

Aspects of the Motor Vehicle Fire Threat from Flammable Liquid Spills on a Road Surface

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NOTE

This report describes results from a Cooperative Research and Development Agreement between the National Institute of Standards and Technology and General Motors Corporation that addresses issues of post-crash automobile fire safety. This report was financed by General Motors pursuant to an agreement between General Motors and the United States Department of Transportation.

The National Institute of Standards and Technology (NIST) is applying its expertise in fire science to this program because of the potentially high impact of this program on vehicle safety in the United States. As a matter of policy, NIST does not test commercial products, especially without the consent of the manufacturers of those products. The National Highway Traffic Safety Administration and General Motors have selected the vehicles to be crash tested and the procedures for those tests. These exploratory tests are only meant to produce a variety of types of vehicle damage that might occur. Not all crash conditions were studied, and the repeatability of the tests cannot be determined since in most cases replicate tests were not conducted due to budgetary constraints. Thus, the results of the tests may facilitate identification of opportunities for improvements in vehicle fire safety, but cannot by themselves be extrapolated to the full fleet of vehicles and all crash conditions. In analyzing the data from these tests, certain vehicles, equipment, instruments or materials are identified in this paper in order to specify the experimental procedure adequately. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the fire safety of a particular vehicle is superior or inferior to any other.

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Abstract

Spills of flammable liquids, particularly gasoline, pose a significant fire hazard subsequent to a motor vehicle crash. Various considerations pertaining to making quantitative estimates of the level of hazard are discussed here. These include preliminary data on the fire point of gasoline/vehicle fluid mixes, estimates of fire size resulting from various gasoline leak rates, limited data on heat transfer from burning gasoline spills and an approximate basis for estimating the heat flux exposure time that is required to ignite the surface of a typical plastic component.

1) Introduction

This report summarizes a portion of the work done under a Cooperative Research and Development Agreement with General Motors Corporation on post--crash automobile fires. This work is in aid of Project B.3 "Fire Initiation and Propagation Tests," particularly Task 3 which is directed at the development of standard fire initiation protocols. The report draws together considerations pertinent to several aspects of fire initiation subsequent to a fuel spill. No attempt has been made to comprehensive. The goal is merely to set down some facts that are of recurring relevance as the tests in Project B.3 are planned and carried out.

While only a small fraction of motor vehicle crashes result in a fire, those crashes which are forceful enough to cause fuel spills are much more likely to be followed by a fire. A NHTSA analysis of police crash reports from the state of Michigan, which includes data on fuel leaks, indicates that the probability of a fire, given a fuel leak, is more than 50 times higher than the probability of having a fire with no fuel leak [1]. Data from the National Fire Incident Reporting System (collected by U.S. fire departments), analyzed by the NFPA, indicate that for passenger road transport vehicle fires (of which automobiles account for over 90%) fuel is the most frequent form of material first ignited (36%) [2]. Although, there are, in fact, more cases of post-crash fire with no reported fuel leak than of fire with fuel leaks, it is reasonable to expect an increase in fire incidents with crashes producing fuel leaks since an easily ignitable fluid is available. Therefore, the development of the fire initiation protocols for this "Fire Initiation and Propagation" project has tended to focus on the effects of flammable liquid spills. This report

introduces some of the parameters affecting the impact which an un-wanted flammable liquid spill has in terms of ease of ignition, size of fire, and heat flux to other flammable objects.

2) Conditions for Flammable Liquid Ignition by Piloted Sources

Most automobile fluids are flammable; i.e., under the right conditions they will burn.¹ A notable exception is battery fluid (and perhaps windshield washer fluid) . Flammable liquids of interest are those which could be released in front and rear-end collisions including: fuel (gasoline or diesel), engine oil, transmission gear oil, automatic transmission fluid, brake fluid, power steering fluid and engine coolant. In a crash, fluids that are miscible because of their chemical nature could possibly mix on a molecular level (as in colliding sprays or drips co-mingling to form puddles) yielding flammability properties falling between those of the two fluids, depending on the mixture composition. The discussion below is limited to ignition by piloted sources such as electric sparks, friction sparks or small flames. Autoignition behavior of automobile fluids could be important in some post-collision fires (e.g., ignition by a hot engine compartment surface), but the focus here is on the piloted flammability of spills on internal vehicle or road surfaces.

Flammability limits. A fuel's vapor-phase flammable range in air is characterized by a lower flammability limit, usually expressed as the volume percent of fuel vapor below which the vapor-air mixture is not ignitable, and an upper flammability limit, above which volume percentage an ignitable mixture is again not produced. Standardized tests exist for obtaining flammability limits; the most widely used method was developed at the U.S. Bureau of Mines [3]. Basically, a known quantity of fuel vapor and air are well mixed at a specific temperature (usually room temperature), then an electrical spark is generated within the mixture, and if a pre-mixed flame propagates away from the spark, the mixture is within the flammable limits.

In the practice of fire safety, the emphasis with open systems (such as in the engine compartment of a post--crash vehicle) is on the lower flammability limit since achievement of this limit is likely to represent the first appearance of an ignitability hazard. In the case of a closed system (such as a fuel tank) where one wants to maintain a non-flammable mixture, the focus could be on either the lower or upper limit depending on the fuel volatility and system operating temperature.

Flash point and fire point. The flash point of a flammable liquid is the minimum liquid-phase temperature at which a flammable mixture is just formed above the liquid surface in air. There are two types of test methods for determining flash point: a closed-cup device and an open-cup device. ASTM D 93-94 [4] details a standard test method for closed cup flash point, while ASTM D 92-90 [5] details a standard test method for open cup flash point. A closed-cup device has a fixed liquid and air volume enclosed in a container. The liquid is heated at a pre-determined rate; the temperature rise is tracked with a thermometer. Periodically a pilot flame is directed into

¹For a fluid such as engine coolant that includes water as a major ingredient, ignition may require a period of heating that selectively removes the water.

the cup until a flashing flame is observed. Thus, at that point the vapor pressure above the liquid surface is sufficiently high to form a flammable mixture (at the lower flammability limit.) This liquid-phase temperature is recorded as the flash point. The open-cup apparatus differs in that the liquid container is open on top (the liquid volume is again fixed as is the distance its surface resides below the lip of the cup). Again a pre-determined rate of temperature rise is followed with a thermometer in the liquid phase and a dipping pilot flame is introduced periodically. When a flashing flame is observed, the liquid temperature is recorded as the flash point. These test methods give different results for the same liquids, and commonly tabulated values will specify the test method. The open-cup flash point is higher than the closed-cup value by sometimes 10's of degrees Celsius. The open-cup device loses fuel vapor from the open top boundary which lowers the concentration above the liquid surface. A higher vaporization rate (and thus liquid temperature) is needed to overcome this loss of vapor. Liquids below their flash point will not be ignited by a pilot source unless they are externally heated to a temperature above their flash point. Table 1 shows some flash point measurements for automotive fluids tabulated in NFPA 921[6]².

Table 1. Flash Points of Several Automobile Fluids

Automotive Fluid	Flash Point (°C)
Gasoline	-38
diesel fuel (#2)	52-96
brake fluid	115-179
motor oil	210-257
automatic transmission fluid	175-193
power steering fluid	177
ethylene glycol (100%)*	111
methanol (100%)*	11
ethanol (100%)*	12

* These fluids are mixed with water and the mixture flash point depends on the mixture ratio.

The open-cup device can be used to obtain another flammability measure, the fire point. The fire point is the minimum liquid-phase temperature where sustained burning of the liquid phase occurs after the ignition of the vapors above the liquid surface. The closed-cup cannot be used for such a

²The data in this table were collected by NFPA from several sources and the measurement methods may vary; the results are indicative, not definitive.

measurement since oxygen depletion occurs after the initial flashing flames. The fire point is a real danger point for liquid pools since it determines at what temperature the liquid can be ignited by a pilot and then continue to burn on its own. The fire point temperature is higher than the open-cup flash point. At the fire point, the mass transfer from the liquid to the gas-phase must be at a rate sufficient to resupply the gas phase with more vapor above the lower flammability limit in order to support continued combustion. Fire points are not routinely measured for flammable liquids; flash points for most flammable liquids, on the other hand, have been measured. Presumably the flash point is taken as a sufficient indication, in most cases, of a proximate hazard.

Pure component fire point measurements can be readily made, while miscible fluids pose some difficulty, especially if the pure fluids have appreciably different volatilities. (Mixtures may pose problems for open-cup flash point determination also; the results can depend on the time available for loss of the more volatile component and thus on the rate of heating of the mixture.) For non-miscible fluids, behavior is dominated by the lower density (floating) liquid.

There are three cases of flammable, miscible liquid mixtures that are of potential interest here: (1) a mix of two flammable liquids, (2) a mix of a non-flammable liquid with a flammable liquid whose normal boiling point is below that of the non-flammable liquid, and (3) a mix of a non-flammable liquid with a flammable liquid whose boiling point is above that of the non-flammable liquid. Examples of such mixtures involving automotive fluids are: (1) gasoline and (engine oil, automatic transmission fluid, power steering fluid or brake fluid), (2) methanol or ethanol and water (windshield washer fluid), and (3) ethylene glycol and water (coolant), respectively. Only case (1) is considered further below, at this point.

Gasoline is the only automotive fluid that is above its fire point at normal automotive operating conditions, thus any gasoline release can readily be ignited by a pilot source (small flame, electrical or mechanical spark, etc.). It is of interest to post-crash fire investigation to know whether and by how much the fire point of other vehicle fluids can be lowered if they are mixed with gasoline.

Some preliminary fire point measurements were made with a non-standardized set-up to explore the effects of mixing gasoline with other miscible fluids.³ The set-up consisted of a 10 cm diameter borosilicate glass petri dish, 1.5 cm high resting on an electric hot plate. The hot plate was enclosed in a chamber to minimize air disturbances. The liquid temperature in the dish was recorded with a 0.5 mm diameter sheathed, grounded thermocouple.

During fire point determination, the heating of liquid mixtures with different volatilities leads to a vapor-phase richer in the lighter component and a liquid phase richer in the heavy component. Therefore, the precise composition of the liquid phase at the fire point is unknown unless a composition measurement is made then. To minimize this fractionation problem for elevated

³A refined apparatus has been constructed for the purpose of checking these preliminary results; a report should be available in 1998.

temperature measurements, the liquid of interest was heated separately in a flask, then rapidly mixed with room temperature gasoline; the mixture was immediately poured into a heated test dish and the temperature recorded. A pilot flame was then applied to the vapor above the liquid surface. Ignition and sustained burning indicated the mixture was at or above the fire point.

While measurement uncertainty was reduced by using accurate pipetting of all fluids (gasoline volume percentage accurate to better than ½%) and using a fast response thermocouple for rapid temperature measurement (± 1 °C) of elevated temperature mixtures, test variability (pilot positioning, timing etc.) is such that repeatability is on the order of 1-2% gasoline by volume.

Results of these preliminary tests for gasoline mixed with other automotive fluids are shown in Figures 1-4. These are go/no-go tests which seek to define the minimum gasoline volume fraction, as a function of mixture temperature, which will just sustain continued burning upon removal of the pilot source. The literature value of gasoline flash point is indicated. Note that only 15-20 percent gasoline, well mixed with these automotive fluids, renders them flammable at room temperature such that once an ignition source is applied they will essentially burn to completion. At higher temperatures the requisite volume of gasoline drops. Note that the results for all four vehicle fluids are similar. Evidently they are dominated by the volatility of the gasoline and its ability in all cases to return sufficient heat to the fluid mix to sustain its burning, even when present as a rather small fraction of the total.

These results suggest that the relative hazard from a small gasoline spill in the engine compartment can be magnified by crash-induced mixing with other fluids that are not as readily ignitable at their normal operating temperatures.

3) Fire Exposure

Consider next the fire that may result from a crash-induced fluid spill. The spill that is the source of the fire could be either impulsive, involving the abrupt draining of a line or reservoir, or it could be slower but continuous in nature, involving an essentially steady loss rate from some large container. Actual crash conditions could, of course, yield a spill behavior between these extremes. Because these two extremes yield quantitatively differing fire behavior, we have examined both. The principal focus is on a gasoline leak since this poses the most immediate threat. As noted above, others fluids can magnify the fire threat of a small gasoline spill, if well mixed into it.

Steady fuel leak rate versus hole size. We examine first the case of a nominally constant leak rate from a large reservoir, e.g., the fuel tank. If the rupture in the fuel system is a circular hole, one can estimate the leak rate from a simple orifice calculation [7]. A significant complication here is that the flow depends on the internal pressure in the tank, and, for gasoline, this pressure is a function of temperature (which increases if the fire impinges on the fuel tank). Thus, in general, the fuel leak rate is not truly steady but rather increases with time in response to fuel tank heat-up.

Figure 5 shows the results of circular orifice flow rate calculations as a function of hole diameter for a few fixed values of internal fuel tank pressure. The lowest curve corresponds to there being no pressure in the tank beyond the ambient value; this would be the case if the crash also produced a hole in the tank (or a connecting line) above the fluid level which completely relieved any vapor pressure build-up. In this case, the only driving force for fluid outflow is the weight of the fluid column above the immersed hole; that column height is taken as 10 cm here. (Fluid column pressure is directly proportional to column height but an orifice-limited flow is proportional to the square root of driving pressure.) The other curves are pertinent to a closed fuel system containing gasoline below and above room temperature. (A typical gasoline has a vapor pressure of 55-70 kPa (gage) (8-10 psig) at 38 °C (100 °F) in a closed container that is 20% filled.)⁴ A noteworthy aspect of Figure 5 is that the immersed hole sizes under consideration are quite small. As will be seen below, such hole sizes can support a substantial fire.

Fire size resulting from a steady fuel flow rate. The steady-state burning characteristics (surface regression rate, flame height) for gasoline pool fires have been measured as a function of diameter of the burning pool of liquid [8].⁵ Here we relate pool diameter to fuel leak rate by assuming that the overall fuel consumption rate (by the fire) equals the leak rate, i.e., that the fire is in a steady state [8]. Thus

$$D_{ss} = 2[V_L/\pi v_{ss}]^{1/2}$$

where D_{ss} is the steady-state pool diameter, V_L is the fuel volumetric leak rate and v_{ss} is the average regression rate of the burning fuel pool surface. Combining this equation with the graphical data on gasoline burning rate and flame height from [8], one obtains the results shown in Figure 6. Note that even the lowest fuel flow rate considered (ca. 10 cm³/min) yields a flame height greater than the typical separation between the road surface and the underside of a vehicle (0.2 - 0.3 m), so that even such a small fire might impinge on flammable components on the underside of the vehicle.

⁴The vapor recovery system on new vehicles vents to the atmosphere through a bed of charcoal. If, in a post--crash situation, this system is fully intact, the internal pressure in the fuel tank will remain low. The 1998 standard is a maximum of 2.5 kPa (10 in. of water). If the vent, or the line to it is plugged, the pressure will tend to rise toward the vapor pressure of the gasoline, but, without any heating, this will take many minutes. If the gasoline is heated by a fire, that pressure rises still more. Even if the vapor recovery vent is open, heating of the gasoline will generate an increasing vapor flow through the charcoal bed toward the vent and this flow resistance will raise the pressure in the fuel tank somewhat.

⁵The following is restricted to horizontal, circular pool fires which is roughly what one would expect from a spill on flat, non-absorbent ground.

A relatively vulnerable part of the fuel tank assembly is the filler neck area since the neck and filler tube are frequently subject to significant displacement in rear-end collisions. Thus the region around the base of the filler neck is a plausible location for the origin of a continuous fill spill. Other locations need to be considered on a case-by-case basis.

Heating of fuel tank. Typically, a fuel spill fire will be on the ground below the fuel tank area of the vehicle (though, due to crash dynamics, it could extend well out from under the vehicle, as well).⁶ Thus, for all but the most insignificant continuous fuel leak rates, ignition of the leak yields a fire which tends to heat the fuel in the tank and which, in turn, tends to make the leak rate grow (assuming the tank will hold pressure). The rate of this heating depends on the overlap between the pool fire flames and the fuel tank surface. The pressure increase due to heating depends on the state of the available vents from the tank and on the particular gasoline blend. The overlap, in turn, depends on the pool diameter, its placement relative to the tank, and on the tank design, thus it cannot, in general, be estimated.

The problem of heating of fuel in a tank is further complicated by the fact that the heat flux from the pool fire is not a constant, even within the flame volume, and the fact that the gasoline itself is a complex mixture of hydrocarbons which have a broad range of volatilities. The heat flux level from a fuel spill is discussed further below.

NHTSA experience with high speed rear-end crashes indicates an average fuel leak rate (when a leak occurs) of about 1 liter per minute (with considerable variability from case to case)[9]. With such a low loss rate of fuel from the tank (which could contain 40-80 liters), we can simplify the fuel heating problem by neglecting this loss and the internal vaporization processes that would accompany it. Then we can make some rough estimates of the initial heating rate of the fuel if the heated area on the tank is prescribed, along with the average heat flux on this area. This problem is described by the following heat balance:

$$\rho_f V_f C_f dT_f / dt = h_{eff} A_h [T_{fl} - T_f]$$

where ρ_f is the fuel density, V_f is the fuel volume in the tank, C_f is the fuel heat capacity, T_f is the average temperature of the fuel in the tank (assumed uniform due to buoyant mixing), h_{eff} is the effective heat transfer coefficient between the flames and the gasoline in the tank, A_h is the area of the tank receiving the flame heat flux (assumed uniform over this area) and T_{fl} is the average temperature of the flame. The heat transfer coefficient is the result of three series resistances to heat transfer: the flame boundary layer on the outside of the tank, the tank wall itself and the liquid boundary layer inside the tank wall. The flame boundary layer coefficient is an effective value that accounts for both convection and radiation from the flames; it is estimated using

⁶Note that a post--crash fuel leak does not automatically lead to a fire. There must be an ignition source available in the space where an ignitable vapor mixture exists. This is often not the case.

measured values of heat flux to immersed surfaces in gasoline pool fires (ca. 75 kW/m², as discussed below) and the approximate flame temperature (1300 K) typical of sooty diffusion flames. The tank wall heat transfer resistance is negligible for a steel tank; it is significant for a plastic (e.g., HDPE) tank and equal to wall thickness over wall thermal conductivity. The internal boundary layer heat transfer resistance is calculated from a natural convection correlation using the properties of gasoline [10,11].

Solving the above equation for heating rate and using the properties as inferred above, one finds, for a 1 m² heated area and 40 liters of gasoline in the tank that a metal tank would yield an initial heating rate of the order of 5 °C/sec and a 0.5 cm thick HDPE tank would yield an initial heating rate of approximately 1 °C/sec. Both rates, if sustained, imply that the fuel would begin to boil in less than one minute. This simple model becomes invalid before that point, however, and inspection of the above equation implies that the heating rate decreases somewhat with time as the fuel heats up. The vaporization endothermicity would decrease it still further as the fuel heats. Note that this initial heating rate is directly proportional to the area of the tank being heated and inversely proportional to the amount of gasoline in the tank. The latter factor is readily accounted for; the former is not. The area heated, as noted above, starts relatively small (if the leak rate is small) and grows as the leak rate grows. In general this will lead to a slower heating rate than that was just estimated.

The heating of a plastic tank is further complicated by the fact that one can estimate (from a one-dimensional heat conduction model discussed further below) that it will soon begin to melt on its outer surface exposed to the flame heating. (Heating of flame-immersed polymers is discussed further below.) It will then presumably begin to drip (at a rate that depends strongly on the polymer melt viscosity) and thus feed more fuel to the pool fire on the ground. One can further estimate that the wall could get substantially thinner (if the melted material does drip away) though it should not melt through in the area wetted by liquid gasoline. Areas not wetted by gasoline, if subjected to comparable heat fluxes, will melt through sooner, especially if the tank is pressurized by gasoline vapors. This melt through would then relieve the pressure and allow the flow rate through a submerged hole to drop back to its un-pressurized level.

Note that Figure 6 indicates that a fuel leak rate of 1 liter/minute implies a pool fire diameter of approximately 0.5 meter and the flame height from such a pool fire is more than one meter. Figure 5 indicates that this leak rate is readily achieved from a 3 mm diameter hole if the tank is pressurized to about 14 kPa (gage) (2 psig). While (and if) the fuel system stays at its initial low pressure, this flow rate requires an approximately 5 mm diameter hole (for the 10 cm fluid head assumed in Fig. 5; for a given flow rate the requisite hole size varies inversely with the 1/4 power of the fluid head).

Impulsive spills. Consider next the case of an impulsive spill in which all of the fuel falls on the road surface in a time short compared to its burning time. The resulting spill quickly flows radially until the hydrodynamic driving forces are balanced by friction from surface roughness and by surface tension. Figure 7 shows measured maximum spill diameter as a function of spill

volume for n-heptane and for gasoline. The spill surface was concrete with a surface roughness comparable to a fairly new road; it was horizontal and nominally level. The spill diameter was determined by equating the spill area to its circular area equivalent. The spill area was obtained from area measurements of digitized video images with an uncertainty estimated to be 5%. The solid line is the computed diameter for a spill that is 0.075 cm in depth. Thus the spill depth is essentially independent of the spill volume.

Figure 8 shows an example of the burn history, in terms of flame height behavior, of an impulsive spill, in this case for 100 ml of n-heptane. Flame heights were determined by measuring the visible flame tips of multiple digitized video frames. Each open symbol is the mean of ten frames at 0.1 s consecutive intervals. Given that the natural pulsation frequency of large fires is greater than 5 Hz, the 10 Hz sampling rate assures no aliasing of the data. The error bars indicate \pm one standard deviation. The 50 % intermittency points are the median of 50 measurements from video frames sampled at 10 Hz, ± 2.5 s about the indicated time on the plots. Measurement uncertainty is estimated to be 5 mm based on pixel resolution. The statistical variability of the time dependent flame height is much greater than the uncertainty in the measurements of it made here. .

Data for two different definitions of flame height are included in Figure 8. Flame height is not a precisely defined quantity in a turbulent pool fire and, even given a precisely defined height criterion, its application is strongly affected by random variations. The error bars on the height data based on peak flame tip height are an appreciable fraction of the average value. The 50% intermittency point, which is the level on the flame centerline above which flames are present less than 50% of the time, gives a lesser value of flame height.

The burning process is clearly very transient; the flame height, which is an approximate measure of the liquid burning rate, rises quickly to a peak then rapidly trails off. The initial transient (increasing flame height) is due to the heating of the liquid layer and the concrete beneath it (substrate heating is discussed further below); the subsequent decay is a result of a shrinking spill diameter as the liquid is consumed fastest at the periphery.

Figure 9 shows the result for a 100 ml spill of gasoline. The peak flame height is quite comparable to that for n-heptane. The burn duration is significantly longer, presumably because of the presence in gasoline of lower volatility constituents. A cross-check of the results here with those in Figure 6 shows that the maximum flame height here is greater than that in Figure 6 for the same pool or spill diameter (ca. 0.9 m vs 0.7 m). The results in Figure 6 in fact derive from a study in which the flame height definition used was not given. A further source of variability is noted in Figure 8 where two replicate tests yielded some scatter in the results (see especially at 20 seconds); this sort of variability can be caused by air flow disturbances in the room which easily cause the fire plume to lean. The gas velocity in the plume is a few meters per second [12] and so can be significantly deflected by a 1 mph (ca. 0.5 m/s) air current.

Alternative substrate. While the preceding tests were performed on a concrete substrate to mimic a road surface as closely as possible, it has proven impractical to use such a surface in

actual vehicle fire tests. These vehicle tests are conducted in a large pan to capture spilled fluids. A simulated road surface is created in the pan by placing 1.3 cm thick fiber-filled cement boards atop a thick layer of sand. As noted above, the thinness of the spilled fuel layer means that the substrate below it is a significant heat sink.

A gasoline pool fire can be ignited with the liquid at a low temperature (e.g., room temperature or below); the flames then heat the liquid to near its boiling temperature, while heating the substrate at the same time. This heating process yields a transient lowering of the burning rate until the liquid reaches its steady-state temperature; this transient will shorten the flame height somewhat, not reduce the local heat flux from the flame. The heat flux into the substrate dies off inversely with the square root of time and its magnitude is directly proportional to the square root of the thermal inertia of the substrate material [13]. This implies that the pool burning rate is always transient via this effect though its impact is probably negligible in twenty seconds or so. The thermal inertia of the cement board used here is four times less than that of a concrete road surface implying a factor of two less transient heat loss. In this sense, the fuel spill on the cement board is slightly faster burning, on average, than it would be if the spill occurred on concrete.

Heat transfer rate from fire plume to solid surfaces. A significant danger from a moderate-sized fuel spill fire under a vehicle (beyond its ability to grow by heating the fuel tank) lies in its ability to ignite solid objects on the vehicle itself, leading, again, to a growing fire that might penetrate the passenger compartment. This tendency to ignite flammable objects is a consequence of the combined convective and radiative heat transfer from the flames.

Pool fires greater than 20-30 cm in diameter consist of turbulent flames. Furthermore, the flames pulsate up and down at a frequency which decreases as the pool diameter increases. For present purposes, the pulsation cycle time is short compared to the thermal response time of any solid objects the flames might impinge upon; thus average properties suffice. Average flame height varies with pool diameter (as Figure 6 implies). For gasoline it varies from five pool diameters for a 10 cm pool down to about 2 diameters for a 1 meter pool [8]. Close to the pool surface, the average gas temperature is relatively low because of the dominance of unburned fuel vapors. The temperature peaks at about 1200-1300 K at roughly one pool diameter above the liquid fuel surface and is down to about 800 K at the average flame height due to turbulent mixing with ambient air; above this, further mixing causes a rapid temperature decrease with height [14]. Heat transfer from this hot gas volume to any immersed surface is both convective and radiative. The latter is enhanced in hydrocarbon fires by the soot formed.

Measurements were made of the heat transfer rate to cool surfaces immersed in the plume of burning n-heptane and gasoline spills on a concrete surface (as in Figures 7, 8 and 9 above). Schmidt-Boelter total heat flux gages, cooled with water at 80 °C (to prevent water condensation on the gage surface), were mounted flush with the surface of steel sheets in horizontal or vertical orientation.

Figure 10 shows the measured heat fluxes to a large horizontal surface placed over a 100 ml

heptane spill at the fixed height of 30 cm above the concrete surface. Reference to Figure 8 shows that one would expect the flame tips to reach the flux gage height (and beyond, in the absence of the horizontal plate) for about 35 seconds. One gage was approximately on the pool centerline; the other was 30 cm away from the first. Both gages looked downward at the fire. The fire plume here is intercepted by the horizontal surface containing the gages; it splays out radially from the center of impingement. The centerline gage made direct contact with the fire plume (as long as the plume was undisturbed) in a region where its temperature should be near its maximum; the other was beyond the average visible flame length in a lower temperature region. The high frequency fluctuation in the flux is due to flame turbulence and height pulsations; the other, more erratic but longer persisting changes are due to movements of the plume caused by room air flow disturbances. As noted in the Figure, the centerline gage sees an average flux of about 70 kW/m^2 and the outer gage a flux just above 20 kW/m^2 .

Figure 11 shows the results of an attempt to make a somewhat different measurement on a 100 ml gasoline spill atop a 100 ml spill of hot oil. The initial oil temperature was $120\text{-}125 \text{ }^\circ\text{C}$ and it was spilled on the concrete slab immediately before the gasoline in an attempt to mimic a possible post-crash scenario. (The mixing of the two fluids was minimal and there was no indication that the oil burned.) The pair of flux gages was mounted flush in much smaller sheet metal surfaces (about 4 cm square), one facing downward and the other facing laterally, with its face perpendicular to the concrete surface. Both were nominally at 30 cm above the concrete and on the spill centerline. Here the test was performed outdoors with adverse consequences for plume stability. The plume did not stay in contact with the gages throughout the burn. Fortunately, the flux gages can respond quickly enough (fraction of one second response time) so that the several seconds of contact that yielded the highest peaks gave credible flux measurements. In other similar tests, the flux on a downward facing gage has reached 140 kW/m^2 . These results, while preliminary, are indicative of the heat flux levels that burning fuel spills can inflict on vehicle surfaces.

Estimated impact of heat flux on a polymer slab. To put the above heat transfer rates into perspective, we have calculated the heating of a polymer slab over a range of heat fluxes such as might be encountered in a fire plume. The basis of this is a numerical, one-dimensional heat conduction model that assumes constant polymer properties, a combined convective plus radiative flux on the front surface (with a Stefan-Boltzmann radiative loss from the surface) and convective plus radiative loss from the rear surface (to a cool ambient atmosphere). The polymer properties used here are the average for nylon (unfilled and without any flame retardants) between room temperature and the assumed ignition temperature of $375 \text{ }^\circ\text{C}$; the heat of fusion is included. While the heat effect of melting is incorporated in the effective heat capacity, the melt layer is not allowed to flow away. With these assumptions, the calculated results are expected to be only semi-quantitative in nature for real automotive polymers.

Figure 12 shows the result for two different thicknesses of the polymer slab as a function of the total (convective plus radiative) initial flux incident on the front surface of the polymer slab. (The word "initial" is used here because the convective component of the flux decreases somewhat as

the surface heats up.) Heating the surface to its ignition temperature is assumed to result in ignition, since the fire plume constitutes a pilot flame. Note that above about 45 kW/m² the thickness ceases to have any noticeable effect; at these higher fluxes the thermal wave in the slab does not reach the rear surface before ignition occurs. At these flux levels, the neglect of polymer flow is acceptable since the melt layer will be quite thin and have little time to flow. Polymer flow/dripping could alter the results at the low flux end. If it occurs in such a configuration as to carry away the heated layer, it will extend the ignition process. The behavior in this Figure is approximately describable by the following dependencies (in the domain of high fluxes where slab thickness is immaterial):

$$t_{ign} \sim (k\rho C)(\Delta T_{ign})^2/q_{net}^2$$

where t_{ign} is the calculated ignition delay time, $(k\rho C)$ is the thermal inertia of the polymer (product of thermal conductivity, density and heat capacity - here including the heat of fusion), ΔT_{ign} is the surface temperature rise from ambient to ignition and q_{net} is the net heat flux into the polymer surface (incident total heat flux minus re-radiation). From this one can see which polymer properties must change to yield differing results. Note in particular the linear dependence on polymer density. The calculations in Fig. 12 were for a polymer at full density. If the material was in the form of a foam, the above relation implies it would ignite much faster at a given heat flux.

Addendum: The preceding discussion has been couched in terms of large fuel spills on the road surface. The much more limited fuel spill that could occur elsewhere on typical fuel-injected vehicles can still create a fire threat. The spill, if ignited, need only burn long enough to ignite, in turn, adjacent materials. The spill itself can be a brief event if the fluid pools in an available catch basin and burns there. Such a situation could be created most readily in the engine compartment. Small, laminar flames can yield high heat fluxes (50-60 kW/m²) in localized areas [15]. For a full density plastic component of 1 mm thickness, ignition could require only 10-20 seconds of such flame impingement from burning fuel (with a thicker material requiring a longer exposure). A foamed material would require less exposure time to such a fuel flame to be ignited. Even fuel-injected engines can have a sufficient reservoir of gasoline in the engine compartment to enable the above events.

4) Acknowledgement

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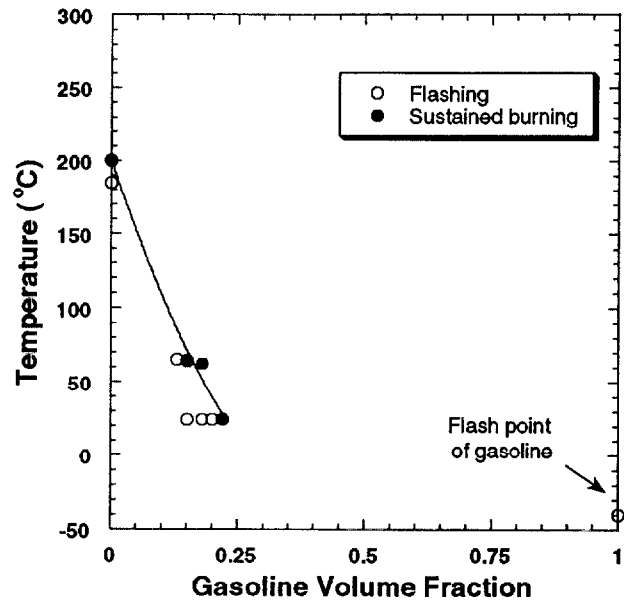


Figure 1 Fire Point of Automatic Transmission Fluid/Gasoline Mixtures.

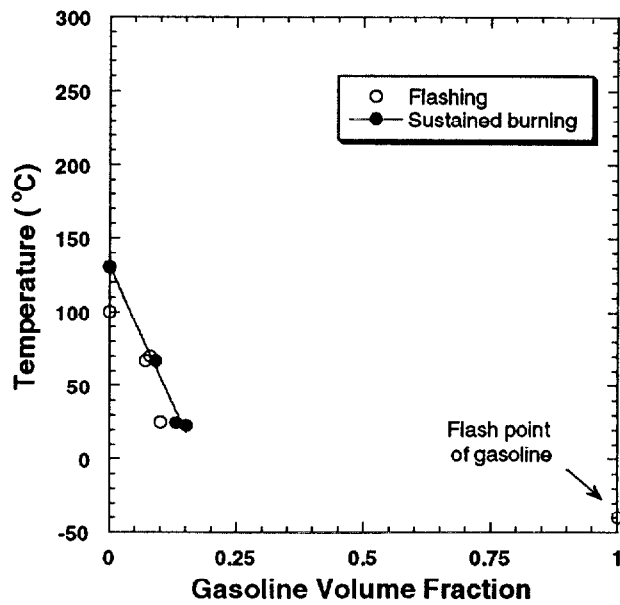


Figure 2 Fire Point of Brake Fluid/Gasoline Mixtures.

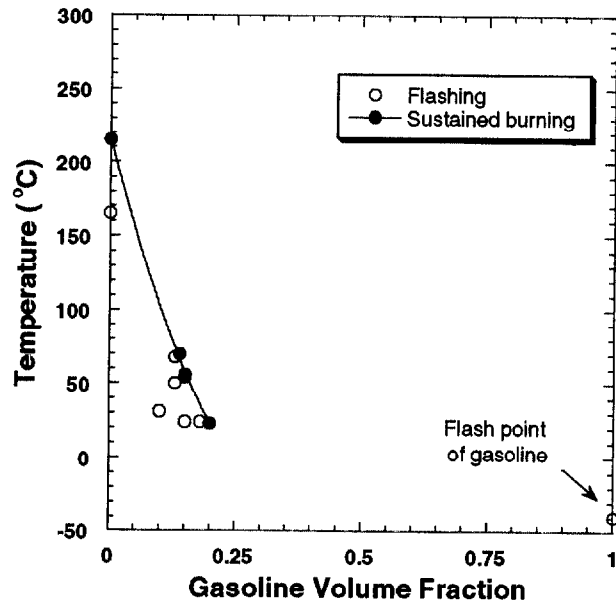


Figure 3 Fire Point of Engine Oil/Gasoline Mixtures.

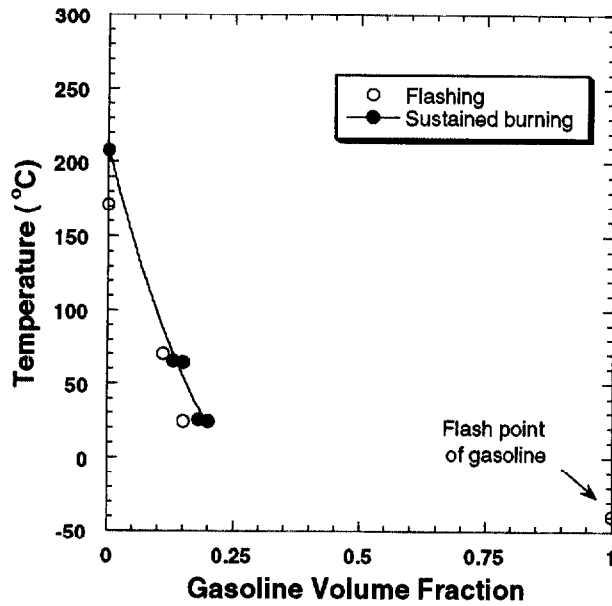


Figure 4 Fire Point of Power Steering Fluid/Gasoline Mixtures.

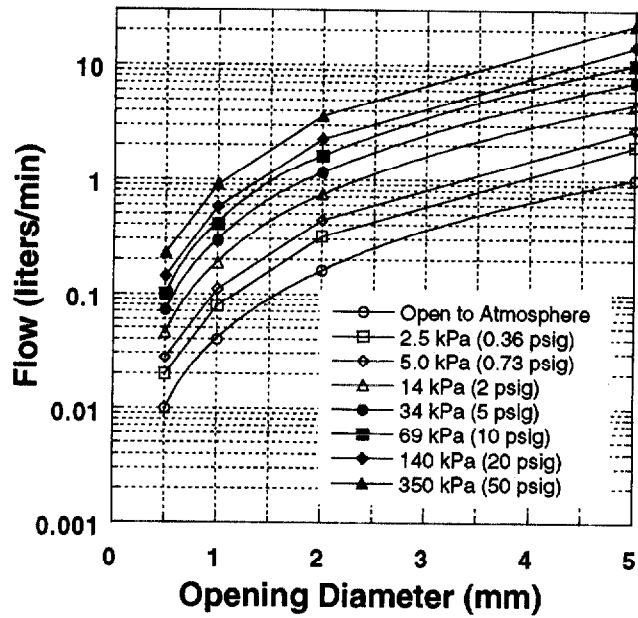


Figure 5 Orifice Flow for Various Opening Diameters.

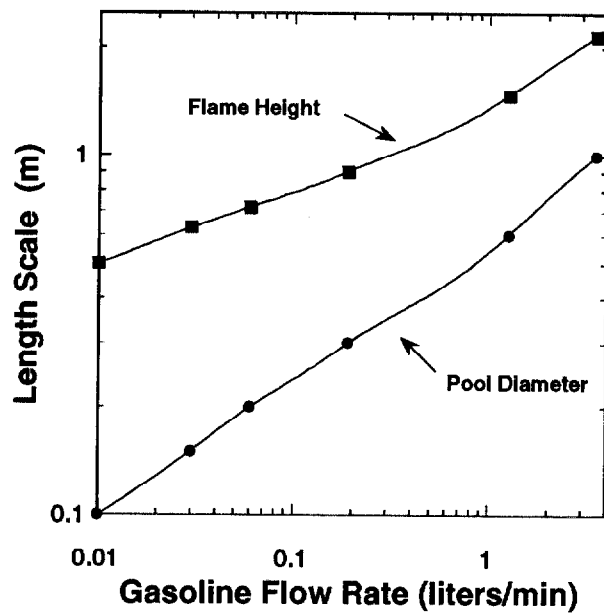


Figure 6 Estimated Gasoline Pool Fire Characteristics.

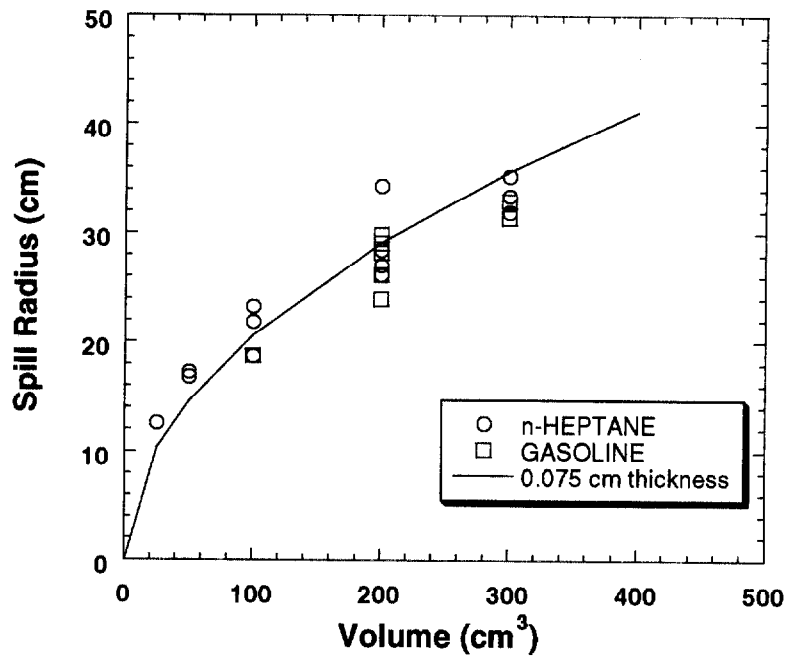


Figure 7 Impulsive Spills on Concrete Surfaces.

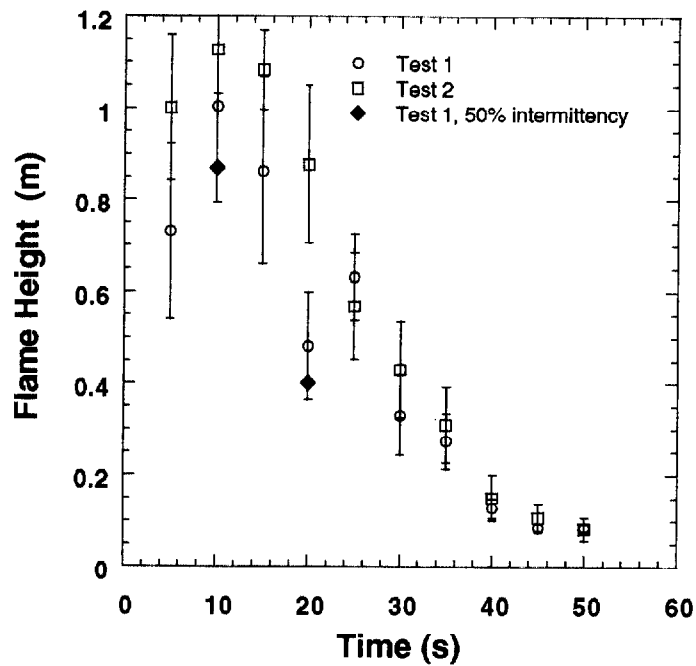


Figure 8 Flame Height of 100 cm³ n-Heptane Spills on a Concrete Surface.

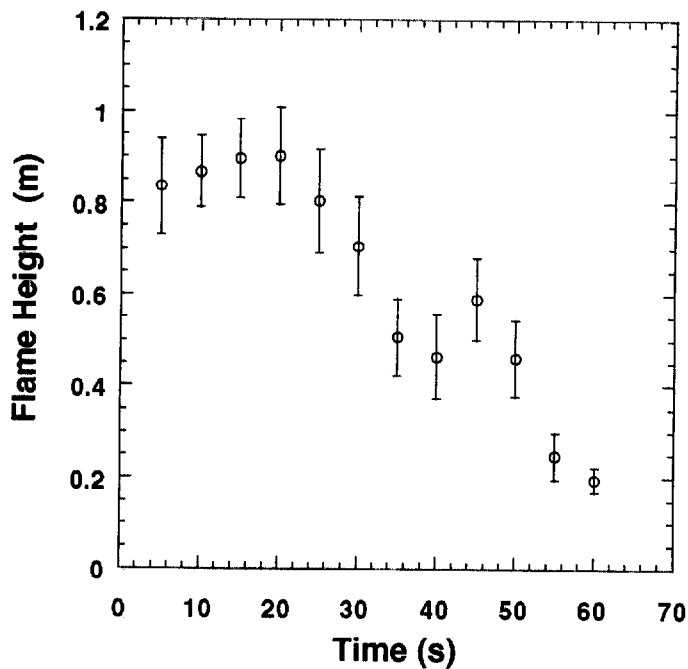


Figure 9 Flame Height of a 100 cm³ Gasoline Spill on a Concrete Surface.

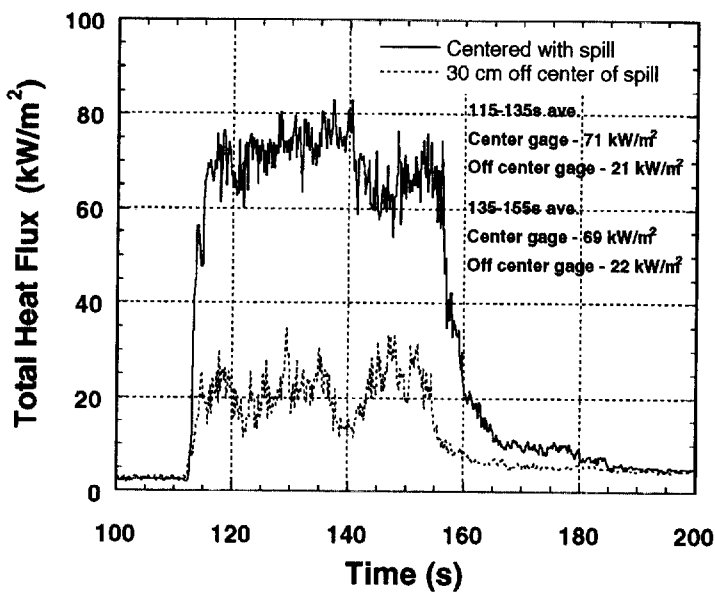


Figure 10 Flame Heat Transfer to Horizontal Plate 0.30 m Above the Spill Surface. 100 cm³ of n-Heptane Spilled.

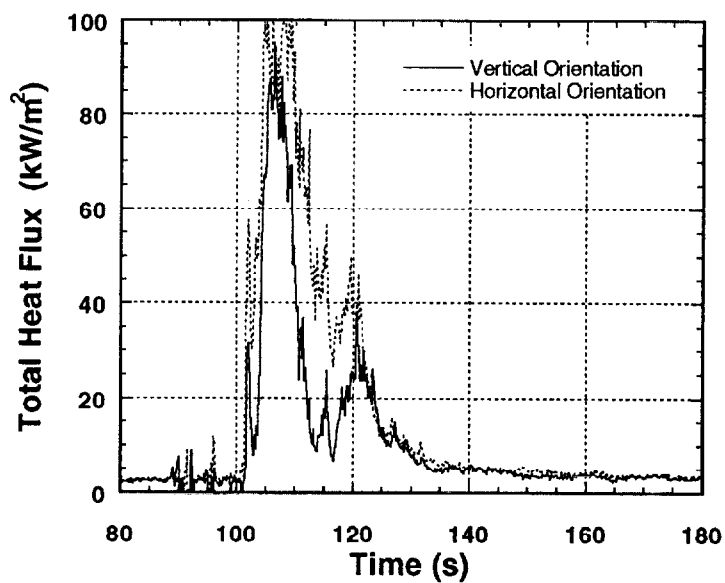


Figure 11 Flame Heat Flux from a 100 cm³ Gasoline Spill Fire to Target Gages 0.30 m Above Spill Surface.

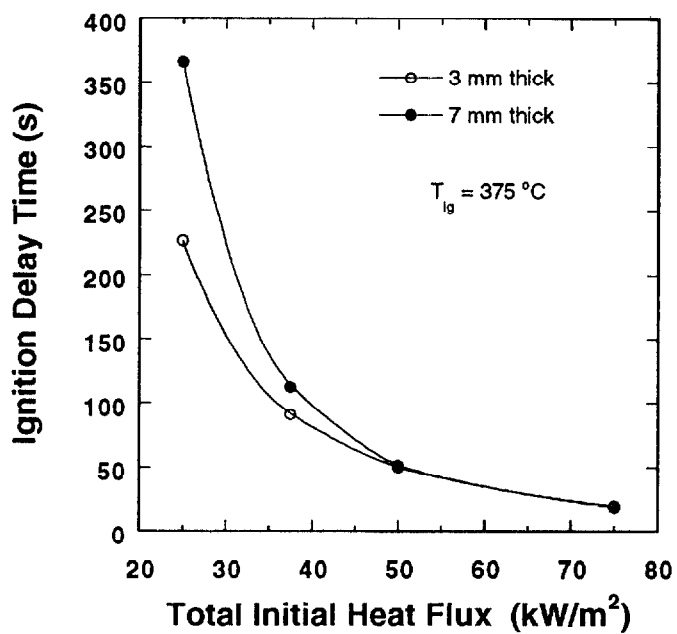


Figure 12 Estimated Ignition Behavior of Unretarded Nylon. Ignition Temperature fixed at 375 °C.

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Spills of flammable liquids, particularly gasoline, pose a significant fire hazard subsequent to a motor vehicle crash. Various considerations pertaining to making quantitative estimates of the level of hazard are discussed here. These include preliminary data on the fire point of gasoline/vehicle fluid mixes, estimates of fire size resulting from various gasoline leak rates, limited data on heat transfer from burning gasoline spills an approximate basis for estimating the heat flux exposure time that is required to ignite the surface of a typical plastic component.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)
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