METHODS OF QUANTIFYING AND MITIGATING AEROSOL FIRE AND EXPLOSION HAZARDS ASSOCIATED WITH LOW VAPOR PRESSURE LIQUIDS

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INTRODUCTION

This paper addresses the hazards associated with aerosolized hydraulic fluids and other liquids designed to be relatively non-flammable with respect to flashpoint and vapor pressure. The studies presented seek to understand and quantify conditions and circumstances that can produce such hazardous conditions. US Navy personnel are particularly susceptible to fuel aerosol hazards due to the widespread use and storage of these materials on both ships and airbases [1-3]. As a result a great deal of research effort has been directed toward designing safer jet fuels, lube oils, and hydraulic fluids. Most of these approaches have focused on improving the thermodynamic properties of the liquids by increasing their flashpoint and lowering their liquid vapor pressure. This approach was used by the Department of Defense (DOD) to reduce aviation fires. The design and implementation of lower volatility aviation fuels such as JP5 (Navy) and JP8 (Air Force) helped to reduce fuel ignition caused by gunfire in combat and help increase fire safety aboard aircraft carriers [4].

The DOD has also put a great deal of effort in the development of fire-resistant hydraulic fluids as a replacement for petroleum-based hydrocarbon fluids still in use today [1,2,5,6]. Though these fluids looked promising, flammability tests suggested aerosols of these fluids had the potential to ignite and burn [1,2,6]. The safety advantages of these fluids were not enough to warrant the cost of switching to these fluids or the potential unknown operational risks of using these fluids, thus they were never implemented [5,6].

Though changing and designing fluids with better thermodynamic properties increases fuel safety in bulk, little work has been done to quantify, predict, and mitigate hazards associated with these liquids when they become aerosolized. These systems are complex because the vapor concentration is dependent on several parameters which include; droplet size, number density, fuel flow rate, and droplet linear velocity. In these studies, large scale tests demonstrate the potential consequences of the atomization of 2190 TEP and the existing technology used to mitigate these hazards. In addition, current methods and techniques used to quantify aerosol composition and the correlations established to identify and predict hazardous aerosol compositions will be demonstrated.

EXPERIMENTAL

The large-scale simulations of hydraulic system explosions were conducted in an compartment in the Naval Research Laboratory's (NRL) ex-*USS Shadwell* full-scale fire test facility, located in Mobile, AL [7-9]. The compartment mockup was built in the port wing wall on the ex-*USS*

Shadwell with lateral dimensions of 8.5 meters by 4 meters. The properties of the hydraulic fluid used in the test series are shown below in Table 1.

Table 1. 2190-TEP Fluid Properties

2190 TEP Property	Property Value
Manufacturer	Chevron Turbine Oil Symbol 2190 TEP
Composition	>99% Heavy paraffinic distillates
Absolute Viscosity (cP)	69.0 @ 40 ^{o}C; 8.4 @ ^{o}C
Flash Point (^{o}C)	246
Boiling Point (^{o}C)	>315
Specific Gravity	0.86 – 0.87
Heat of Combustion (MJ/Kg)	42.7

The hydraulic fluid was pressurized to 10 MPa (1450 psi) in a 190 liter (50 gal.) pressure vessel using a 12-cylinder nitrogen manifold. The cylinder was connected to a nozzle array using 1.3 cm (0.5 inch) diameter welded stainless steel pipe. The array consisted of five in-line positions, which were plugged when not being used. The nozzles were Bete Fog Nozzles, Inc. model P24, 90^{o} solid cone spray nozzles. The fluid temperature at the nozzles was approximately 45 – 50 ^{o}C.

Ignition of the aerosols was achieved using an electric arc, energized by an Allson type 4258 transformer (120 VAC, 450 VA input; 15 kv, 30 mA output). The 3 cm spark gap was located above the nozzle array. The pressure transducers (1-2 psi) (Omegadyne model PX02C1-002G5T) were installed outside the test compartment and were connected to short, large bore stainless steel tubing that penetrated the bulkhead. This allowed fast pressure transient measurements to be made during the tests.

The fire extinguishing agents tested for mitigation were standard PKP, CO_2, and AFFF extinguishers and hand held water mist systems. In each test, the agents were completely discharged into the mist cloud before the area was secured and the explosion was initiated. The water mist systems had no characteristic discharge time, so water was applied to the mist cloud the longest. Further experimental details are reported elsewhere [8,9].

Small scale aerosol studies were conducted using a rotary atomizer and JP5 kerosene. The kerosene was purchased from Putuxent River Naval Air Station. Figure 1 shows a diagram of the test apparatus used to generate the aerosols. The aluminum test stand has a trough and splash guards to contain aerosol generation. An aluminum rotary disk, 3.0 inches (7.6 cm) in diameter and 0.50 inches (1.3 cm) thick, is located at the center of the test stand. The disk has a cavity 1.0 inch (2.5 cm) in diameter and approximately 0.25 inches (0.63 cm) deep in the center with four radial holes. The radial holes are spaced 90 degrees apart and were drilled from the outer rim of the disk to the center of the cavity. The Figure shows fluid is delivered to the center of the disk and a motor creates centrifugal forces that push the fluid through the radial holes, producing an aerosol. A propane fed Bunsen burner, located 5.2 inches (13 cm) from the edge of the disk, is the aerosol ignition source. Each aerosol system is studied over a range of rotational speeds (1000 – 16000 rpm) and liquid flow rates to the disk (50 – 200 mL/min).

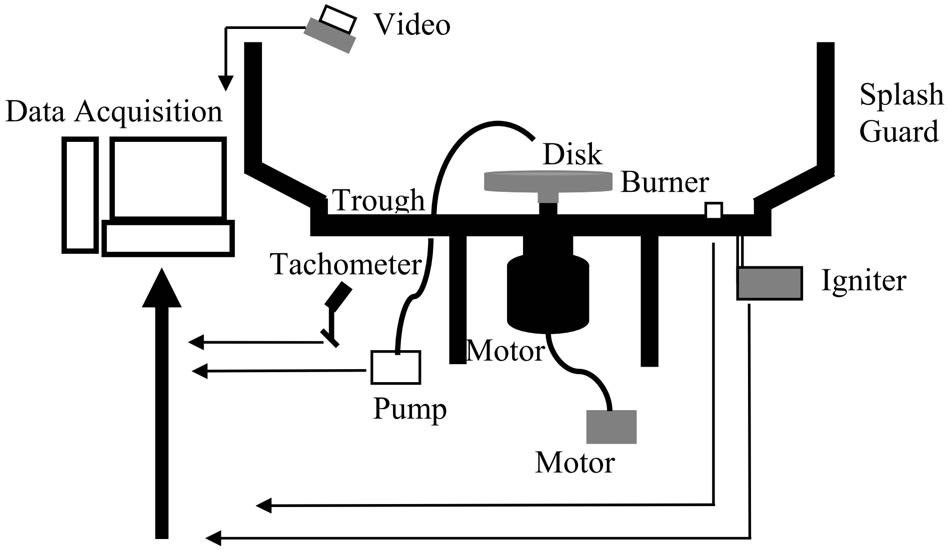

Figure 1. Diagram of rotary atomizer apparatus

A stainless steel thermocouple assembly was designed to arrange an ensemble of K type thermocouples to detect and measure aerosol ignition and flame propagation. The horseshoe shaped (260 degree) thermocouple assembly is 0.25 inch (0.63 cm) stainless steel and sits in the trough of the pan. Ten K type thermocouples have been situated approximately 5.0 inches (13 cm) apart, with the first thermocouple 3.5 inches (8.9 cm) from the burner. A video system has also been implemented to visually monitor both the ignition of the fuel mist and propagation of the ignited flame. The video system consists of three cameras (color, IR, and black and white).

A similar apparatus was coupled to a droplet size analyzer (Malvern Spraytec Malvern Instruments Inc., Southborough, MA) to provide droplet size distribution characteristics of the mist generated. When the disk reached a steady rotational speed, liquid was pumped to the center of the disk at a constant flow rate for approximately 3 to 5 seconds. The Spraytech, configured for continuous mode, took size distribution measurements during this period. Further apparatus and experimental details can be found elsewhere [10,11].

RESULTS

Aboard US Navy platforms, 2190 TEP functions as both a hydraulic fluid and lube oil. In many instances 2190 TEP is operating at elevated temperatures and pressures that can increase its risk of being aerosolized and becoming flammable. In the large-scale explosion tests aboard the ex-*USS Shadwell*, 2190 TEP was heated to 50 ^{o}C and pressurized to 1450 psi. Figure 2 shows the explosion overpressures measured for a 65 second continuous spray of 2190 TEP. The spray was generated using a single nozzle in the nozzle array and it was determined the mist flow rate was approximately 2.45 liters/min. The results of the three baseline explosions show the average overpressures generated were about 5.5 kPa.

Figure 3 shows the results of the explosion mitigation experiments using fire extinguishers. The objective of testing these extinguishing agents was to determine if existing agents could prevent or mitigate an explosion after the aerosol cloud was detected. The Figure shows that PKP was the most effective by reducing the overpressures to less than a third of the baseline explosions. In some instances it prevented the ignition of the fuel mist entirely. It is believed ignition was prevented by the increase in effective breakdown voltage of the air. The CO_2 extinguisher showed a 22% reduction in the explosion overpressures. The cause of mitigation may be attributed to the dilution of the available oxygen needed for combustion. The experiments conducted with water and AFFF are not shown because they were essentially ineffective in reducing explosion overpressures.

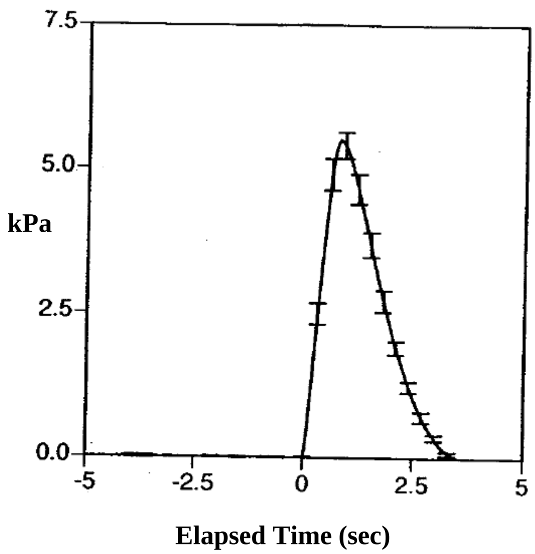

Figure 2. Baseline 2190 TEP Aerosol Explosions

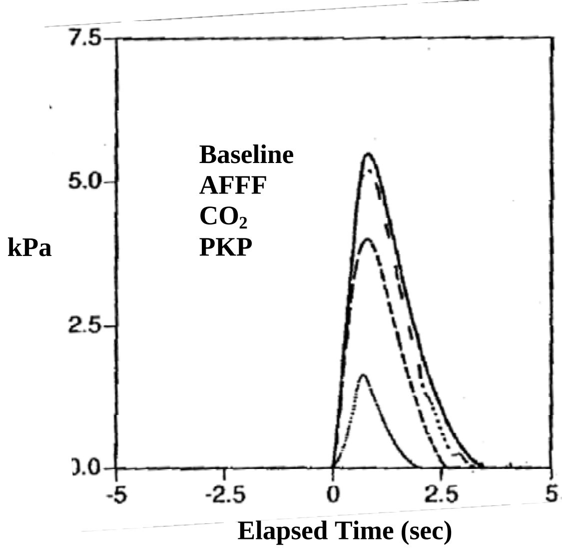

Figure 3. 2190 TEP Aerosol Mitigation Explosions

Aerosol/air mixtures are complex systems because the vapor concentration is dependent on several parameters which include; droplet size, number density, flow rate, and droplet linear velocity. The objective of the smaller scale studies is to investigate and understand how each of these critical parameters plays a role in the ignition and combustion properties of the aerosol. Figure 4 shows the steady state combustion temperature of JP5 measured as a function of disk speed and liquid flow rate to the disk. In Figure 4 the flame temperature is measured at the 1st thermocouple in the thermocouple array to show the effect disk speed has on the flame temperature short distances (2.5 inches, 6.3 cm) from the igniter. Previous research indicates that disk speed has the most effect on aerosol droplet size distribution and thus fuel aerosol flammability characteristics [10-12]. As the disk speed is increased in Figure 4, the droplets get smaller and the fuel droplet number density near the igniter increases. This leads to an increase in the combustion rate and flame temperatures. The fuel vapor concentration and flame temperatures are also increased as the fuel flow rate to the disk is increased from 42 mL/min to 183 mL/min. This is caused by the increase in droplet number density near the igniter.

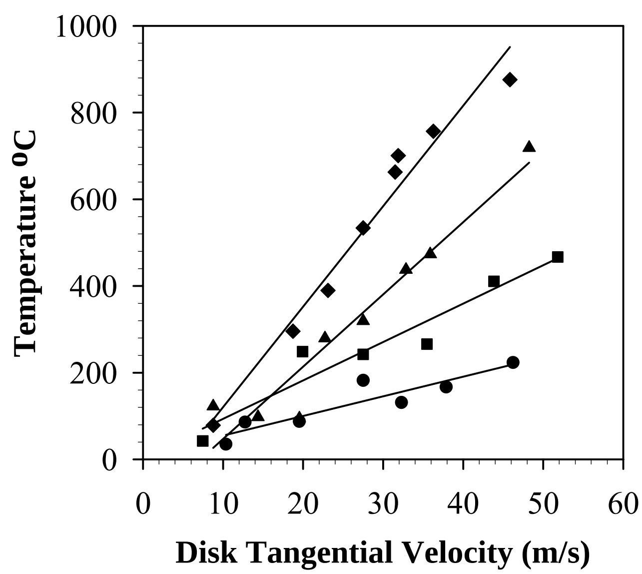

Figure 4. Steady Combustion Temperature of JP5 measured at the first thermocouple of the array as a function of disk speed and liquid flow rate [(•) 42 mL/min, (■) 95 mL/min, (▲) 141 mL/min, (♦) 183 mL/min].

Figure 5 illustrates the transition from the pilot flame to a steady circular flame as the disk tangential velocity is increased from 9 to 52 m/s at a fixed flow rate of 183 mL/min. When the disk speed is increased the droplets get smaller and can evaporate more readily at relatively low plume temperatures. This allows the flame to propagate until a steady state disk flame is formed. The critical values of disk speed and fuel flow rate that produce conditions in which the flame propagates to form a disk flame are shown in Figure 6 for JP5 and heptane.

Pilot Flame

Disk Velocity 9 m/s

Disk Velocity 27 m/s

Disk Velocity 36 m/s

Disk Velocity 52 m/s

Figure 5. Transition from Pilot Flame to Steady Circular Disk Flame

In Figure 6, as the disk speed increases above the curve, the vapor concentration increases to form a flammable mixture with the surrounding air. This results in the rapid propagation of the flame to form a steady state disk flame as illustrated in Figure 5. At disk speeds below the curve, the flame propagates to fixed length in the azimuthal direction and never forms a disk flame. At disk speeds well below the curve, ignition does not happen since the flame is extinguished when the pilot flame is secured. Similarly, for low fixed disk speed, more fuel (greater number density) is needed to form a flammable aerosol air mixture composition that will result in a disk flame.

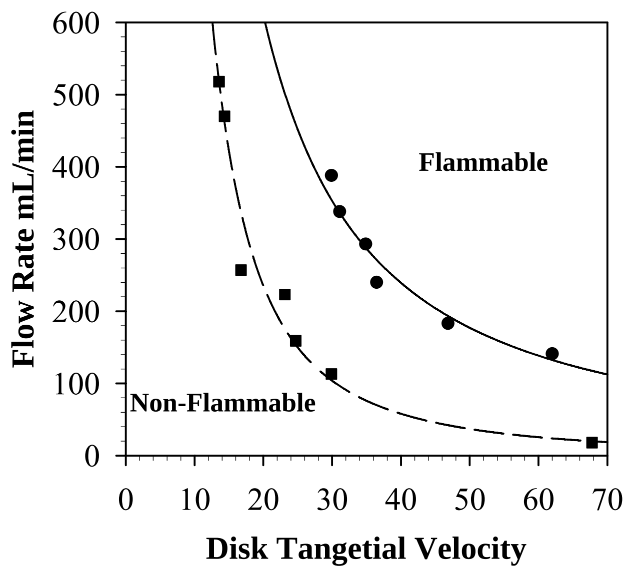

Figure 6. (•) JP5 and (■) Heptane aerosol lower flammability limit measured by rotary atomizer.

The thermodynamic properties of heptane and JP5 are significantly different. Based on their flashpoint, heptane is classified as highly flammable with a flashpoint of -4 ^{o}C, while JP5 is only moderately flammable with a flashpoint of 60 ^{o}C. The flammability curves in Figure 6 are significantly different for JP5 and heptane. For a defined disk speed, the critical flow rate needed to form a flammable aerosol mixture composition is higher by a factor of 3 to 5 for JP5 than for heptane. Figure 6 suggests that a factor of 2 to 3 change in disk speed can make JP5 behave like heptane in terms of flammability at a fixed flow rate. Clearly, aerosol behavior is fundamentally different from the thermodynamic behavior of a liquid. The Figure also provides a quantitative measurement of aerosol flammability in terms of flow rate and disk speed; however it may not be applied easily to quantify the flammability characteristics of aerosols generated by
other mechanisms.

The droplet size distribution has been shown to be a function of disk speed so Figure 6 may be represented in terms of flow rate and droplet diameter as shown in Figure 7. In the event of a leak or rupture in a hose line, the flow rate may be thought of as the amount of fuel aerosol released from the line at any given time. Depending on its droplet size distribution, this aerosol can be quantitatively estimated as flammable or non-flammable with respect to the diagram. As a result the flammability diagram may be applied to other aerosol release scenarios regardless of the way in which it was generated.

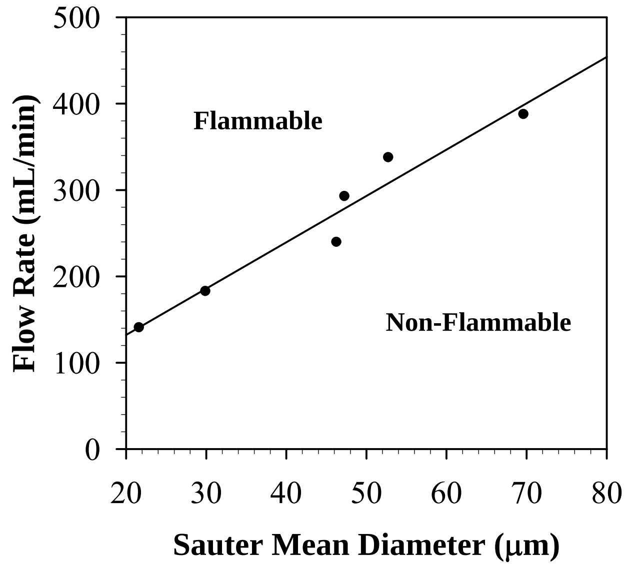

Figure 7. (•) JP5 lower flammability limit.

CONCLUSIONS

Large-scale mist explosions illustrated the potential hazardous associated with the atomization of the low vapor pressure liquid 2190 TEP. Existing extinguishing agents were used to test their ability to prevent or mitigate overpressures created by an explosion of a 2190 TEP mist cloud. Of the agents tested, PKP proved to be the most effective at mitigation. In some instances it prevented the ignition of the fuel aerosol completely. The small-scale tests produced flammability diagrams that establish quantitative relationships between flammability, droplet size, and fuel flow rates. They showed differences in aerosol behavior of liquids that differ significantly in terms of their flashpoints, and thus their flammability classification. Efforts are underway to develop similar relationships for 2190 TEP.

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