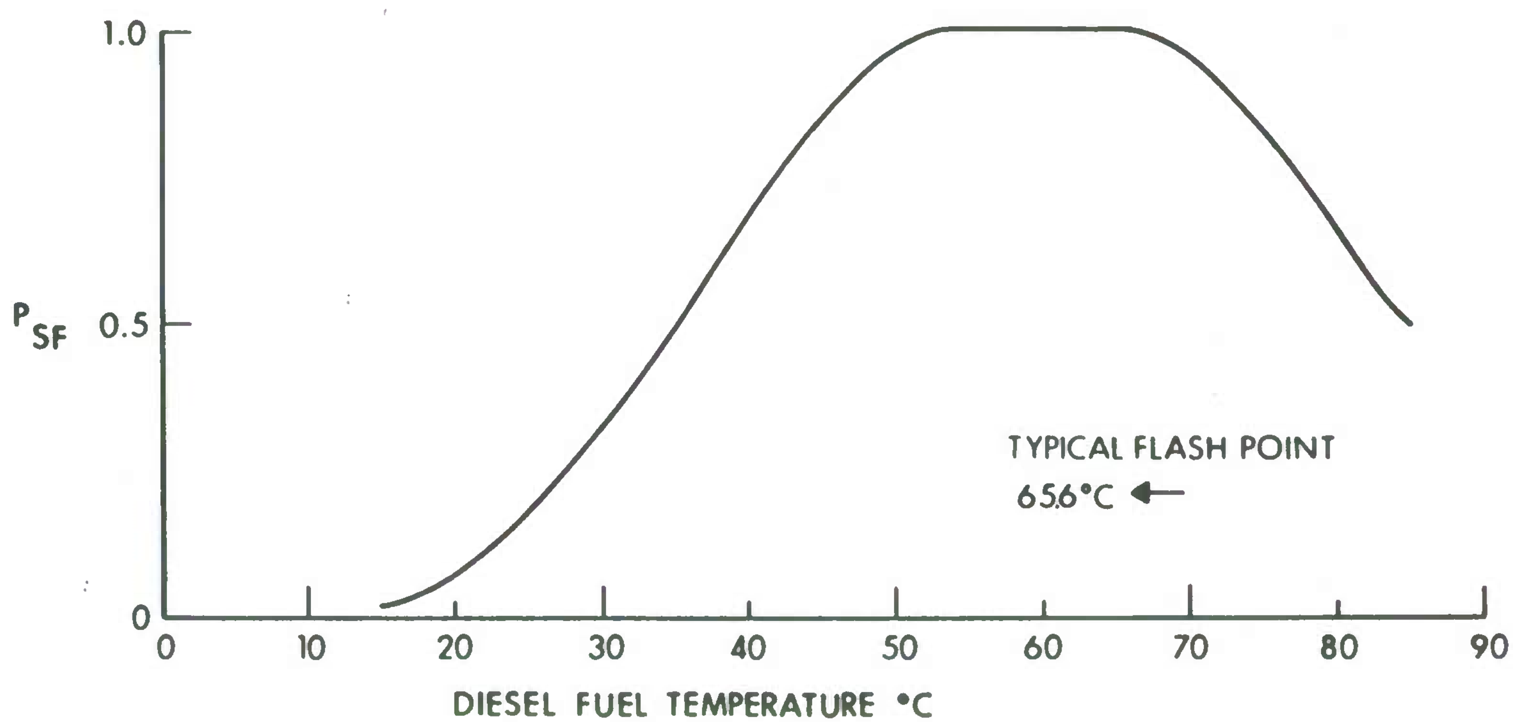

Figure 2. Probability of a Sustained Fire When an 81 mm (3.2 inch) Precision Shaped Charge is used to Attack Diesel Fuel in an Aluminum Test Fixture without Adequate Ventilation.

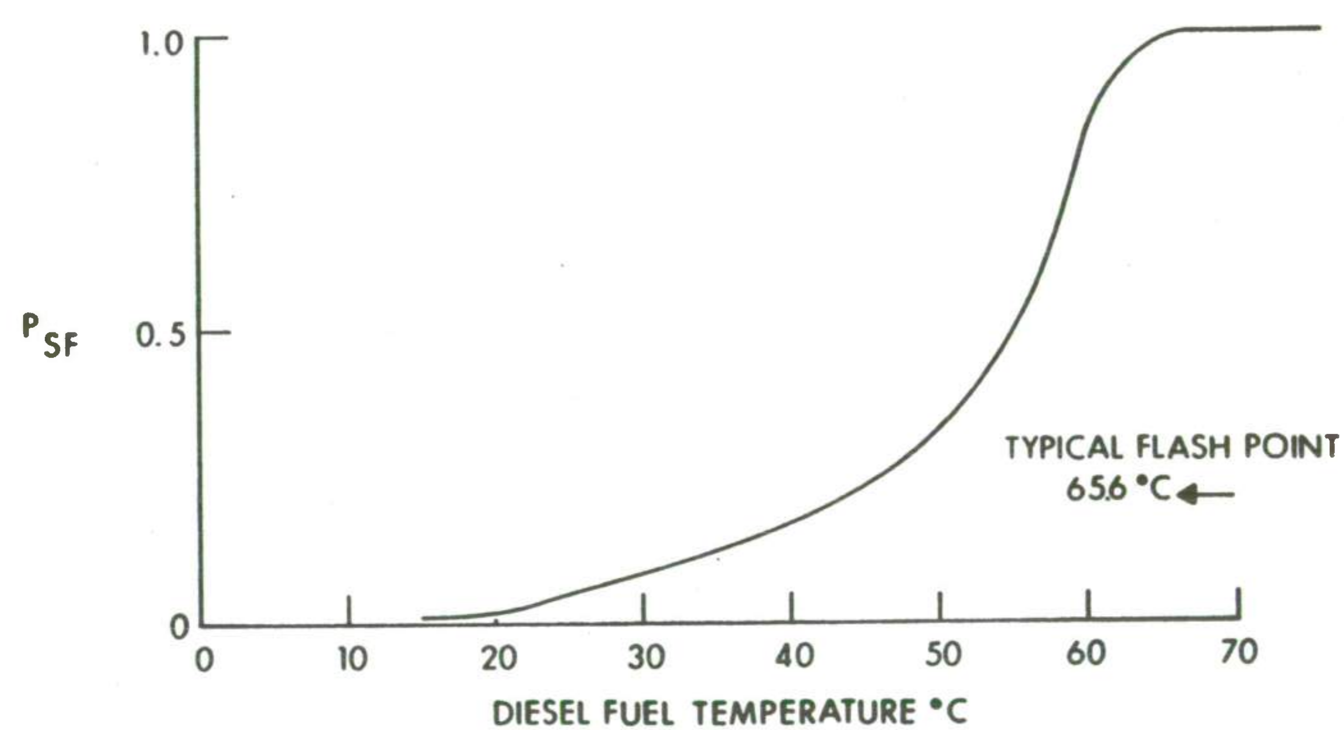

Figure 3. Probability of a Sustained Fire When an 81 mm (3.2 inch) Shaped Charge is used to Attack Diesel Fuel in a Steel Test Fixture.

will cause other cells to empty. The probability that the fuel component exists in a state which could lead to a sustained fire is given the symbol $P_{E/FC}$.

Finally, in order for there to be a sustained fire, the fuel component must actually be damaged. The probability of a hit on the fuel component is derived from the computer codes of the Vulnerability/Lethality Division of the Ballistic Research Laboratory. These codes give the probability of actually striking a fuel component for a given vehicle using various weapons at different attack angles and azmuths. This probability of striking a fuel component is given the symbol $P_{H/FC}$.

The model for a sustained vehicle fire is given by:

$$P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$$

where P_{SF} is the probability of a sustained fire

$P_{SF/H}$ is the probability of a sustained fire given a hit on the flammable component by the weapon in question.

$P_{F/AFSS}$ is the probability of failure of the automatic fire suppression system. It is "1" if no AFSS is present.

$P_{E/FC}$ is the probability that the fuel component in question actually exists in a form which can lead to a sustained fire.

$P_{H/FC}$ is the probability of a hit on the flammable component in question by a particular weapon at a set angle and azmuith.

Numerical values for $P_{SF/H}$, $P_{F/AFSS}$ and $P_{E/FC}$ have been worked out for several vehicles using available data and judgment. Numerical values for $P_{H/FC}$ have been derived for the vehicles using several attacking weapons by the Vulnerability/Lethality Division of the BRL. The actual numerical values are not given here. Since these numbers represent the vulnerabilities of real vehicles to real threats, the numbers are classified. It is our intention that this work be unclassified so that it may be given the widest distribution.

4. INDIVIDUAL VEHICLES AND ASSUMPTIONS

It would have been an extremely large and difficult task to predict the probability of fuel fires for all combat vehicles under all conditions. Therefore, only certain vehicles were chosen as representative of those in the Army inventory. The vehicles included in this study are M1A1, M2, M113A1, Improved TOW Vehicles (ITV), and HMMWV.

The following assumptions were made concerning these vehicles:

a. All vehicles contain diesel fuel having a flash point of 65.5°C (150°F).

b. Ambient temperature is 8°C (46°F).

c. For vehicles utilizing diesel engines, the temperature rise of the fuel in the fuel cell (due to recirculation), as a function of the amount of fuel remaining in the cell, is assumed to be the same for all engines using the common-rail method of metering fuel. A similar assumption is made for all engines utilizing the jerk-pump system. Tests at Aberdeen Proving Ground[39] have shown that when one-half the fuel supply has been consumed, the temperature rise in the fuel cell of a common-rail engine is 45.6°C (82°F). The temperature rise in the fuel cell of a jerk-pump engine is 11°C (20°F).

d. In the case of a turbine powered vehicle (the M1A1 tank), there is no recirculation of hot fuel back to the fuel cells. Therefore, it is assumed that the fuel in the hull fuel cells remains at ambient temperature. Since the engine compartment and sponson fuel cells are exposed to a relatively hot environment (even though the engine compartment cells are insulated), the fuel in these cells is assumed to undergo a modest temperature rise of 16°C (29°F).[44]

e. While Fire Resistant Hydraulic (FRH) Fluid does not present any danger to vehicles from pool burning, FRH Fluid mists which are released from damaged, pressurized lines are extremely flammable.[40] A fire loss of the vehicle can occur if a sufficient quantity of fluid is released as a burning mist.

f. Lubricating oils and transmission fluids are not judged to be threats to fire-kill a vehicle. In a study of accidental fires in Army vehicles, it was found that the worse transmission oil fires caused only an 11% damage level to M1 tanks.[41]

g. Based on data concerning accidental fires in Army vehicles, it is assumed that the automatic fire suppression system (AFSS) currently in the M1A1 tank is not effective in suppressing engine compartment fires.[41 42]

h. It is assumed that the AFSS is effective in suppressing crew compartment fires.

5. FIRE PROBABILITIES FOR INDIVIDUAL VEHICLES

The probability of a sustained fire is extremely vehicle dependent. The following factors must be taken into consideration when predicting fire probabilities.

a. Internal vs. External Fuel Cells

b. Presence of an AFSS

c. Temperature of the Diesel Fuel - Strongly Influenced by Engine Design

d. Steel vs. Aluminum Vehicle

e. Construction of Fuel Cells and Related Connections

These factors (along with a certain amount of judgment) must be applied to each vehicle when predicting the probability of a sustained fire.

5.1 <u>The M1A1 Tank</u>.

5.1.1 Observations on the Fuel System of the M1A1 Tank. The following observations are made concerning the M1A1 fuel system:

a. The two hull fuel cells are connected. If fuel leaks out of one, both will drain.

b. The two engine fuel cells are connected. If fuel leaks out of one, both will drain.

c. Each sponson fuel cell is connected to its respective engine fuel cell. If one sponson cell leaks, both will drain.

d. If one engine fuel cell leaks, both sponsor cells will drain, in addition to the other engine fuel cell.

e. The hull fuel cells cannot send fuel directly to the engine. They can only send fuel to an engine fuel cell. Therefore, if one engine fuel cell leaks, the engine cannot receive fuel.

f. The M1A1 has a single shot AFSS in the crew compartment and a two-shot AFSS in the engine compartment.

5.1.2 Assumptions on the Fuel System of the M1A1 Tank. The following assumptions are made concerning the functioning and status of the M1A1 fuel system:

a. The fuel type is neat diesel fuel with a flash point of 65.6°C (150°F).

b. The temperature of the fuel in the hull cells is 8°C (46°F).

c. The temperature of fuel in the engine fuel cells is 24°C (75°F).

d. The sponson fuel cells are full only if the fuel system is at full capacity. Any fuel in the sponson cells is at 24°C (75°F).

e. The AFSS is capable of extinguishing hydrocarbon type fires in the crew compartment.

f. The AFSS in the crew compartment will function any time the crew compartment is penetrated by any projectile. The AFSS will function even if there is no hydrocarbon fire to be extinguished.

g. The AFSS is not effective in extinguishing engine compartment fires.[41]

h. The lubricating oil and the transmission fluid are not considered to be fire threats which are strong enough to destroy the vehicle.

i. A broken fuel line is not considered to be a fire threat which is strong enough to destroy the vehicle.

j. Pressurized hydraulic fluid, escaping from a break in the hydraulic system, is a fire threat to the vehicle.[40] Hydraulic fluid escaping from an unpressurized portion of the system is not considered a fire threat.

5.1.3 Code for Locations of Flammable Components of M1A1 Tank.

For the M1A1 tank, the following code is used to identify the locations of flammable materials and locations where pools of flammable materials may collect after a hit on the vehicle. The probability of hitting the component (~ location) in question is given a letter code of A...etc.

LHFC is the left hull fuel cell. (A)

RHFC is the right hull fuel cell. (B)

REFC is the right engine fuel cell. (C)

LEFC is the left engine fuel cell. (D)

RSFC is the right sponson fuel cell. (E)

LSFC is the left sponson fuel cell. (F)

CHY is the crew compartment hydraulics. (G)

EHY is the engine compartment hydraulics. (H)

CC is the crew compartment itself. (I)

EC is the engine compartment itself. (J)

5.1.4 Probabilities of Ignition of Flammable Components of M1A1 by an Overmatching Shaped Charge. The threats are the 125mm HEAT, the AT5, and the AT8.

For the M1A1 tank, the values assigned to the probability of a sustained fire given a hit by an overmatching shaped charge were arrived at by taking the following into consideration:

a. The M1A1 is a steel vehicle. The probability of an overmatching shaped charge starting a sustained fire with 8°C diesel fuel is .15.

b. The probability of an overmatching shaped charge starting a sustained fire in the steel M1E1 with 24°C diesel fuel is .25.

c. The probability of a shaped charge starting a sustained fire when hitting a full sponson cell is .1. There are 12mm to 25mm of RHA separating the sponson cells from the engine compartment. It is expected that only a small amount of fuel would be spilled into the engine compartment. Most of the fuel would be spilled on the outside of the vehicle and onto the ground.

d. The probability of a sustained fire in the crew compartment from previously spilled 8°C fuel is taken to be zero. There will be no mist fireball to provide energy to vaporize the pool of fuel.

e. The probability of a sustained fire in the engine compartment from previously spilled fuel is taken as .75. The diesel fuel, initially 24°C, will be heated by the hot surfaces in the engine compartment.

f. The probability of a sustained fire from a broken hydraulic line is taken to be .5. The spray of FRH fluid from a severed pressurized hydraulic line is extremely flammable. However, only a portion of the hydraulic system is pressurized. Therefore, it is assumed that only one-half of the hits on the hydraulic system will yield sustained fires. This applies to both the crew compartment and the engine compartment.

5.1.5 Probability of a Sustained Fire Given a First Hit by an Overmatching Shaped Charge. Fuel is at one-half capacity.

Before the first hit the vehicle is undamaged and all systems are in good working order.

Location			
Location	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	
LHFC	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .15 \cdot 0 \cdot 1 \cdot A$
RHFC	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .15 \cdot 0 \cdot 1 \cdot B$
REFC	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .25 \cdot 1 \cdot 1 \cdot C$
LEFC	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .25 \cdot 1 \cdot 1 \cdot D$
RSFC	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .1 \cdot 1 \cdot 0 \cdot E$
LSFC	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .1 \cdot 1 \cdot 0 \cdot F$
CHY	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .5 \cdot 0 \cdot 1 \cdot G$
EHY	P_{SF}	$= P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	$= .5 \cdot 1 \cdot 1 \cdot H$

5.1.6 Probabilities of a Sustained Fire Given a Second Hit by an Overmatching Shaped Charge. Fuel is at one-half capacity.

Given the one-half capacity fuel supply, as above, but also given that the M1A1 has suffered one hit, the probabilities of a sustained fire on the second hit by a 125mm shaped-charge round are given by the following calculations. It should be noted that the probabilities of hitting flammable components (A...etc.) are identical to those used for the initial hits on the vehicle. It is assumed that the same attacking weapon and aim point are used for the second hit as were used for the first hit. Since A was the probability of hitting the LHFC for the first hit on the vehicle, (1-A) is the probability that the LHFC exists in an undamaged state after the first vehicle hit. Similar expressions are used to describe the probabilities of other components existing in undamaged states. For any fuel to be in the LHFC it is necessary for both the LHFC and the RHFC to be undamaged. Therefore, the probability of fuel being in the LHFC is the product of the probabilities of LHFC and RHFC being undamaged or (1-A)·(1-B).

Since the AFSS of the M1A1 will function with any penetration into the crew compartment, the AFSS will always function on the first hit. Therefore, there will be no AFSS available for the second hit, whether or not there was a hydrocarbon fire in the crew compartment on the first hit.

LHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .15 \cdot 1 \cdot (1-A)(1-B) \cdot A$

RHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .15 \cdot 1 \cdot (1-A)(1-B) \cdot B$

REFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{F/FC} = .25 \cdot 1 \cdot (1-C)(1-D) \cdot C$

LEFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{F/FC} = .25 \cdot 1 \cdot (1-C)(1-D) \cdot D$

RSFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .1 \cdot 1 \cdot 0 \cdot E$

LSFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{F/FC} = .1 \cdot 1 \cdot 0 \cdot F$

CHY $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot (1-G)(1-H) \cdot G$

EHY $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot (1-G)(1-H) \cdot H$

CC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot [1-(1-A)(1-B)] \cdot I$

EC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} =$
$.75 \cdot 1 \cdot [1-(1-C)(1-D)] \cdot J$

5.1.7 Probabilities of a Sustained Fire Given a First Hit by an Overmatching Shaped Charge. Fuel is at full capacity.

In the case of the M1A1 tank with fuel cells filled to capacity, the probabilities of a sustained fuel fire on the first hit by an overmatching shaped charge are given by the following:

LHFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.15 \cdot 0 \cdot 1 \cdot A$
RHFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.15 \cdot 0 \cdot 1 \cdot B$
REFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.25 \cdot 1 \cdot 1 \cdot C$
LEFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.25 \cdot 1 \cdot 1 \cdot D$
RSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.1 \cdot 1 \cdot 1 \cdot E$
LSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.1 \cdot 1 \cdot 1 \cdot F$
CHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.5 \cdot 0 \cdot 1 \cdot G$
EHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.5 \cdot 1 \cdot 1 \cdot H$

5.1.8 Probabilities of a Sustained Fire Given a Second Hit by an Overmatching Shaped Charge. Fuel is at full capacity.

For the second hit by an overmatching shaped charge, the probabilities of a sustained fire became:

LHFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.15 \cdot 1 \cdot (1-A)(1-B) \cdot A$
RHFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.15 \cdot 1 \cdot (1-A)(1-B) \cdot B$
REFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.25 \cdot 1 \cdot (1-C)(1-D) \cdot C$
LEFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.25 \cdot 1 \cdot (1-C)(1-D) \cdot D$
RSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$ = $.1 \cdot 1 \cdot (1-E)(1-F)(1-C)(1-D) \cdot E$		
LSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$ = $.1 \cdot 1 \cdot (1-E)(1-F)(1-C)(1-D) \cdot F$		
CHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.5 \cdot 1 \cdot (1-G)(1-H) \cdot G$
EHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.5 \cdot 1 \cdot (1-G)(1-H) \cdot H$
CC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$0 \cdot 1 \cdot [1-(1-A)(1-B)] \cdot I$
EC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	=	$.75 \cdot 1 \cdot [1-(1-C)(1-D)] \cdot J$

5.1.9 Probabilities of Ignition of Flammable Components of M1A1 by a 125mm KE Round.

In the case of a large kinetic energy (KE) projectile penetrating the M1A1 tank, the predictions for probabilities of sustained fires were made using the following considerations:

a. There is only limited test data available on large KE rounds against diesel fuel targets.

b. The probability of a 125mm KE starting a sustained fire with 8°C diesel fuel in a steel M1A1 tank is taken as .5.

c. The probability of a 125mm KE starting a sustained fire with 24°C diesel fuel in a steel M1A1 tank is taken as .6.

d. The probability of a 125mm KE starting a sustained fire with 24°C diesel fuel in a sponson cell is taken as .3. The round will break a large hole into the 12mm to 25mm thick RHA which separates the sponson cell from the engine compartment. There is a reasonable chance that enough fuel will spill into the engine compartment to cause a sustained fire.

e. The probability of a sustained fire in the crew compartment from previously spilled 8°C fuel is taken as zero. There would be no mist fire-ball to provide energy to vaporize the pool of diesel fuel.

f. The probability of a sustained fire in the engine compartment from previously spilled 8°C fuel is taken as .75. The fuel will be heated by hot surfaces in the engine compartment.

g. The probability of a sustained fire due to severing a hydraulic line is taken as .5. The spray of FRH fluid from a broken pressurized line is extremely flammable. However, only a portion of the hydraulic system is pressurized. Therefore, it is assumed that only one-half of the hits on the hydraulic system will yield sustained fires. This applies to both the crew compartment and the engine compartment.

5.1.10 Probabilities of a sustained fire given a first hit by a 125mm KE round. Fuel is at one-half capacity.

The same code is used for the 125mm KE attack on the M1A1 tank as was used for the shaped-charge attack. The following probabilities of sustained fires were formulated for an initial hit on a M1A1 tank by a 125mm KE round. All systems are in good working order.

LHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 0 \cdot 1 \cdot A$

RHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 0 \cdot 1 \cdot B$

REFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .6 \cdot 1 \cdot 1 \cdot C$

LEFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .6 \cdot 1 \cdot 1 \cdot D$

RSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.3 \cdot 1 \cdot 0 \cdot E$
LSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.3 \cdot 1 \cdot 0 \cdot F$
CHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.5 \cdot 0 \cdot 1 \cdot G$
EHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.5 \cdot 1 \cdot 1 \cdot H$

5.1.11 Probabilities of a sustained fire given a second hit by a 125mm KE round. Fuel is at one-half capacity.

Given the situation in which the vehicle has suffered one hit by a large KE penetrator, we can calculate the probabilities of a sustained fire on the second hit. As in the case of the shaped-charge attack, the probabilities of hitting individual components (A...etc.) are identical to those for the undamaged case. Again, the probabilities that the components were damaged on the first hit must be taken into account. The AFSS is assumed to be unavailable after the first hit.

LHFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.5 \cdot 1 \cdot (1-A)(1-B) \cdot A$
RHFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.5 \cdot 1 \cdot (1-A)(1-B) \cdot B$
REFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.6 \cdot 1 \cdot (1-C)(1-D) \cdot C$
LEFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.6 \cdot 1 \cdot (1-C)(1-D) \cdot D$
RSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.3 \cdot 1 \cdot 0 \cdot E$
LSFC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.3 \cdot 1 \cdot 0 \cdot F$
CHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.5 \cdot 1 \cdot (1-G)(1-H) \cdot G$
EHY	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$	= $.5 \cdot 1 \cdot (1-G)(1-H) \cdot H$
CC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$ = $0 \cdot 1 \cdot [1-(1-A)(1-B)] \cdot I$	
EC	P_{SF}	=	$P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC}$ = $.75 \cdot 1 \cdot [1-(1-C)(1-D)] \cdot J$	

5.1.12 Probabilities of a Fire Given a First Hit by a 125mm KE Round. Fuel is at full capacity.

In the case of the M1A1 tank with the fuel cells filled to capacity when it receives the first hit by a 125mm KE round, the probabilities of a sustained fire are given by the following:

LHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 0 \cdot 1 \cdot A$

RHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 0 \cdot 1 \cdot B$

REFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .6 \cdot 1 \cdot 1 \cdot C$

LEFC $P_{SF} = R_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .6 \cdot 1 \cdot 1 \cdot D$

RSFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .3 \cdot 1 \cdot 1 \cdot E$

LSFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .3 \cdot 1 \cdot 1 \cdot F$

CHY $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 0 \cdot 1 \cdot G$

EHY $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot 1 \cdot H$

5.1.13 Probabilities of a Sustained Fire Given a Second Hit by a 125mm KE Round. Fuel is at full capacity.

For a second hit by a 125mm KE round on an M1A1 tank with a full fuel system, the probabilities of a sustained fire are as follows:

LHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{F/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot (1-A)(1-B) \cdot A$

RHFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot (1-A)(1-B) \cdot B$

REFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .6 \cdot 1 \cdot (1-C)(1-D) \cdot C$

LEFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .6 \cdot 1 \cdot (1-C)(1-D) \cdot D$

RSFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} =$
$.3 \cdot 1 \cdot (1-C)(1-D)(1-E)(1-F) \cdot E$

LSFC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} =$
$.3 \cdot 1 \cdot (1-C)(1-D)(1-E)(1-F) \cdot F$

CHY $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot (1-G)(1-H) \cdot G$

EHY $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot (1-G)(1-H) \cdot H$

CC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot [1-(1-A)(1-B)] \cdot I$

EC $P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} =$
$.75 \cdot 1 \cdot [1-(1-C)(1-D)] \cdot J$

5.2 The M113 Armored Personnel Carrier.

5.2.1 Observations on the Fuel System of the M113.

The following observations are made concerning the M113's fuel system:

a. The M113 has only one fuel cell, which is located in the crew compartment.

b. The engine of the M113 utilizes a common-rail system to meter fuel to the engine.

c. The M113 has no AFSS.

d. There is no hydraulic fluid fire threat.

5.2.2 Assumptions on the Fuel System of the M113.

The following assumptions are made concerning the fuel system of the M113:

a. The fuel used is neat diesel fuel with a flash point of 65.6°C.

b. The temperature of the fuel which is in the fuel cell is 53°C due to recirculation of hot fuel from the engine back to the fuel cell.

c. The lubricants and transmission fluid are not considered to be fire threats which would lead to destruction of the vehicle.

d. A broken fuel line is not considered to be a fire threat which could cause the loss of the vehicle.

5.2.3 Code for Location of Flammable Components of the M113. For the M113 the following code is used for identifying fuel locations and probabilities of penetrating those locataions with a particular weapon.

FC is the fuel cell (A).

CC is the crew compartment (B).

5.2.4 Probability of Ignition of Flammable Components of M113 by a RPG-18.

For the M113, the probabilities of igniting a sustained fire, given a hit by an RPG-18, were assigned taking the following into consideration:

a. The M113 is an aluminum vehicle. The probability of an RPG-18 starting a sustained fire with 53°C fuel is .9.

b. The probability of an RPG-18 starting a sustained fire from previously spilled fuel in the crew compartment is taken as .75. The initially 53°C fuel will be cooled by the colder surfaces in the crew compartment. The cooler fuel will be more difficult to ignite than the 53°C fuel. There will also be no mist fireball. However, the jet passing through the aluminum armor will produce a large quantity of spall. This burning aluminum spall is an excellent ignition source.

5.2.5 Probabilities of a Sustained Fire Given a First Hit by an RPG-18. Fuel is at one-half capacity.

Before the first hit by an RPG-18 the vehicle is assumed to be undamaged with all systems in good working order.

$$\text{FC} \qquad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 1 \cdot 1 \cdot A$$

5.2.6 Probabilities of a Sustained Fire Given a Second Hit by a RPG-18. Fuel is at one-half capacity.

After the first hit on the M113, the probabilities of a sustained fire on the next hit by a RPG-18 are given by the following.

$$\text{FC} \qquad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 1 \cdot (1-A) \cdot A$$

$$\text{CC} \qquad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot 1 \cdot A \cdot B$$

5.2.7 Probability of Ignition of Flammable Components of M113 by a 30mm APDS. Fuel is at one-half capacity.

In the case where the attacking munition is a 30mm APDS round, the values assigned to the probabilities of igniting a sustained fire are as follows:

a. The probability of a 30mm APDS round causing a sustained fire with 53°C fuel in a M113 is taken as .9.

b. The probability of a 30mm APDS round igniting a pool of diesel fuel, originally at 53°C but cooled by the metal surfaces of the crew compartment, is taken as .5. It is expected that less burning aluminum spall will be produced by the 30mm APDS round than by a RPG-18 shaped-charge device.

5.2.8 Probability of a sustained fire given a first hit by a 30mm APDS. Fuel is at one-half capacity.

Before the first hit by the 30mm APDS round, it is assumed that the M113 is undamaged.

$$\text{FC} \qquad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 1 \cdot 1 \cdot A$$

5.2.9 Probabilities of a Sustained Fire Given a Second Hit by a 30mm APDS. Fuel is at one-half capacity.

For a second hit on the M113 by a 30mm APDS with the same aim point, the probabilities of ignition with sustained fire are as follows:

$$\text{FC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 1 \cdot (1-A) \cdot A$$

$$\text{CC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot 1 \cdot A \cdot B$$

5.3 The ITV Improved TOW Vehicle.

5.3.1 Observations on the Fuel System of the ITV.

The following observations are made on the fuel system of the ITV:

a. It is expected that there will be two fuel cells, both outside the crew compartment, at the rear of the vehicle.

b. The engine uses the common-rail method of metering fuel to the engine.

c. There is no AFSS.

d. There is a hydraulic system using FRH fluid.

5.3.2 Assumptions on the Fuel System of the ITV.

The following assumptions are made concerning the fuel system of the ITV.

a. The fuel used is neat diesel fuel with a flash point of 65.6^{o}C.

b. The temperature of the fuel which is in the fuel cells is 53^{o}C, due to recirculation of hot fuel from the engine back to the fuel cells.

c. The lubricating oil and the transmission fluid are not considered to be threats which could cause sustained fires and loss of the vehicle.

d. A broken fuel line is not considered a threat which would cause a sustained fire.

e. Pressurized FRH fluid, escaping from a pressurized portion of the hydrualic system, is considered to be a fire threat to the vehicle. FRH fluid escaping from an unpressurized portion of the hydraulic system is not considered to be a fire threat.

5.3.3 Code for Locations of Flammable Components of ITV. For the ITV the following code is used for location of flammable components and probabilities of hitting the component in question:

RFC is the right fuel cell (A).

LFC is the left fuel cell (B).

HC is the hydraulic system (C).

CC is the crew compartment (D).

5.3.4 Probabilities of Ignition of Flammable Components of ITV by an Overmatching Shaped Charge.

For the ITV, the values assigned to the probabilities of sustained fires which could destroy the vehicle given a hit by a overmatching shaped charge (AT5 or AT8) were made taking the following into consideration:

a. Since the fuel cells are attached to the outside portion of the vehicle, a fuel spill will be onto the ground. This should not be a threat to destroy the vehicle. Therefore, the probability of a sustained fire given a hit by an overmatching shaped charge on either fuel cell is taken as zero.[43]

b. Approximately 75% of the penetrations into the hydraulic system are expected to be into the pressurized portion. Therefore, a value of .75 is assigned to the probability of a sustained fire, given a hit, since the FRH fluid mist which is released from the pressurized portion of the system is extremely flammable.

c. A pool of FRH fluid in the crew compartment is given a value of zero for sustained fire probability.

5.3.5 Probabilities of a Sustained Fire Given a First Hit by an Overmatching Shaped Charge. Fuel is at one-half capacity.

Before the first hit by an overmatching shaped charge, it is assumed that the vehicle is undamaged and all systems are in good working order.

RFC $\quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot 1 \cdot A$

LFC $\quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot 1 \cdot B$

HS $\quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot 1 \cdot 1 \cdot C$

5.3.6 Probabilities of a Sustained Fire Given a Second Hit by an Overmatching Shaped Charge. Fuel is at one-half capacaity.

After the first hit by an overmatching shaped charge, the probabilities of a sustained fire on the second hit are given by the following:

$$\text{RFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot (1-A) \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot (1-B) \cdot B$$

$$\text{HS} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot 1 \cdot (1-C) \cdot C$$

$$\text{CC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot C \cdot D$$

5.3.7 Probabilities of Ignition of Flammable Components of ITV by an ICM.

For the case in which the ITV is attacked by an ICM (small shaped charge delivered by overhead attack) the values assigned to the probabilities of a sustained fire which could destroy the vehicle were made taking the following into consideration:

a. There is no fuel fire threat to destroy the vehicle since the fuel cells are attached to the exterior portion of the vehicle.

b. Approximately 75% of the penetrations of the hydraulic system are expected to involve pressurized portions of the System. It is also believed that the ICM shaped charges are powerful enough to open the hydrualic system of the ITV. An ICM should also provide a good ignition source (cloud of burning aluminum spall).

c. Any pool of FRH fluid in the crew compartment will not pose a fire threat to the vehicle.

5.3.8 Probabilities of a Sustained Fire Given a First Hit by an ICM. Fuel is at one-half capacity.

Before the first hit by an ICM, it is assumed that the vehicle is undamaged and all systems are in good working order.

$$\text{RFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot 1 \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot 1 \cdot B$$

$$\text{HS} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot 1 \cdot 1 \cdot C$$

5.3.9 Probabilities of a Sustained Fire Given a Second Hit by an ICM. Fuel is at one-half capacity.

After the first hit by an ICM, the probabilities of a sustained fire due to a second hit are given by the following:

$$\text{RFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot (1-A) \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot (1-B) \cdot B$$

$$HS \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot 1 \cdot (1-C) \cdot C$$

$$CC \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 1 \cdot C \cdot D$$

5.4 The M2 - Infantry Fighting Vehicle.

5.4.1 Observations on the Fuel System of the M2.

The following observations are made concerning the fuel system of the M2 vehicle.

a. The M2 has two fuel cells in the crew compartment, a large lower cell and a small upper cell. Fuel is delivered to the engine only by gravity feed from the upper cell. Fuel is constantly pumped from the lower cell up to the upper cell. Excess fuel is returned to the lower cell via a standpipe. Therefore, the fuel level in the upper cell is constant. It is also true that if the upper cell should be destroyed, the pumps will continue to deliver fuel to the "open space" that was formerly a fuel cell. All this fuel will be pumped into the crew compartment. Both fuel cells are made of nylon.

b. The engine of the M2 utilizes a common-rail system to meter fuel to the engine. Excess hot fuel is returned to the lower fuel cell.

c. The M2 has a single shot AFSS in the crew compartment. There is a single shot manually controlled fire extinguishing system in the engine compartment.

d. There is no hydraulic fluid fire threat to the vehicle.

5.4.2 Assumptions on the Fuel System of the M2.

The following assumptions are made concerning the fuel system of the M2 vehicle:

a. The fuel used is neat diesel fuel with a flash point of 65.6°C.

b. The temperature of the fuel in both fuel cells is 53°C.

c. The lubricants and transmission fluid are not considered to be fire threats to the vehicle.

d. A broken fuel line is not consdiered to be a fire threat to the vehicle.

e. The AFSS discriminates properly about one-half the times that the vehicle is penetrated by KE rounds and large shaped charges. This means that the single shot AFSS does discharge one-half the times that the crew compartment is penetrated but there is no fire.

f. The AFSS discriminates properly when the vehicle is attacked by ICM's (small shaped charges). This means that the AFSS does not discharge if there is no fire.

g. The AFSS does extinguish fires successfully.

5.4.3 Code for Locations of Flammable Components of M2.

For the M2, the following code is used to identify fuel locations and probabilities of penetrating these locations for a particular weapon:

UFC is the upper fuel cell (A).

LFC is the lower fuel cell (B).

CC is the crew compartment (C).

5.4.4 Comments on the Ignition of Flammable Components of the M2 by an Overmatching Shaped Charge.

For the M2, the values assigned to the probabilities of igniting a sustained fire, given a hit by a 125mm HEAT, AT5 or AT8 were arrived at taking the following into consideration:

a. The M2 is an aluminum vehicle. The probability of a large shaped charge starting a sustained fire with 53°C fuel is .9.

b. The probability of a large shaped charge starting a sustained fire with 53°C diesel fuel which has been cooled by coming into contact with colder metal surfaces is .75. While the fuel will be cooled, the large shaped charge will produce an extremely large and intense cloud of burning aluminum spall. This cloud will provide both a heat source to vaporize the pooled fuel and an ignition source.

5.4.5 Probabilities of a Sustained Fire Given a First Hit by an Overmatching Shaped Charge. Fuel is at one-half capacity.

Before the first hit by an overmatching shaped charge, the vehicle is assumed to be undamaged and all systems are in good working order.

$$\text{UFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 0 \cdot 1 \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 0 \cdot 1 \cdot B$$

5.4.6 Probabilities of a Sustained Fire Given a Second Hit by an Overmatching Shaped Charge. Fuel is at one-half capacity.

After the first hit on the M2, there is a certain probability that the single shot AFSS functioned and is no longer available. If either fuel cell was struck by the first hit and a fire was started, the AFSS functioned and is not available. If neither cell was struck, there is still a

.5 probability that the AFSS functioned. Therefore the probability that the AFSS functioned on the first hit is .9 (A+B), which is the probability that a fire was indeed started, plus .5 (C-.9[A+B]). This last term represents one-half the probability that no fire was started. In this C represents the total probability of penetrating the crew compartment and .9[A+B] represents the probability of starting a fire by hitting the upper fuel cell or the lower fuel cell. Therefore, the probability that the AFSS did function on the first hit so as to be unavailable on the second hit is .9(A+B) + .5(C-.9[A+B]). This is the probability of failure of the AFSS at the time of the second hit. The probabilities of a sustained fire due to a second hit by a large shaped-charge jet are given by the following:

$$\text{UFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot \left[.9(A+B) + .5(C-.9[A+B])\right] \cdot (1-A) \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot \left[.9(A+B) + .5(C-.9[A+B])\right] \cdot (1-B) \cdot B$$

$$\text{CC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot \left[.9(A+B) + .5(C-.9[A+B])\right] \cdot [1-(1-A)(1-B)] \cdot C$$

5.4.7 Comments on Ignition of Flammable Components of M2 by a 125mm KE Round.

For the M2 vehicle, the values assigned to the probabilities of igniting a sustained fire given a hit by a 125mm KE round were arrived at by taking the following into consideration:

a. The M2 is an aluminum vehicle whose armor is significantly less effective than the armor found on the M1A1 tank. The 125mm KE round is designed to penetrate and destroy tanks. This round is a great overmatch for an aluminum vehicle. There are no reports in the literature to provide data on this type of overmatch situation. It is assumed, with a high degree of confidence, that a great deal of damage will be done to the vehicle when it is penetrated by the 125mm KE round. The literature does indicate that, in the case of steel vehicles, a KE round does more damage and is more likely to start a fire than the same size HEAT round.[5] Therefore, a value of .9 (the same value given the 125mm HEAT round) is assigned as the fire starting probability when the 125mm KE round hits a flammable component of the M2.

b. The probability of the 125mm KE round starting a fire with 53°C diesel fuel which has been cooled by coming into contact with colder aluminum surfaces is taken as .75, the same value given the 125mm HEAT round. It is assumed that the KE round will provide a large cloud of burning aluminum spall, just as a HEAT round will.

5.4.8 Probabilities of a Sustained Fire Given a First Hit by a 125mm KE Round. Fuel is at one-half capacity.

Before the first hit by a 125mm KE round, the vehicle is assumed to be undamaged and all systems are in good working order.

$$\text{UFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 0 \cdot 1 \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 0 \cdot 1 \cdot B$$

5.4.9 Probability of a Sustained Fire Given a Second Hit by a 125mm KE Round. Fuel is at one-half capacity.

After the first hit on the M2, there is a certain probability that the single shot AFSS functioned and is no longer available. If either fuel cell were struck by the 125mm KE round and a fire was started, it is assumed that the AFSS functioned and is not available for the second shot. If neither cell was struck, there is still a .5 probability that the AFSS functioned even though there was no fire. Therefore, the probability that the AFSS functioned when the vehicle was hit is .9 (A+B) which is the probability that a fire was indeed started plus .5 (C-.9[A+B]). The last term is one-half the probability that the crew compartment was penetrated but no fire was started. In this C represents the total probability of penetrating the crew compartment and .9[A+B] represents the probability of starting a fire by hitting the upper or lower fuel cell. Therefore, the probability that the AFSS did function on the first hit by a 125mm KE round is .9(A+B) + .5(C-.9[A+B]). This is the probability that the AFSS is unavailable at the time of the second hit on the M2. It is also the probability of failure of the AFSS on the second hit.

The probabilities of a sustained fire due to a second hit by a 125mm KE round on a M2 are given by the following:

$$\text{UFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot \left[.9(A+B) + .5(C-.9[A+B])\right] \cdot (1-A) \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot \left[.9(A+B) + .5(C-.9[A+B])\right] \cdot (1-B) \cdot B$$

$$\text{CC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot \left[.9(A+B) + .5(C-.9[A+B])\right] \cdot \left[1-(1-A)(1-B)\right] \cdot C$$

5.4.10 Comments on Ignition of Flammable Components of M2 by a 30mm APDS round.

For the M2 vehicle, the values assigned to the probabilities of igniting a sustained fire given a hit by a 30mm APDS round were decided on taking the following into consideration:

a. There is no data in the literature for tests of the round in question attacking fuel. It is not even clear whether or not the round has incendiary capabilities by itself. However, this size round, penetrating an aluminum vehicle, should produce a reasonably large cloud of burning aluminum spall. For our purposes, we will assume that the round does, of itself, have incendiary capabilities in addition to any burning aluminum spall which is produced by the round penetrating the M2. A value of .9 is taken as the probability of sustained fire, given a hit on a cell containing diesel fuel at 53°C by the 30mm APDS.

b. The probability of this round starting a sustained fire with 53°C diesel fuel which has been spilled onto cooler surfaces is taken as .5. Even with an incendiary capability, this round should not produce an ignition source as intense as that produced by a 125mm KE round.

5.4.11 Probabilities of a Sustained Fire Given a First Hit by a 30mm APDS Round. Fuel is at one-half capability.

Before the first hit by a 30mm APDS round, the vehicle is assumed to be undamaged and all systems are in good working order.

$$\text{UFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 0 \cdot 1 \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 0 \cdot 1 \cdot B$$

5.4.12 Probabilities of a Sustained Fire Given a Second Hit by a 30mm APDS Round. Fuel is at one-half capacity.

After the first hit on the M2 by a 30mm APDS, there is a certain probability that the AFSS functioned and is no longer available. There is no data on the probability of this round causing the AFSS to function even when there is no fire. Therefore, we will assume that the AFSS functions the same way it does when hit by a large shaped charge.

The probabilities of a sustained fire in the M2 due to a second hit by a 30mm APDS are given by the following:

$$\text{UFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} =$$
$$.9 \cdot [.9(A+B) + .5[C-.9(A+B)]] \cdot (1-A) \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} =$$
$$.9 \cdot [.9(A+B) + .5[C-.9(A+B)]] \cdot (1-B) \cdot B$$

$$\text{CC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} =$$
$$.5 \cdot [.9(A+B) + .5[C-.9(A+B)]] \cdot [1-(1-A)(1-B)] \cdot C$$

5.4.13 Comments on Ignition of Flammable Components of the M2 by an ICM.

For the M2, the values assigned to the probabilities of igniting a sustained fire, given a hit by an ICM (improved conventional munition - small shaped charges delivered by artillery) were arrived at taking the following into consideration:

a. The M2 armor should be penetrated easily by an ICM. It is expected that the jet should be able to travel through the upper fuel cell and then exit into the crew compartment. The jet should produce a cloud of burning aluminum spall to act as an ignition source for the fuel spray which comes from the bottom of the upper fuel cell. This cloud should be capable of igniting 53°C diesel fuel. Therefore, a value of .9 is assigned to the probability of a sustained fire, given a hit on the upper fuel cell.

b. The lower fuel cell rests on the hull of the M2. It is expected that a jet from an ICM would be capable of penetrating into the vehicle and down into the lower fuel cell. If and when the jet exited the bottom of the lower fuel cell, the jet would encounter the vehicle's hull. The aluminum spall eroded from the hull as the jet went through would be ejected into the liquid fuel. Lack of oxygen would prevent this spall from burning and/or igniting the diesel fuel. The fuel that followed the jet out of the fuel cell would leave the vehicle. Any fire would be external to the vehicle. It is also expected that if the jet did make it all the way through the bottom hull, the exit hole would be quite small and the fuel leakage rate would also be small. A value of zero is assigned to the probability of an ICM starting a sustained fire by striking the lower fuel cell of a M2 vehicle.

c. Due to the small size of the ICM's (and correspondingly small signatures) the AFSS is thought to discriminate properly when an ICM penetrates a M2. This means that the AFSS functions when there is a fire in the vehicle and does not function when the jet from an ICM passes through the M2 without causing a fire in the vehicle.

d. The probability of an ICM initiating a sustained fire with 53°C diesel fuel which has been spilled onto colder aluminum surfaces is taken as .75. It is expected that even this small shaped-charge device will produce enough burning aluminum spall to be an efficient ignition source for the spilled diesel fuel.

5.4.14 Probabilities of a Sustained Fire Given a First Hit by an ICM. Fuel is at one-half capacity.

Before the first ICM hit, the M2 is assumed to be undamaged and all systems are in good working order.

$$\text{UFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot 0 \cdot 1 \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot 0 \cdot 1 \cdot B$$

5.4.15 Probabilities of a Sustained Fire Given a Second Hit by an ICM. Fuel is at one-half capacity.

The probabilities of a sustained fire in the M2 due to a second hit by an ICM are given by the following:

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .9 \cdot (.9A) \cdot (1-A) \cdot A$$

$$\text{LFC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = 0 \cdot (.9A) \cdot (1-B) \cdot B$$

$$\text{CC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .75 \cdot (.9A) \cdot [1-(1-A)(1-B)] \cdot C$$

5.5 The HMMWV - High Mobility Mechanized Wheeled Vehicle.

5.5.1 Observations on the Fuel System of the HMMWV.

The following observations are made concerning the fuel system of the HMMWV:

a. This truck type vehicle has a single fuel cell which is located under the body, between the steel frame rails. The cell is made of nylon.

b. The fuel cell is located close to the muffler. The cell can be heated by the muffler. In tests, in very hot weather, the temperature of the outer skin of the fuel cell has been measured at nearly 57°C.

c. The engine of the HMMWV uses a jerk-pump method of fuel distribution, which causes only a small fuel temperature rise.

d. The HMMWV has no AFSS. However, the fuel cell is actually outside the body of the vehicle, near the rear. Spilled fuel will fall onto the ground, under the vehicle. In some cases (taken as one-half), the driver may simply drive the HMMWV away from the fuel spill and any fire. Therefore, a value of .5 is assigned to the AFSS term used in the fire probability model of the HMMWV. The location of the fuel cell in the HMMWV is superior to that of many trucks, where the fuel cells are right under the drivers.

e. There is no hydraulic fluid fire threat to this vehicle.

5.5.2 Assumptions on the Fuel System of the HMMWV.

The following assumptions are made concerning the fuel system of the HMMWV.

a. The fuel used is neat diesel fuel with a flash point of 65.6°C.

b. The temperature of the fuel in the fuel cells is 26°C.

c. The lubricants and transmission fluid are not considered to be fire threats to the vehicle.

d. A broken fuel line is not considered to be a fire threat to the vehicle.

5.5.3 Code for Location of the Flammable Component of the HMMWV.

For the HMMWV the only location for a fire is the fuel cell, given the code (FC) and a probability of penetrating the fuel cell, for a particular weapon, of (A).

5.5.4 Comments on Ignition of Flammable Component.

The value assigned to the probability of starting a sustained fire, given a hit by a 12.7mm round was arrived at by taking the following into consideration:

a. The fuel cell is in a location where it is well protected by steel structures. It would be difficult for a 12.7mm round to penetrate these steel parts and hit the fuel cell. Nevertheless, tests have shown that this caliber round can penetrate steel plate and retain its incendiary or tracer parts. Therefore, there is still some fire starting potential for this round against the fuel cell of the HMMWV containing 26°C diesel fuel. A value of .1 is taken as the probability of sustained fire given a hit by a 12.7mm round.

5.5.5 Probability of a Sustained Fire Given a First Hit by a 12.7mm Round. Fuel is at one-half capacity.

Before the first 12.7mm hit, the vehicle is assumed to be undamaged.

$$\text{FC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .1 \cdot .5 \cdot 1 \cdot A$$

5.5.6 Probability of a Sustained Fire Given a Second Hit by a 12.7mm Round. Fuel is at one-half capacity.

The only important difference to the HMMWV after the first hit is the possibility that the fuel tank was struck by the first hit and is no longer available when the second 12.7mm round hits.

$$\text{FC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .1 \cdot .5 \cdot (1-A) \cdot A$$

5.5.7 Comments on Ignition of Flammable Component of HMMWV by a 30mm APDS Round.

The value assigned to the probability of igniting the fuel in the HMMWV given a hit by a 30mm APDS was arrived at taking the following into consideration:

a. While the fuel cell is well protected by steel structures, a 30mm round is really a large overmatch for a vehicle like the HMMWV. This round should be able to penetrate to and cause severe damage to the fuel cell. It is assumed that this round has incendiary or at least tracer material which will remain with the round all the way to the fuel cell. Therefore, a value of .5 is assigned to the fire starting capability of this round with 26°C diesel fuel.

5.5.8 Probability of a Sustained Fire Given a First Hit by a 30mm APDS Round. Fuel is at one-half capacity.

Before the first 30mm hit, the vehicle is assumed to be undamaged.

$$\text{FC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot .5 \cdot 1 \cdot A$$

5.5.9 Probability of a Sustained Fire Given a Second Hit by a 30mm APDS Round. Fuel is at one-half capacity.

On the second 30mm hit, the possibility of loss of the fuel cell on the first hit must be taken into account. Therefore, for the second hit

$$\text{FC} \quad P_{SF} = P_{SF/H} \cdot P_{F/AFSS} \cdot P_{E/FC} \cdot P_{H/FC} = .5 \cdot .5 \cdot (1-A) \cdot A$$

6. SUMMARY

A simple model was used to predict probabilities of sustained fires when Army vehicles are hit in combat. Both kinetic energy and shaped-charge rounds were considered penetrating the vehicles and striking flammable components (only hydrocarbon materials were considered, ammunition is not included in the model).

Quite a wide spectrum of vehicle types, fuel temperatures and attacking munitions was used in this study. The five vehicles were:

a. the M1A1 tank

b. the M2 infantry fighting vehicle

c. the M113A1 armored personnel carrier

d. the ITV improved TOW vehicle

e. the HMMWV high mobility mechanized wheeled vehicle

These vehicles cover both steel and aluminum hulls with steel, aluminum, nylon and polyethylene fuel cells.

The only fuel considered was diesel fuel. The fuel temperature range used was $8^{o}C$ to $53^{o}C$. Fuel quantities of full and one-half capacities were examined. Fuel spills internal and external to the vehicle were considered in this study. The presence or absence of an automatic fire extinguishing system was taken into account along with an estimate of the probability of the system functioning properly. The probability of a system discharge due to a penetration which does not initiate a fire was also estimated.

The model was used to predict the probability of a sustained fire on both the first and second hit on the vehicle by the same weapon. The probability of damage to the vehicle by the first hit was taken into account to set up the condition of the vehicle before the second hit.

The weapons considered in this study were:

a. the 125mm kinetic energy round (tungsten)

b. the 125mm HEAT round

c. the RPG-18 rocket propelled grenade

d. the 30mm APDS round

e. the 12.7mm round

f. the AT5 and AT8 rockets

g. the ICM improved conventional munition (small shaped charge used for overhead attack).

7. CONCLUSIONS

There are sufficient data available to enable one to use a simple model to predict probability of sustained fires when vehicles are struck by weapons in combat. It is also possible to take into account the condition of vehicles after initial hits to allow for fuel spills, damaged fuel cells, etc.

The main problem with this simple model is that it requires the user to examine each particular vehicle in detail. It is not enough to know the materials of construction of the vehicle, type of fuel, fuel temperature and attacking weapon. To use the model, it is necessary to have a detailed knowledge of the fuel system of the vehicle. It is also necessary to know how the automatic fire suppression system (if any) functions. Fortunately, the model is gross enough that exact characteristics of the fuel (flash point and fire point) are not required. However, residual penetrations from weapon-armor interactions are required. These can be provided by the BRL Vulnerability/Lethality models.

When more information becomes available on weapon-fuel interactions, it will be possible to use a more exact model of ignition and sustained combustion. An improved model should give improved estimates of vehicle loses due to fuel fires, along with personnel casualties which are not even addressed by the simple model which was used in this study.

APPENDIX A

PROBABILITIES OF SUSTAINED FIRES IN VARIOUS VEHICLES

Vehicle	Type	Fuel Temperature	Weapon	Probability of Sustained Fire Given a Hit
M1A1	Steel	$8^{o}C$ ($46^{o}F$)(hull)	Overmatching S.C.	.15
		24^{o} ($75^{o}F$)(engine)	"	.25
		$8^{o}C$ ($46^{o}F$)(sponson)	"	.10
		$77^{o}C$ ($170^{o}F$)(hydraulics)	"	.5
		$8^{o}C$ ($46^{o}F$)(pool-hull)	"	0
		$24^{o}C$ ($75^{o}F$) plus (pool-engine)	"	.75
		$8^{o}C$ ($46^{o}F$)(hull)	125mm KE (tungsten)	.5
		$24^{o}C$ ($75^{o}F$)(engine)	"	.6
		$8^{o}C$ ($46^{o}F$)(sponson)	"	.3
		$77^{o}C$ ($170^{o}F$)(hydraulics)	"	.5
		$8^{o}C$ ($46^{o}F$)(pool hull)	"	0
		$24^{o}C$ ($75^{o}F$) plus (pool-engine)	"	.75
M2	Aluminum	$53^{o}C$ ($128^{o}F$)(upper)	Overmatching S.C.	.9
		$53^{o}C$ ($128^{o}F$)(lower)	"	.9
		$53^{o}C$ ($128^{o}F$)(pool-crew comp)	"	.75
		$53^{o}C$ ($128^{o}F$)(upper)	ICM	.9
		$53^{o}C$ ($128^{o}F$)(lower)	"	0
		$53^{o}C$ ($128^{o}F$)(pool-crew comp)	"	.75
		$53^{o}C$ ($128^{o}F$)(upper)	30mm APDS	.9
		$53^{o}C$ ($128^{o}F$)(lower)	"	.9
		$53^{o}C$ ($128^{o}F$)(pool-crew comp)	"	.5

PROBABILITIES OF SUSTAINED FIRES IN VARIOUS VEHICLES (CONT'D)

Vehicle	Type	Fuel Temperaure	Weapon	Probability of Sustained Fire Given a Hit
M2	Aluminum	53°C (128°F)(upper)	125mm KE (tungsten)	.9
(Continued)		53°C (128°F)(lower)	"	.9
		53°C (128°F)(pool-crew comp)	"	.75
M113	Aluminum	53°C (128°F)(cell in crew comp)	Overmatching S.C.	.9
		53°C (128°F)(pool in crew comp)	"	.75
		53°C (128°F)(cell in crew comp)	30mm APDS	.9
		53°C (128°F)(pool in crew comp)	"	.5
ITV	Aluminum	53°C (128°F)(cell-outside vehicle)	Overmatching S.C.	0
		77°C (170°F)(hydraulics)	"	.75
		77°C (170°F)(pool-hydraulic fluid)	"	0
		77°C (170°F)(hydraulics)	ICM	.75
		77°C (170°F)(pool-hydraulic fluid)	"	0
		53°C (128°F)(cell-outside vehicle)	"	0
HMMWV	Steel	26°C (79°F)(cell-between frame rails)	12.7mm	.1
		26°C (79°F)(cell-between frame rails)	30mm APDS	.5

APPENDIX B

PROBABILITIES OF SUSTAINED FIRES IN VARIOUS VEHICLES ATTACKED BY DEPLETED URANIUM (DU) WEAPONS

Vehicle	Type	Fuel Temperature	Weapon	Probability of Sustained Fire Given a Hit
M1	Steel	8°C (46°F)(hull)	125mm DU, KE	.8
		24°C (75°F)(engine)	"	1
		8°C (46°F)(sponson)	"	.4
		77°C (170°F)(hydraulics)	"	.5
		8°C (46°F)(pool-hull)	"	.1
		24°C (75°F)(pool-engine)	"	.9
M2	Aluminum	53°C (128°F)(upper)	30mm DU, APDS	1
		53°C (128°F)(lower)	"	1
		53°C (128°F)(pool-crew comp)	"	1
		53°C (128°F)(upper)	125mm DU, KE	1
		53°C (128°F)(lower)	"	1
		53°C (128°F)(pool-crew comp)	"	1
M113	Aluminum	53°C (128°F)(cell-crew comp)	30mm DU, APDS	1
		53°C (128°F)(pool-crew comp)	"	1
ITV	Aluminum	53°C (128°F)(cell-outside vehicle)	30mm DU, APDS	0
		77°C (170°F)(hydraulics)	"	.75
		77°C (170°F)(pool-hydraulic fluid)	"	0
HMMWV	Steel	26°C (79°F)(cell-bet frame rails)	12.7mm DU	1
		26°C (79°F)(cell-bet frame rails)	30mm DU, APDS	1

APPENDIX C

SOME DO'S AND DON'TS OF FUEL SYSTEM DESIGN

1. A study of the fuel systems (and related systems containing flammable fluids) of several US Army vehicles has led to the conclusion that these systems were designed just to give reliable over-the-road operation. It is painfully obvious that little or no thought has been given to the fact that the fuel systems of these vehicles may someday suffer combat damage. In some cases one realizes how little damage needs to be done to the vehicles to render them inoperable, or even worse, burned out wrecks.

2. General ideas on the design of fuel and related systems are given in the following comments (Do's and Don'ts).

	Do	Don't
a.	Use diesel fuel.	Use gasoline or JP8.
b.	Use engine designs that heat fuel to only a minimal amount (temperature rise of fuel only about 20°F above ambient).	Use engine designs that heat fuel excessively (temperature rise of fuel can be as much as as 120°F above ambient).
c.	Place fuel cells on exterior portion of vehicle or compartmentalize fuel.	Place fuel cells in crew compartment.
d.	Use multiple fuel cells.	Use a single fuel cell.
e.	Use redundant fuel feeds to engine.	Use single fuel feed to engine.
f.	Use shut-off valves between fuel cells.	Use permanent interconnects between fuel cells.
g.	Use fuel cell design which minimizes damage due to hydrodynamic ram.	Use fuel cell geometry which leads to major damage to cells due to hydrodynamic ram.
h.	Provide ullage (vapor space) above fuel.	Fill fuel cells completely.
i.	Surround fuel cells with non-pyrophoric materials (e.g. plastic).	Surround fuel cells with pyrophoric materials (e.g. aluminum).
j.	Use non-flammable hydraulic fluid.	Use low flash point hydraulic fluid.
k.	Use hydraulic fluid reservoir design which minimizes hydrodynamic ram effect.	Use hydrualic fluid reservoir design which leads to major failure of reservoir due to hydrodynamic ram.

3. Examples will now be given of how these comments apply to current vehicles.

a. JP8 is much more flammable than is diesel fuel. Typical measurements of flash points of diesel fuel are generally around 150°F. The flash point of JP8 can be as low as 104°F, with a typical value only a few degrees higher. In the name of fuel commonality, the US Army is seriously considering using JP8 in our ground combat vehicles in Europe. This can only lead to more vehicle fuel fires in the event of combat.

b. Some combat vehicles (ex. M2, M3 and M113) use a fuel distribution system known as the common-rail system. In this system, fuel flows through a gallery in the head of the engine. Excess fuel is returned to the fuel cell. This excess fuel is heated through contact with the hot engine. Tests at Aberdeen Proving Ground showed that in the M113, the excess fuel returned to the cell can be heated as much as 120°F above ambient. As the fuel level drops, the bulk fuel in the cell undergoes a continued temperature rise. At very low fuel levels, the remaining fuel can experience the 120°F temperature rise. However, in hot weather, even with a substantial amount of fuel remaining in the cell, the fuel can be above its flash point. Both laboratory tests and field tests have shown that when diesel fuel is above its flash point, it is as flammable as gasoline.

Tests at Aberdeen Proving Ground on the M60 tank, which has a fuel distribution system known as the jerk-pump system, indicates that the fuel undergoes a temperature rise of only about 20°F above ambient. This is the type of fuel distribution system which should be used in combat vehicles.

c. The M2, M3, and M113, which tend to have high fuel temperatures, also place the fuel cells in the crew compartment. In case of a hit on a fuel cell in combat, both the vehicle and the crew are in grave danger. Tests have been conducted with a modified M113 which had two fuel cells attached to the rear of the vehicle. The cells were protected by normal M113 type armor. Neither shaped charge nor kinetic energy round attack could cause serious internal fires in this vehicle. The danger of catastrophic fires was reduced for both crew and vehicle.

d and e. The modified M113 used in the tests mentioned in "C" had independent fuel feeds to the engine. Therefore, a hit on one fuel cell did not result in a mobility kill, since the vehicle could use fuel from the undamaged cell.

The M1 tank has six fuel cells but, if only one rear fuel cell is broken, it is impossible to send fuel to the engine from the front, undamaged cells. The fuel can go from the front cells only to a rear cell. There is no independent fuel line from the front cells to the engine. Therefore, a hole or break in one rear fuel cell renders the vehicle inoperable.

f. The M1 tank has four rear fuel cells, two main cells, and two sponson cells. The sponson cells are above the main cells and send fuel into the main cells by gravity feed. The two main cells, one on each side of the engine, are connected by a pipe. There are no fuel shut-offs in this four cell system. A hole in one of the rear main cells will cause loss of the fuel from all four rear cells. Since, as mentioned above, the front cells can send fuel only to a rear fuel cell, all fuel will be lost as far as the engine is concerned. There should be shut-off valves which can be activated if a cell is punctured during combat.

g. The upper fuel cells of the M2 and M3 vehicles are constructed of nylon. There is no particular reason not to use a plastic fuel cell. However, these cells are made with relatively sharp corners which can crack easily if the cells are subjected to large stresses, particularly those stresses caused by the passage of penetrators through the cells. The large flat sides of the cells which face the crew compartments are unsupported. These cells were not designed for survivability. Tests conducted at the Ballistic Research Laboratory and at Southwest Research Institute have shown that with the addition of energy absorbing material and a reinforcing structure, cells can survive a shaped-charge jet with only a small entrance hole and a small exit hole. Only a small amount of fluid spray is lost. Leakage of liquid occurs down to the holes. Fluid is retained below the holes. Therefore, the vehicles would not necessarily experience a mobility kill, even though a shaped-charge jet has passed through the fuel cell. Fuel is still available to run the engine. In addition, the cells are easily repairable, perhaps even by the crew. This could be important in the event that repair facilities are overtaxed due to large numbers of combat damaged vehicles.

h. If a fuel cell (or any fluid container) is penetrated in combat, there must be adequate ullage to prevent total disruption of the cell by hydrodynamic ram pressures. In a fuel system, if one cell is fed by another, care must be taken to provide an ullage in the cell. A completely filled M1 rear cell was destroyed when struck by a shaped-charge jet. A similar cell, half-full, received relatively minor damage when struck by a similar jet. The fuel system designer must keep in mind the need for ullage.

i. There is substantial hi-speed motion picture evidence that the fuel mist released from a cell which has been perforated by a shaped-charge jet does not ignite immediately. A good ignition source is required to ignite the spray. After exiting the fuel cell, the shaped-charge jet continues across the vehicle to strike some interior surface. If this surface is aluminum, a large cloud of burning aluminum is formed. This is an excellent ignition source. Data shows that even burning steel is not as good an ignition source as is burning aluminum. It is expected that if the surface surrounding the fuel cell was non-pyrophoric, a poor ignition source would be formed. This would decrease the probability of ignition of the fuel spray. Use of plastics or paints containing fire extinguishing agents may be helpful.

j. The US Army has fielded a fire resistant hydraulic (FRH) fluid in response to reports that combat damage to tanks can lead to hydraulic fluid fires. However, the FRH fluid, when released from pressurized lines, will form a spray. Data shows that this spray is very flammable. It is the bulk FRH fluid which is resistant to pool burning. Extensive damage from spray burning is still possible. A truly non-flammable hydrualic fluid is needed. Such a fluid is only at the laboratory stage. It should be fielded as soon as possible.

k. The principle mentioned above which can protect fuel cells from catastrophic damage applies also to hydraulic fluid reservoirs. Surrounding the reservoir with shock absorbing material, placing a metal confining box over the shock absorbing material and securing the reservoir to its mounts will keep the reservoir intact and in place. Fluid will be lost only down to the level of the penetrator entrance and exit holes. The amount of fluid spray will be minimized. The system may still function on the remaining fluid and should be relatively easily repairable.

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