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UNIQUE CHALLENGES OF FLAMMABLE LIQUID FIRES IN GROUND VEHICLES
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14. ABSTRACT

In 2006, the Fire Research Team of the Air Force Research Laboratory began studies on fire suppression for ground vehicles. The Fire Research Team is part of the Airbase Technologies Division in the Materials and Manufacturing Directorate and is located at Tyndall Air Force Base near Panama City, Florida. The studies were to look at the problem of protecting occupants in vehicles, not engine compartment or fuel tank fires. Specifically of interest were fires caused by flammable liquid fuel accompanied by fire entering vehicles from the outside through the windows. This scenario was of particular interest because existing in-vehicle fire suppression systems seemed ill suited to this type of fire event. No specific fire suppression systems designed for ground vehicles were evaluated during this study. The purpose of the work was to achieve a better understanding of the scope and complexity of the problem. This paper outlines the problem, describes the methods used to study this category of vehicle fire, discusses the data obtained from those studies, and suggests aspects for consideration by designers of fire extinguishing systems for use in ground vehicles that might be exposed to this fire scenario.

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UNIQUE CHALLENGES

OF FLAMMABLE LIQUID FIRES IN GROUND VEHICLES

By John Hawk

***John Hawk** has been a senior engineer at the U.S. Air Force Research Laboratory (AFRL) fire research facility for six years and has done several studies involving ultra high speed fire suppression and blast mitigation systems. The AFRL fire research facility is located on Tyndall Air Force Base near Panama City, Florida.*

In 2006, researchers at the Air Force Research Laboratory's (AFRL) fire facility began studies on the subject of fire suppression for ground vehicles. The studies were undertaken to assess the problems associated with protecting vehicle occupants, not engine compartment or fuel tank fires. Of particular interest were fires caused by flammable liquid fuel accompanied by fire entering vehicles from the outside through the windows. Existing in-vehicle fire suppression systems seemed ill suited to this type of fire event. No specific fire suppression systems designed for ground vehicles were evaluated during this study. The purpose of the work was to reach a better understanding of the scope and complexity of the problem. This paper outlines the problem, describes the methods used to study this category of vehicle fire, presents the data from those studies, and suggests criteria for consideration by designers of fire extinguishing systems for use in ground vehicles that might be exposed to this fire scenario.

THE PROBLEM

Ground vehicle fire suppression systems are typically designed to target the most likely sources of fire in a vehicle. They are usually intended to suppress or extinguish fires in engine compartments, fuel tank areas, electrical cabinets, coolant heater compartments, wheel wells, and other areas where fire hazards exist. Some vehicles are equipped with automatic or manually initiated systems to control or extinguish fires in the passenger compartment, primarily for fires that spread from the engine compartment or fuel tank. For fires that progress slowly, systems initiated

Figure 1. *Gasoline and small explosive charge incendiary device*

manually or by optical detectors mounted inside passenger compartments are typically adequate. Fires that come from outside a vehicle present unique problems that challenge traditional vehicle fire suppression systems.

Explosions involving flammable liquid (gasoline, kerosene, heating oil, biodiesel, ethanol, etc.) can throw unburned fuel into vehicles through opened windows, or in some cases through windows damaged by the explosion itself. The unburned fuel can wet skin, clothing, and the inside surfaces of the crew cabin and subsequently be ignited by the flame front. The most popular agents used in vehicular fire suppression systems are gaseous flooding and dry chemical suppressants, and neither acts to cool a fire inside a passenger compartment. In addition, the success of gaseous flooding agents is in large part determined by the ability to concentrate the chemical at the location of the fire, which is difficult to achieve when windows are open or breached.

In a rapidly evolving fire event, fire progresses too quickly for passengers to respond with portable extinguishers, and even installed systems that are manually initiated may not respond in adequate time to prevent severe burns or mortality. The challenges to a gaseous or dry chemical extinguisher system and the rapidity of the event combine to make this scenario particularly difficult to mitigate.

PROCEDURES

The fireball was created by detonating an incendiary device consisting of a half-pound of high explosive on one side of a cardboard box that contained a two gallon bag filled with gasoline (Figure 1). The device was located eight feet from the test vehicle and elevated three feet above the ground using a cardboard tube. The device was oriented so the force of the detonation would push the gasoline in the direction of the test vehicle.

A test vehicle mockup (Figure 2) was constructed from 1/8th inch steel plate. A mockup was used instead of an actual vehicle so that multiple tests could be done on the fixture without causing a significant amount of damage. The mockup was essentially a rectangular box with dimensions characteristic of the crew cabin in any ground vehicle with two rows of seats. Two 10 inch x 14 inch windows were cut into the side of the vehicle that faced the incendiary device, and the side opposite the windows was left open to give an unobstructed view of the interior during the fires. A pressure sensor was mounted on one side not oriented directly toward the detonation, and a heat flux sensor was mounted inside the vehicle above one of the windows. A high-speed camera was used to capture video records of the tests, kept safely inside a protective enclosure behind the vehicle, with a view of the open interior of the vehicle (Figure 3).

A data acquisition system was set to start recording data from the pressure and heat flux sensors, and to trigger the high-speed video camera when the detonator for the incendiary device was initiated. The pressure instrument recorded time of arrival for the pressure wave caused by the detonation, from which an approximate speed for the wave could be calculated. High-speed video was used to establish the time of arrival of the flame front, which could then be used to estimate an approximate velocity for the advancing front.

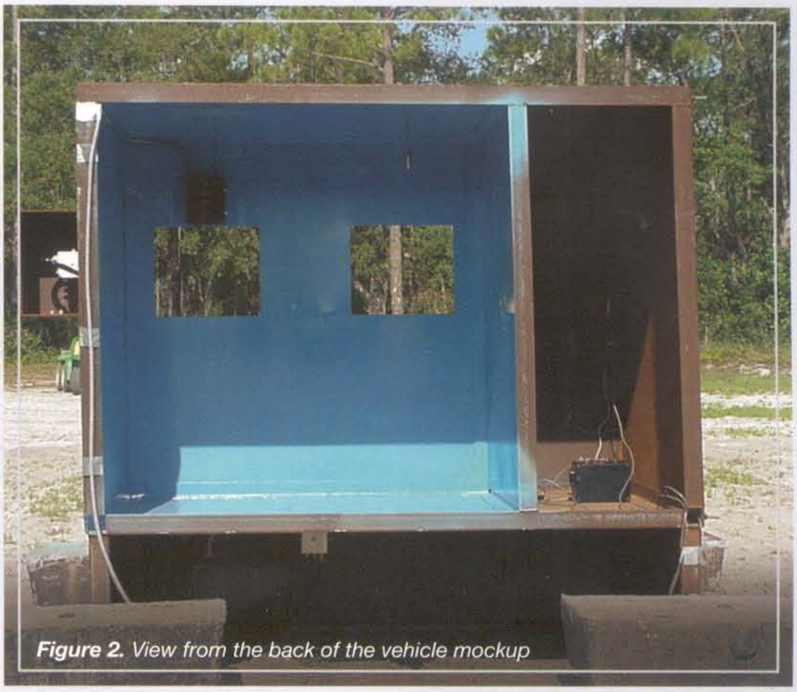

Figure 2. *View from the back of the vehicle mockup*

Data from the heat flux sensor showed variation in heat flux inside the vehicle over the duration of the fire, and cumulative heat energy could be calculated from the data.

RESULTS AND DISCUSSION

The pressure wave from the explosion arrived at the face of the vehicle six milliseconds after detonation, which equates to an average velocity of about 1333 feet per second. Video records showed that unburned gasoline began to enter the vehicle through the open windows 27 milliseconds later, and 20 milliseconds after that the flame front reached the vehicle, a total of just 53 milliseconds after detonation. Note the absence of flame on the side toward the vehicle mockup during the initial detonation, shown in Frame 1 of Figure 4. What appears to be dirt thrown in the direction of the mockup is in fact gasoline. Heat flux reached 4.4 Btu/sec-ft^2 (50 kW/m^2) 147 milliseconds after detonation, 8.8 Btu/sec-ft^2 (100 kW/m^2) at 155 milliseconds, and maximum heat flux of 30 Btu/sec-ft^2 (340 kW/m^2) was attained 210 milliseconds after flames first reached the vehicle. To put that into perspective, a complete blink of an eye for most people takes about 300-400 milliseconds. Heat flux remained above 4.4 Btu/sec-ft^2 for nearly three seconds and above 8.8 Btu/sec-ft^2 for about two seconds. A heat flux of 4.4 Btu/sec-ft^2 causes burns to human skin after about one second of exposure, and 8.8 Btu/sec-ft^2 corresponds to the heat flux at the flame tip of a propane torch.

Flame first reached the vehicle 53 milliseconds after detonation. Assuming the flame front began to move outward from the origin at the instant of detonation, an average speed of

Figure 3. *Test bed: incendiary device, mockup, and protective enclosure for the high-speed camera*

the flame front can be estimated to be 150 feet per second. Because there is a slight delay between detonation of the explosive charge and ignition of gasoline near the origin of the explosion, 150 feet per second is a lower limit on speed; the flame front was likely moving a little faster than 150 feet per second, but for the sake of this argument the estimated speed will suffice. Advancing at 150 feet per second, the flame front would travel more than five inches into the interior of the vehicle in three milliseconds, the earliest that a high quality dual or triple band infrared detector would be expected to respond. For the 20 milliseconds preceding arrival of the flame front, unburned fuel would spread inside the vehicle, dousing the occupants and exposed surfaces inside the vehicle and filling the cabin with a spray of gasoline. The rapidly advancing flame front would then ignite this unburned fuel and could spread throughout an eight foot wide passenger cabin in a little more than 50 milliseconds.

This demonstrates the serious challenges to fire suppression that a scenario such as this presents, and it illustrates the importance of fast response. Detection must occur, the system must activate, the passenger compartment must be flooded with agent, and the fire must be extinguished in less than a second if occupants are to be protected from severe burn injuries. Also, the amount of agent delivered into the crew compartment must be of sufficient quantity and delivered at a sufficient rate to extinguish the fire even if the compartment is vented through open windows, which allows agent to escape the compartment while oxygen continues to flow in and replenish the fire. Even if the fire was quickly extinguished, liquid fuel would remain on the skin and clothes of occupants and on surfaces in the vehicle, and any hot spot or spark could reignite the fire.

Frame 1 *Frame 2* *Frame 3*

Figure 4. *Frames from high-speed camera showing progression of the fire*

CONCLUSIONS AND RECOMMENDATIONS

In explosions involving flammable liquids, fire and unburned fuel can enter open or damaged windows and spread rapidly inside passenger vehicles. The speed at which the scenario unfolds and the dangers in the unburned fuel present rare challenges. Studies conducted at the AFRL fire facility at Tyndall Air Force Base are a first step toward better understanding the threat to ground vehicles from fires involving flammable liquids. Only enough trials were done to gain a better understanding of the scope of the problem, so there was not enough data collected to be statistically conclusive and additional research is needed. However, several observations from the experiments should be considered in design or selection criteria.

Consideration should be given to using a detection system capable of sensing the event before fire reaches the interior of the vehicle, making possible initiation of the fire suppression system in advance of the flame front. This might be accomplished by use of a pressure sensor alone or in combination with an optical sensor. Since the pressure front travels in advance of the flames in a case such as this, initiating the suppression system or alerting the system so it is prepared to respond more quickly if an optical cue is also received could reduce the time that occupants are put at risk.

Fire extinguishing systems must respond quickly under these circumstances. A sufficient amount of agent must be directed into the passenger compartment quickly enough to limit heat flux to a tolerable level and prevent serious burn injuries. Gaseous and dry chemical agents can flood a compartment and extinguish a fire quickly, but they will also leak through open or damaged windows, which will lower the concentration of agent inside the vehicle and allow a fire to reignite and grow. Gaseous and dry chemical agents don't provide cooling either, and that means that temperature and heat remain high inside a vehicle even after a fire is extinguished. Consequently, there is greater likelihood of people inside being exposed to a dangerous level of heat flux and greater likelihood of a fire being reignited from a hot spot or spark. Water or water based agents like foam and fire gel, provide cooling, and water based agents directed inside a vehicle would be less likely to escape through open windows. A water based agent would also coat exposed skin and clothing, creating a barrier to heat. A dual agent system that uses dry chemical or a gaseous agent to quickly knock down flames and reduce heat flux, in combination with a water based agent to provide cooling and re-flash protection might be a better solution than either of the agents used alone.

Finally, system performance testing of in-vehicle fire extinguishing systems should not be accomplished by substituting gaseous fuel for liquid fuel because of the unique problems posed by the flammable liquid. Some research and development of fire suppression systems has been done using propane, butane, or similar hydrocarbon gasses to supply the flame for testing system response. This is a convenient method for producing the test flame because turnaround time for successive tests is short in comparison to tests done using flammable liquid fuels. However, one of the uniquely challenging characteristics of a flammable liquid explosion and fire derives from the unburned liquid fuel that is dispersed by the explosion. This aspect of the threat cannot be genuinely simulated by a gaseous fuel, and use of gaseous fuel in place of flammable liquid fuel in evaluations of system performance will give a false sense of the true performance of the system in response to a fire from flammable liquid. ■