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August 21, 1998

The Honorable Philip R. Recht
Deputy Administrator
NATIONAL HIGHWAY TRAFFIC
SAFETY ADMINISTRATION
400 Seventh Street, S.W., Room 5220
Washington, DC 20590

Dear Mr. Recht:

Re: **Settlement Agreement**
Section B. Fire Safety Research

Enclosed is a report authored by Anthony Hamins of National Institute of Standards and Technology entitled "Evaluation of Intumescent Body Panel Coatings in Simulated Post-Accident Vehicle Fires."

This report relates to Project B.4 Evaluation of Potential Fire Intervention Materials and Technologies.

Sincerely,

David A. Collins
Attorney

Enclosure

NISTIR 6157

**Evaluation of Intumescent Body Panel Coatings in
Simulated Post-Accident Vehicle Fires**

Anthony Hamins

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NIST

United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NISTIR 6157

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Simulated Post-Accident Vehicle Fires**

Anthony Hamins

April 1998
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Gaithersburg, MD 20899



U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

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 fire 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 collision 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. In addition, certain trade names and company products are mentioned in the text to specify adequately the experimental procedure and equipment used or to identify types of currently available commercial products. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

Evaluation of Intumescent Body Panel Coatings in Simulated Post-Collision Vehicle Fires

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ABSTRACT

This report describes a portion of the work undertaken in Project B.4 (Evaluation of Potential Fire Intervention Materials and Technologies) of the Cooperative Research Agreement between General Motors and NIST. This report was financed by General Motors pursuant to an agreement between General Motors and the United States Department of Transportation. The key objectives of this project are reduction of flame penetration, heat transfer and transport of toxic gases to the passenger compartment in a post-collision vehicle fire. To accomplish these goals, experiments were conducted using a passive fire protection technology involving intumescent paints and caulks. These materials are used in the construction industry to reduce material flammability and to reduce the penetration of heat and smoke through doorways and vents. In this study, experiments investigated the effectiveness of these materials in protecting body panels during simulated post-collision vehicle fires. The tested intumescent coatings reduced heat conduction through a metal body panel, but failed to close and prevent flames from penetrating even small (6 mm) holes, which can occur due to the impact associated with a vehicle collision.

1. Introduction

This report focuses on a passive fire protection strategy for reducing the fire hazard from post-collision vehicle fires. The key objectives of this study are reduction of flame penetration, heat transfer and transport of toxic gases to the passenger compartment in a post-collision vehicle fire. One way to accomplish this effectively is for the body panels separating the passenger compartment from the engine compartment, underbody, and the trunk compartment to act as fire-barriers during a vehicle fire. Experiments have shown that the integrity of these body panels or the seams between them may be breached during a vehicle collision.

Potentially effective passive fire protection strategies to address this problem include compartmentalization, elimination of potential ignition sources, and reduction of material flammability properties, which can be realized through material substitution, material reformulation (e.g., fire retarded polymers), or application of appropriate coatings. Intumescent paints and caulks are currently used in the construction industry to prevent the penetration of heat and smoke through doorways and vents during fire. This is achieved through the unique behavior of these coatings, which are designed to swell in the presence of heat, creating an expanded insulating char layer. In this study, experiments were conducted

to appraise the effectiveness of several types of intumescent coatings when applied to simulated post-collision vehicle body panels.

This report is divided into five sections. The remainder of Section 1 is a brief overview of the fire protection problem in post-collision vehicles, including a review of vehicle geometry and a discussion of passive fire suppression strategies. In Section 2, a series of experiments is described which measured the effectiveness of intumescent coatings in preventing the penetration of heat and smoke through simulated vehicle body panels. A detailed description of the experimental methods is included. The experimental results are discussed in Section 3. Key findings and recommendations are compiled in Section 4. References are listed in Section 5.

1.1 Review of Vehicle Geometry

There are a number of conditions that must be considered in post-collision vehicle fires that differ from fires in intact vehicles. These conditions limit and help define possible fire mitigation strategies. Here, a brief review of vehicle geometry and the parameters that characterize post-collision vehicles is presented.

Each vehicle is distinguished by a unique geometry and the body panels on each vehicle are characterized by distinct sizes and shapes. The forward bulkhead or dash panel separates the passenger compartment from the engine compartment. The number, size, and placement of components that pass through the forward bulkhead also varies from vehicle to vehicle. In terms of developing rational fire intervention strategies, however, there are certain shared characteristics among most vehicles. The forward bulkhead is typically composed of sheet metal, which has been spot welded together from smaller panels along one or more seams. A large number of components pass-through the forward bulkhead. These include relatively large components, such as the heating and air conditioning units, the steering column, as well as smaller components such as wires and wire bundles. The rear bulkhead, which separates the trunk (for those passenger vehicles with a trunk) from the passenger compartment, may be composed of a flammable material such as fiberboard (sometimes carpeted). The floor pan is composed of sheet metal. Small openings, which exist in the floor pan may be filled with a thermoplastic or metal plug. A series of materials lay on top of the floor pan. These often include a low-density fibrous material, such as cotton-shoddy, under a polyester or nylon-based carpet.

1.2 Collision and Burn Experiments

A number of controlled collision and burn experiments, which form a portion of Project B.3 (Fire Initiation and Propagation) of this program, were observed and the video records of those experiments were studied. Some general observations are made here regarding those experiments from the perspective of fire intervention.

Vehicle crash experiments in this program have shown that a collision can transform a metal body panel from a continuous barrier to one containing openings, punctures, and openings of various sizes and shapes. In front-end collisions, pass-through components were displaced from their original positions, leaving openings as large as 10 cm to 20 cm in length and several centimeters in width. In both front and rear-end collisions, spot welded seams in wheel wells, the floor pan, side panels, and the forward and rear bulkheads were observed to open, with the damage related to the collision scenario. The dimensions of the openings varied. After front or rear-end collisions, the vehicle structure isolating the passenger compartment were partially breached and openings or gaps were formed. The location and size of the openings were scenario dependent. After rear-end collisions, large openings were apparent in the rear wheel well. The exact locations of the openings were dependent on the vehicle type and the details of the collision scenario such as the momentum of the collision, and the location of impact.

The body panel openings provide possible pathways for flames or combustion byproducts such as smoke and heat, to enter the passenger compartment. In this manner, they can represent a significant threat. The experiments described below consider passive protection of the bulkheads and pan separating the passenger compartment, from the engine compartment, the trunk compartment, and the vehicle underbody, by use of intumescent coatings. In this manner, the strategy will address many of the possible fire pathways into the passenger compartment, which have been observed during the collision experiments.

1.3 Protection of Passenger Compartment Body Panels using Intumescent Products

Reduction of heat penetration through the body panels, which enclose the passenger compartment of the vehicle is one possible strategy in protecting passengers during a post-collision vehicle fire. Intumescent paints and coatings offer attractive features in terms of improving the thermal properties of a body panel and in terms of filling collision induced openings or gaps by expansion of the material. When exposed to heat, intumescent materials expand or intumesce by a factor from 2 to 50 in volume to form a porous char. In this manner, a 1 mm layer of intumescent material with a density of $\approx 1.5 \text{ g/cm}^3$ can expand to form a non-combustible highly insulating thermal layer 2 mm to 50 mm thick, with a density of 0.7 g/cm^3 to 0.03 g/cm^3 .

Although heat and smoke penetration through body panel openings may be a significant post-collision fire problem, it is not the only problem. Heat transfer through a thin sheet metal body panel may lead to pyrolysis of a thermoplastic or other material attached to the other side of the body panel. This may include, for example, carpeting material attached to the floor pan or a thermoplastic attached as trim. A body panel coating with beneficial insulation properties (e.g., low thermal diffusivity) could provide enough thermal resistance to prevent pyrolysis and ignition of an attached flammable material. Thus, beyond its ability to expand, the thermal properties of the intumesced material are also of interest.

1.3.1 Description of Intumescent Products

Generally, intumescent formulations are composed of three active classes of ingredients including an acid source, a carbonific source and a spumific agent [Bourbigot et al., 1996]. A series of chemical and physical events combine to control intumescence [Vandersall, 1971]. As the virgin material is exposed to heat, the temperature rises, releasing an inorganic acid. In the presence of an organic catalyst, the acid is thought to react with carbon compounds forming a melt. An endothermic reaction subsequently releases gases which form bubbles, resulting in an intumescent foam which solidifies into a multi-cellular char [Butler, 1997] with a final volume typically two to fifty times that of the original material. The timing of each of these events is important in controlling the final character of the intumesced material. If the blowing agent is activated too early or too late, intumescence is reduced because the solid melt is either too viscous or the char has already solidified. If the solid melt becomes too fluid, relatively large cell structures are formed, which are rather ineffective as an insulating material [Vandersall, 1971]. Cellular voids are filled with gases, causing the char to act as an insulating barrier. The gases are principally CO₂ and H₂O, although smaller amounts of CH₄ and H₂ are also found [Anderson et al., 1988]. The char itself will not burn at flame temperatures, but will reach high temperatures and reject the flame heat by radiating it away. As flame heating continues, this process occurs in depth, layer after layer, until the material is depleted or the incident heat flux is reduced. The final form of the intumesced layer acts as an insulating barrier, which protects the underlying material from flame heat flux.

Anderson et al. [1988] reported measurements on the thermal conductivity of 13 different intumesced chars that averaged 0.096 (\pm 0.033) W/K-m, a value nearly 500 times smaller than the conductivity of steel. Because thermal conductivity is temperature dependent (with the thermal conductivity of gases and solids increasing and decreasing with temperature respectively), the measurements were made dynamically during a series of fire experiments. Their results were favorably compared to the weighted sum of the thermal conductivities of a carbon-based solid and the vapors of CO₂ and H₂O. This is consistent with the notion that the gas-filled porous cells that comprise the bulk volume of the intumesced material dominate the intumescent's thermal conductivity.

A large number of commercial products based on intumescent materials have been developed. They are used in a wide range of residential and industrial applications [Gillon, 1989; Rhys, 1980; Hulin, 1993; Ohlemiller and Shields, 1996]. For example, intumescent coatings are used to protect metal structures and fuel valves in off-shore oil platforms and are being considered as a coating for protection of flammable composite materials in marine applications. In the construction industry, intumescent paints are used to improve fire protection in historic buildings and residences. Intumescent caulks are used to seal cable trays and openings in fire walls, and intumescent strips are used on doorways to prevent heat and smoke transport. Intumescent ventilation grilles are used to seal a room and prevent the transport of smoke into a ventilation system in the event of a fire. Intumescent coatings are available in latex, solvent, or epoxy resin based coatings which can be sprayed, trowled, or rolled onto a

substrate. Depending on the application, some intumescent require a topcoat of a polyurethane or other material to combat weathering. Depending on the specific coating, application is not recommended in areas where temperatures exceed 100 °C to 200 °C. Application of an intumescent coating for protection in post-collision vehicle fires must consider the existence of openings in the coatings and/or substrate.

2. Experimental Description

Three series of experiments relevant to post-collision vehicle fire protection are described below. The first series of experiments addressed the thermal properties of the samples, whereas the second and third series tested the expansion properties of the samples in closing breached body panels. In all of these experiments, intumescent systems were tested in a small-scale configuration, independent of the details associated with the many variables that may differ from fire to fire in realistic applications, such as the flow field geometry, the fuel heat release rate, as well as the geometric relationship and orientation of the coated body panel to the fire. Although most experiments were conducted for a horizontally oriented body panel, a vertical orientation was also investigated.

2.1 Effectiveness of Intumescent Coatings in Body Panel Applications

In all experiments, 2.5 mm thick carbon steel panels (15 cm x 30 cm) were coated with intumescent materials prior to exposure to fire source. Although this is not a thickness typically used in vehicle body panels, steel has little thermal resistance. The thermal diffusivity, specific heat, and thermal conductivity of the carbon steel plates were analyzed using flash photolysis by Holometrix Labs [Campbell, 1996]. The thermal diffusivity of a material (α) is a key parameter influencing the rate of heat penetration and the final temperature profile in the material. It is listed in Table 1 for steel and is defined as:

$$\alpha = k/(\rho \cdot c_p)$$

where ρ is the material density, c_p is the specific heat, and k is the thermal conductivity. Consideration of the one-dimensional heat conduction equation and the thermal properties allows estimation of the difference in the back surface temperature of the plate as a function of plate thickness [Ozisik, 1977]. Calculations show that as a flux is applied to the plate (75 kW/m²), the temperature rise is faster for a 0.4 mm steel plate as compared to a 2.5 mm plate, but that the final steady back surface temperature is nearly the same (within a few degrees) for the same boundary conditions.

To improve adhesion, the steel plates were bead blasted to add surface roughness and remove any oils. The plates were stored in a coated, non-oxidizing paper until coated. They were then dried at room temperature over several days until completely cured.

Table 1 Thermal Properties of the Steel Sample Plates
[Campbell, 1996].

Property	T= 294 K	T=573 K
Density (g/cm ³)	7.77	7.8*
Specific Heat (J/g·K)	0.453	0.568
Conductivity (W/m·K)	56.3	47.3
Diffusivity (cm ² /s)	0.160	0.107

* estimated from the linear expansion coefficient of steel.

A Schmidt-Boelter thermopile gauge, 6 mm in diameter, painted with a high emissivity spectrally flat black paint was used to measure the total heat flux from the source fire onto the sample plates. The gauges were cooled with hot water (≈ 80 °C) to prevent water condensation on the sensing element. The gauges were calibrated using a high heat flux radiation lamp and a gauge traceable to NIST standards. The flux incident on the steel sample plates was measured by drilling holes at the center and at four symmetric locations (3.0 cm and 7.5 cm off-center as shown in Figure 1) on a test plate. The center plate location is denoted as position number 1, and the other positions as number 2 through 5. The heat flux at these locations was measured by positioning the gauge through the hole until it was flush with the bottom surface of the sample plate.

Five type K (0.5 mm diameter) thermocouples were used to measure the back surface temperature of the plate. Attaching the thermocouples to the plate using tape and a small weight proved unreliable, so they were attached by independently spot welding each of the leads to the plate in close proximity (within 2 mm) of each other. The five thermocouples were positioned at locations corresponding to the locations where heat flux measurements had been made, i.e., at the plate center and at four symmetric locations (3.0 cm and 7.5 cm off-center) as indicated in Figure 1. After spot welding the thermocouples to the plate, the back surface was sprayed with a thin coat of a high emissivity, spectrally flat black paint. The back surface boundary condition of the plate will impact the plate temperature. In a vehicle body panel, the back surface boundary condition will be specific to the panel function, location, and vehicle type. An insulated back surface condition would lead to diminished heat losses and higher plate temperatures. In this study, the back surface was painted black to avoid ambiguities associated with radiative heat losses and for consistency.

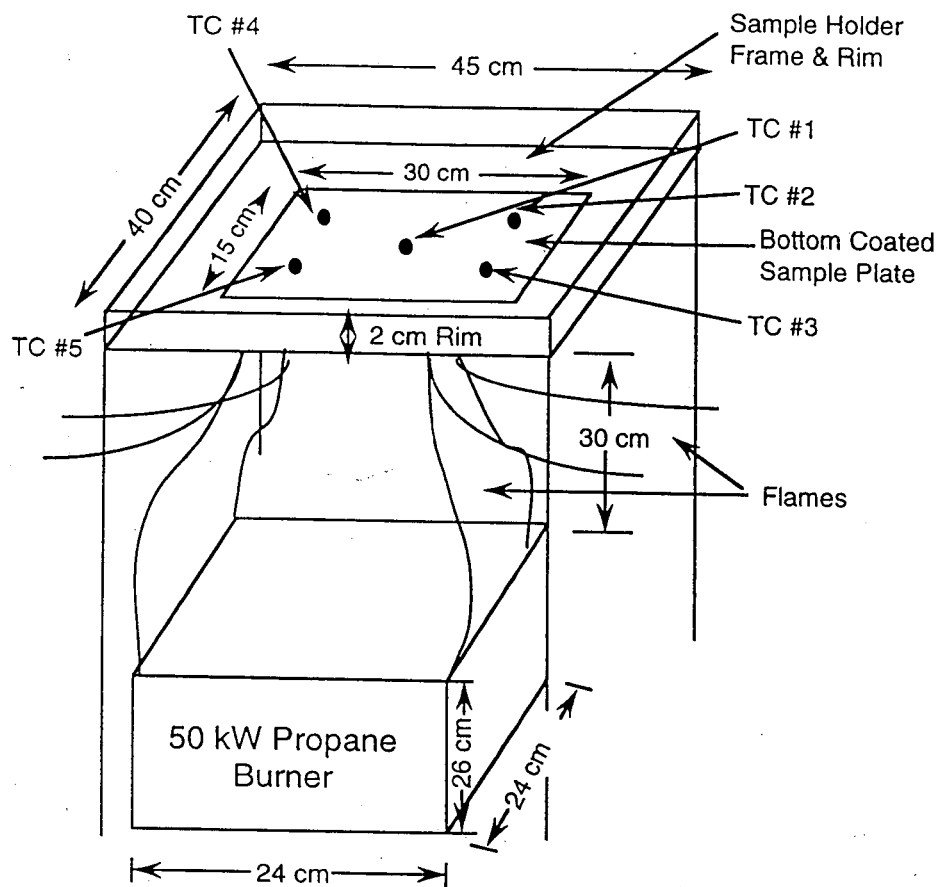


Figure 1. Diagram of the flame exposure experiment for coated sample plates in a horizontal orientation. The thermocouple arrangement is also shown.

The fire source and locations of the sample plates relative to the fire were selected based on experiments with gasoline and heptane fuel spills. The experimental apparatus is shown in Figure 2. Three heat flux gauges were positioned on the walls and in the gap of two steel plates, which were located 20 cm above a cement slab, a distance selected as representative of the distance a vehicle floor panel is above the ground. The heat flux gauge locations represent possible locations of under-hood components. The liquid fuel was spilled between the plates and the total heat flux was measured. The spill volume, the gap distance between the plates, and gauge locations were varied. The results of these experiments are described in Section 3.1. Once a heat flux range was selected, the fuel flow and the distance between the sample plates and the fire source were selected.

Propane was used as the fuel source. Its flow was measured using a dry test meter (corrected for super-ambient internal pressure) and a stopwatch. All experiments utilized a non-varying 50 kW fire. The fuel flow was verified at least twice during the experiment. The samples were exposed for 30 min.

The test plates were held in either a horizontal or vertical orientation as shown in Figures 1 and 3, respectively. As shown in Figure 1, a sand-filled burner was positioned below the panels for the experiments with the test panels oriented horizontally with the coated side facing down. The burner was square in shape (24 cm by 24 cm) and was filled with 20 cm of fine (≈ 0.2 mm diameter) sand. For experiments with the test panels oriented vertically, the burner was placed 15 cm below the plate frame and 23 cm below the plates. The burner edge extended 2 cm beyond the plane defined by the vertical sample plate. Visual observations and thermocouple measurements showed that the hot combustion products flowed exclusively over the front surface of the coated plates.

The sample holder was designed with a lip so that no gaps existed between the sample plate and the sample holder. On occasion a gap occurred because a sample plate was not completely flat. Ceramic felt was then used to fill any gaps between the sample plate and the frame. The sample plates were held in place by four screw-mounted clips that were attached to the metal frame. The sample holder was 40 cm by 45 cm and had a 2 cm deep wall around the edges (see Figures 1 and 3) to prevent hot combustion gases from flowing near the back surface of the sample plates. The temperature ≈ 3 mm behind the back of the sample plates was measured with thermocouples to confirm this.

In the horizontal configuration shown in Figure 1, the 50 kW propane fire imposed an average (combined radiative and convective) heat flux of 65 ± 5 kW/m² at plate positions 2 through 5 and a flux of approximately 75 ± 5 kW/m² at the plate center. This flux was comparable to the measured heat flux (using the same type of flux gauges) on a horizontal plate above small (≈ 50 ml to 150 ml) heptane and gasoline spills on cement. In the vertical orientation shown in Figure 3, the 50 kW propane fire imposed a nearly uniform heat flux of approximately 47 ± 8 kW/m² over the entire surface of the panel.

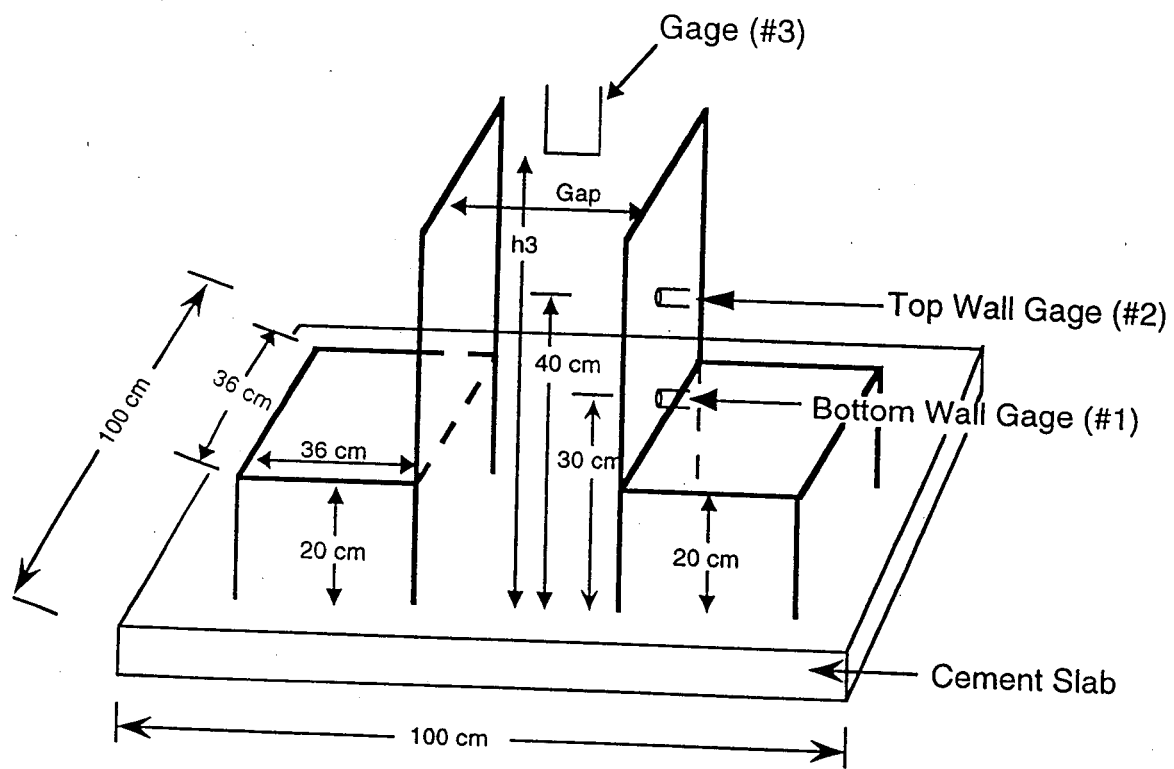


Figure 2. Diagram of the apparatus used to measure the total heat flux onto vertical and horizontal surfaces due to spills of heptane and gasoline.

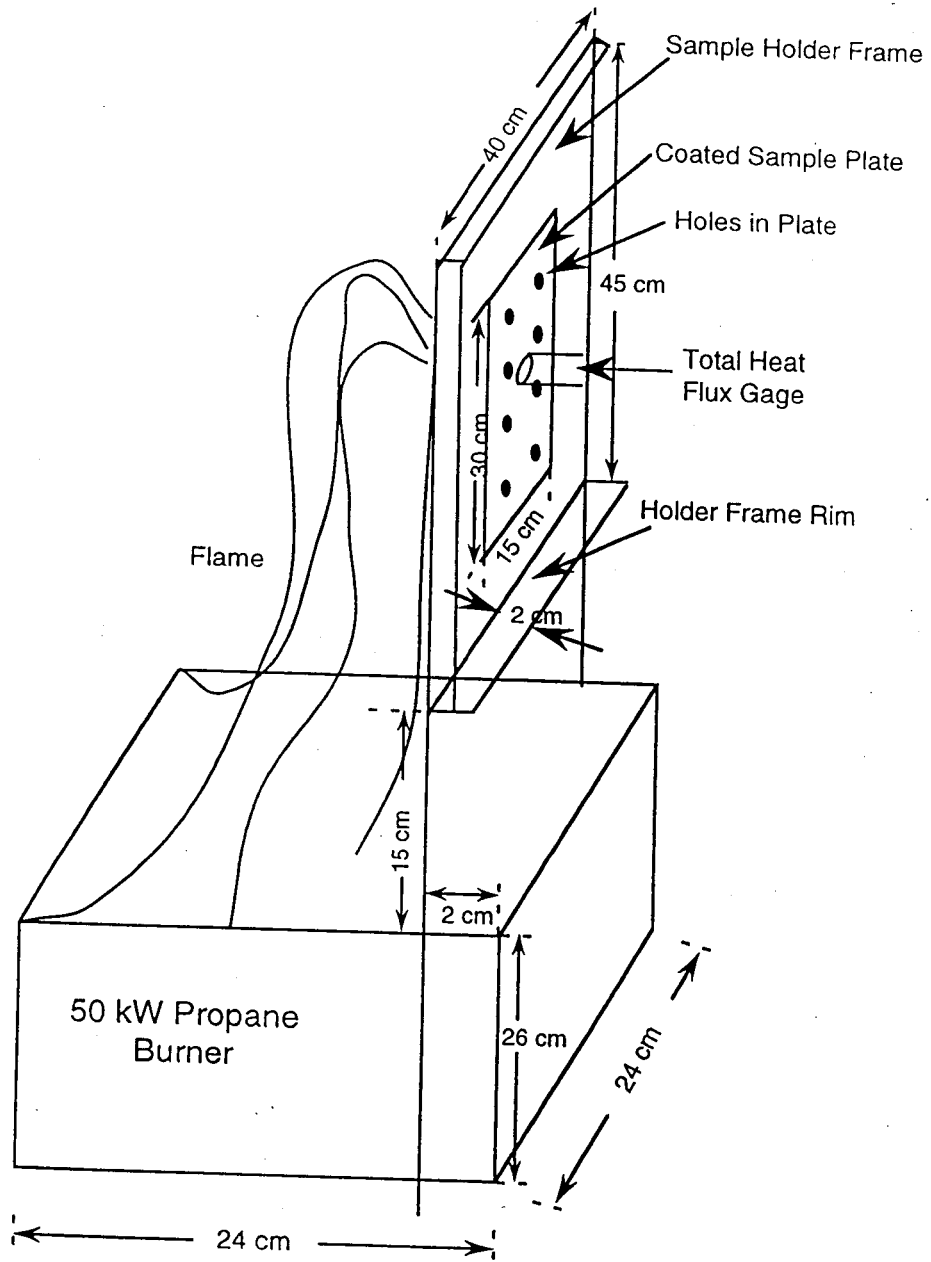


Figure 3. Diagram of the flame exposure experiment for coated sample plates in a vertical orientation.

A number of parameters were measured including the initial and final coating thickness, the temperature on the back surface of the plates as a function of exposure time, and final mass which was indicative of the adhesion integrity of the coating. Control experiments measured the back surface temperature of uncoated sample plates.

2.2 Collision Induced Openings in the Vehicle Structure

As described above, protection of a body panel for a post-collision fire scenario must consider collision induced openings. For these reasons, experiments examined the effectiveness of intumescent paints and caulks in closing small and moderate sized holes drilled through the coated steel panels. In the second series of experiments, holes with diameters from 3 mm to 20 mm were drilled through the coated plates in a pattern similar to that shown in Figure 4. The dry thickness of the applied coatings varied from 3 mm to 18 mm. A cutaway view of the test configuration is shown in the bottom of Figure 5. Flame penetration through the holes of the coated sample plates was recorded using a HI-8 video camera. The character of the intumesced coating was inspected after the 30 min fire exposure and the final mass was measured.

In the third series of experiments, the effectiveness of intumescent applied to the inner wall of the steel panels was tested. This configuration is relevant for the following reasons. A number of vehicle components are designed to pass through the forward bulkhead separating the engine compartment from the passenger compartment. Gaskets or caulking material are often used to seal these components onto the body panel and hold them in position. Examples include the steering column, wire bundles, and so on. In an accident, these components may become dislodged from their original positions relative to the bulkhead, creating significant openings. If a portion of the pass-through item was covered with an intumescent gasket or coating and that portion of the pass-through moved away from the body panel, then the intumescent would serve little purpose. If, however, an intumescent was coated on the inner wall of a pass-through hole, which was then exposed to fire, the intumescent could possibly fill the gap. The experimental configuration is shown on the top of Figure 5. To achieve this configuration, the plate was first drilled. Then, the plate surface and the inside wall of the hole were coated. The holes, 19 mm in diameter, were drilled through the 3 mm steel sample plates and a 3 mm coating was applied to the entire plate. A series of holes (9 mm, 12 mm, and 14 mm in diameter) were then drilled through the intumescent-filled holes. This provided a thin layer of coating on the inner wall of the holes (see the top of Figure 5), varying in thickness from 2.5 mm to 5 mm. The coated plates were exposed for 30 min to the 50 kW propane fire in a horizontal orientation as shown in Figure 1. The effectiveness of the intumescent coatings to close the holes and prevent flame and heat penetration was observed using a Hi-8 video camera. In addition, 0.50 mm diameter type K thermocouples were positioned on the back of the sample plate, within 1 mm of the center of the holes as shown in Fig 4. High temperatures were an indication of flames penetrating the holes. Most of the experiments were conducted using a horizontal configuration for the sample plate. The plates were positioned horizontally, with the coated surface facing down, over the center

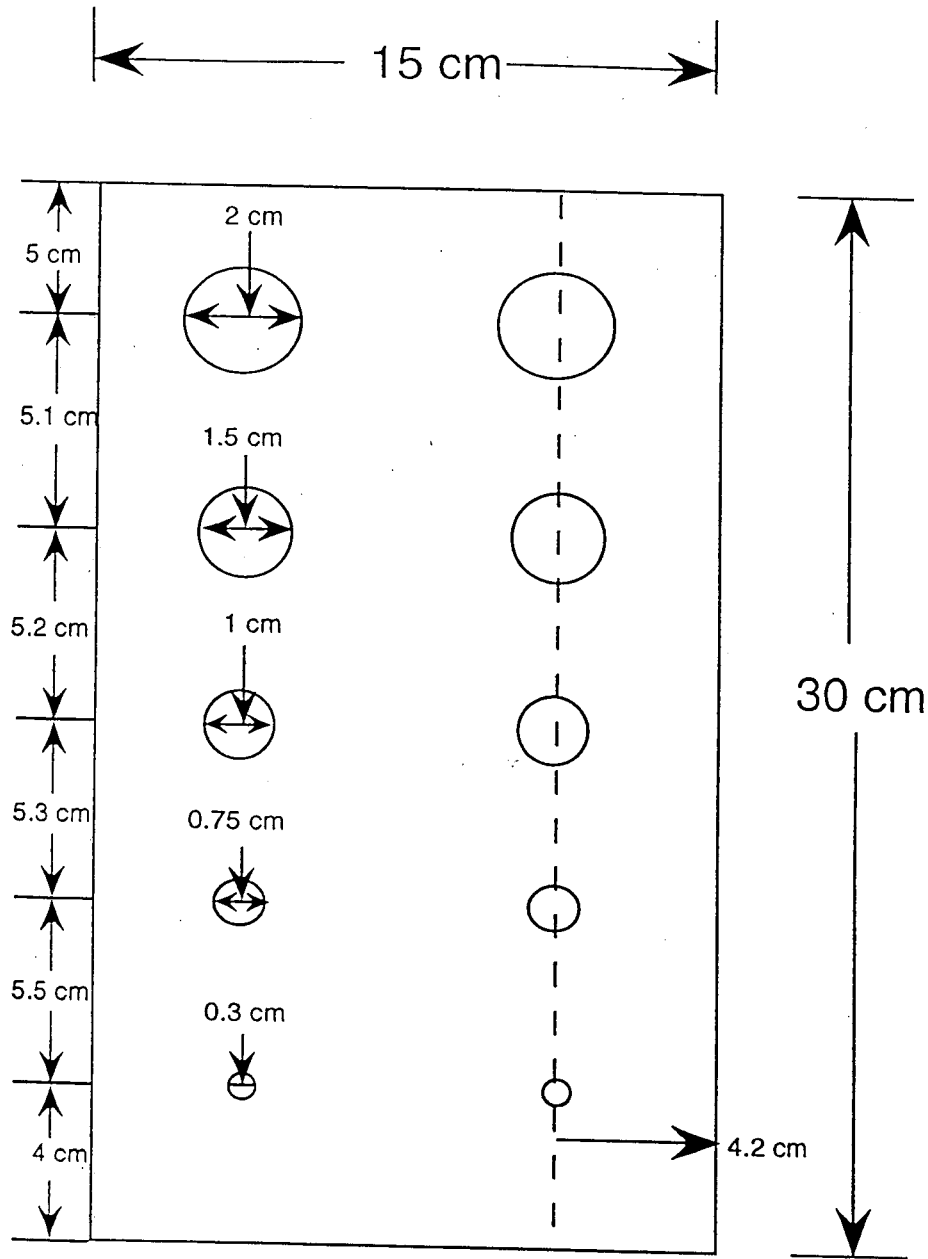


Figure 4. Diagram of the coated sample plate and arrangement of holes.

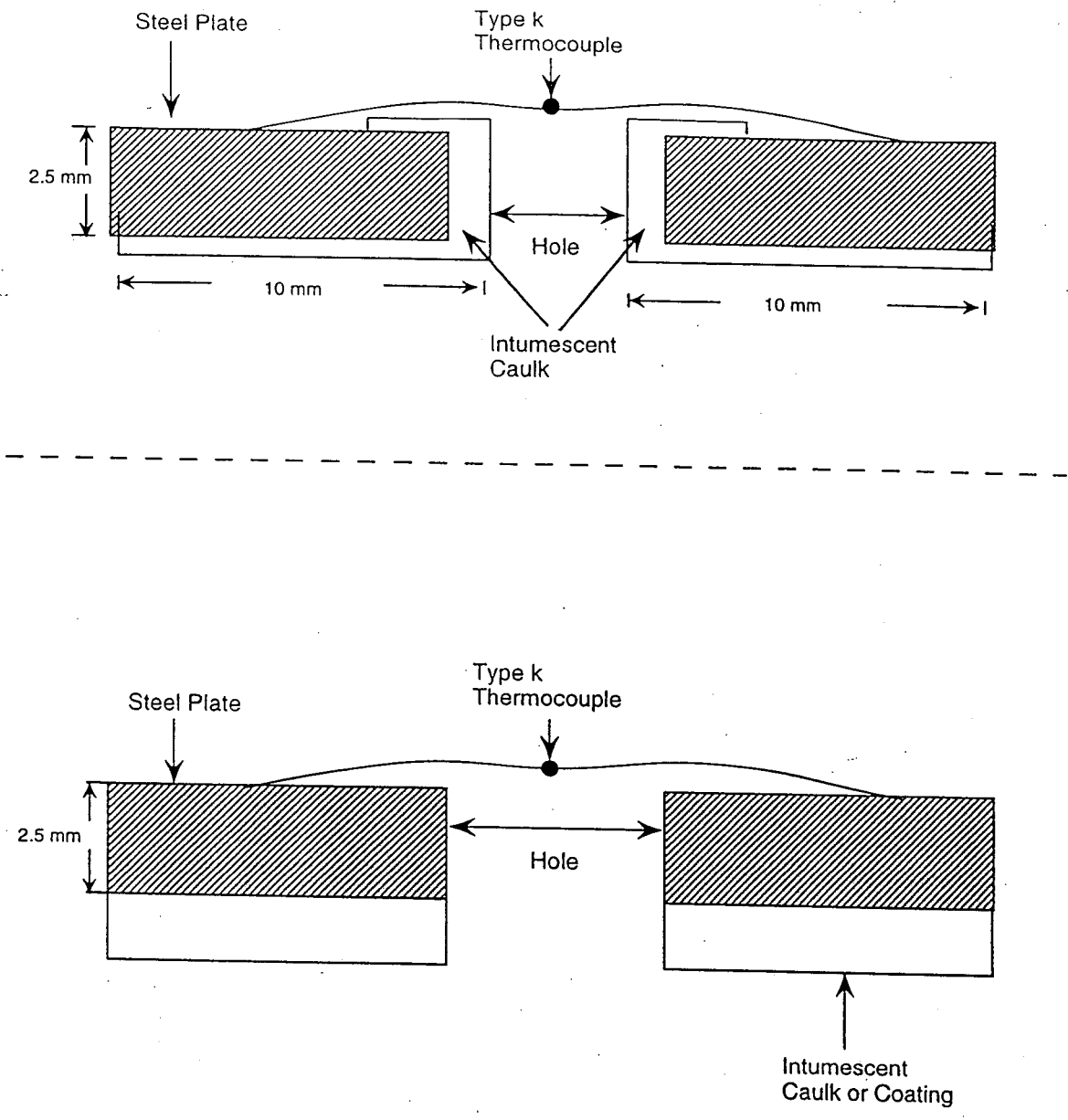


Figure 5. Cutaway view of the coated sample plate with (top diagram) intumescent coating on its face and an intumescent coating on the inner wall (bottom diagram).

of the propane burner. The surface of the coatings and the expansion of the coating thickness were difficult to observe due to visual obscuration by the luminous fire. Thus, the final thickness of the expanded intumescent was observed after a 30 min fire exposure, when the fire was extinguished. In some experiments, the samples were exposed in a vertical orientation using the apparatus shown in Figure 3. In that case, a flux gauge monitored heat transfer from the flame through the holes.

2.3 Intumescent Materials

Several different coatings were investigated including latex, epoxy, and oil based intumescent, as well as some intumescent mastics or caulks. The coating type and the initial coating thickness are listed in Tables 2-5 below. Also shown is the measured dry mass per unit area normalized for a 1 mm coating thickness. The applied coating thickness itself varied, due in some cases to the intumescent supplier who applied the coatings with special spray equipment at a thickness that they deemed appropriate. For some coating types, multiple coating thicknesses were investigated. The uniformity of the coating thickness varied from sample to sample. This is indicated by the standard deviation in Table 3, which represents measurements made at various locations on the sample.

Coating 1 in Table 2 was a solvent based intumescent coating intended for protection of structural steel and can be applied by an airless spray or brush. A topcoat thixotropic flame retardant sealer in a hydrocarbon solvent provides against the effects of atmospheric humidity. Coating 1 was advertised to expand by a factor of 50, once the substrate temperature reaches 200 °C. The manufacturer recommends surface preparation that included priming with a zinc phosphate or red oxide primer. In this study, a thin layer (≈ 40 micron) of red oxide primer was used. The coating was applied in our laboratory using a paint roller.

Coatings 2 and 5 were water based latex products intended for residential or light industrial use. Although the manufacturer recommends a topcoat for weather resistance in exterior applications, it was not applied for this study. Both formulations included ceramic fibers, although Coating 2 was not typically available with these additives. The coatings were applied using a paint roller. Multiple applications were necessary to build the thickness to the desired level. The smallest thickness for Coating 2 required 4 coats, whereas the larger thickness required approximately 10 coats.

Coatings 3 and 4 were epoxy based intumescent intended for structural protection of hydrocarbon processing plants and custom fireproofing of fuel handling components. The materials were sprayed onto our sample plates by the manufacturers.

Coatings 6-8 were caulks or mastics intended for residential or industrial use to provide a smoke and fire resistant seal at junctions in structural building elements such as floors, walls, door assemblies, or where materials are penetrated by cables or pipes. These materials were

applied with a trowel. The caulks were typically characterized by higher density than the paints. Coating 7 was an exception to this generalization.

Table 2 Coating designation, density per unit depth, and type.

Coating Designation	Mass per Area for 1 mm Depth (g/cm ²)	Type
1	0.11	solvent based
2	0.11	water based latex with ceramic fibers
3	0.11	epoxy resin based
4	0.13	epoxy based
5	0.13	water based latex with ceramic fibers
6	0.15	water based acrylic emulsion
7	0.11	latex based high solids compound
8	0.16	aqueous acrylic emulsion with mineral fillers

3. Discussion of Results

3.1 Local Heat Flux from Fuel Spills

Figure 6 shows the total heat flux to vertical and horizontal surfaces for a 15 cm gap (see Figure 2) from a spill of 200 ml of gasoline. Ignition occurred at 10 s and the fuel was nearly fully consumed after 60 s. At times, the flames filled the gap between the plates. On occasion, a convective current caused the plume to lean away from the gauges. The measured flux varied as a function of time due to the flame leaning. The flux also decreased as a function of time as the fuel was consumed. The heat flux measured by gauge 3 was much larger than that of gauges 1 and 2 mounted on the walls, which were similar in value. The heat flux measured in the gap between the walls by gauge 3 peaked at 130 kW/m², whereas the fluxes measured by gauges 1 and 2 peaked near 70 kW/m². These results are consistent with those reported by Ohlemiller and Cleary [1997]. Figure 7 shows results from an analogous experiment using 200 ml of heptane fuel instead of gasoline. The fluxes were generally larger than in the gasoline fire.

Figures 8, 9, and 10 compare the heat fluxes to gauges 1, 2, and 3, respectively, as the gap distance was varied from 2.5 to 15 cm for 100 ml heptane fuel spills. The gauge locations were somewhat different than those used in Figures 6 and 7. Gauge 3 was located at

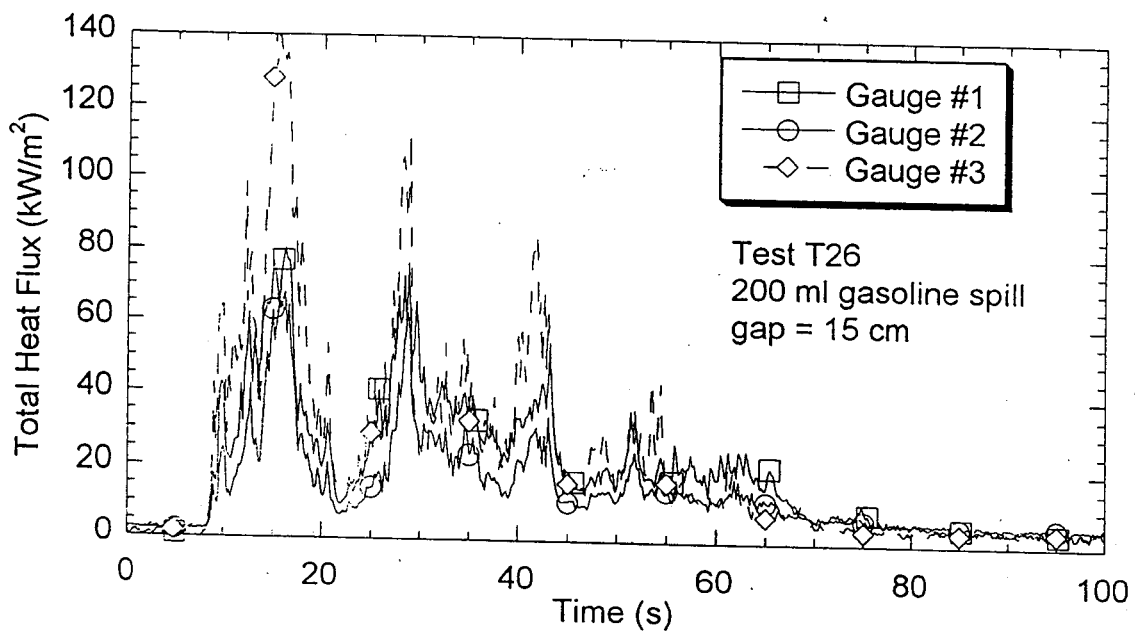


Figure 6. The total heat flux to vertical and horizontal surfaces for a 15 cm gap from a spill of 200 ml of gasoline.

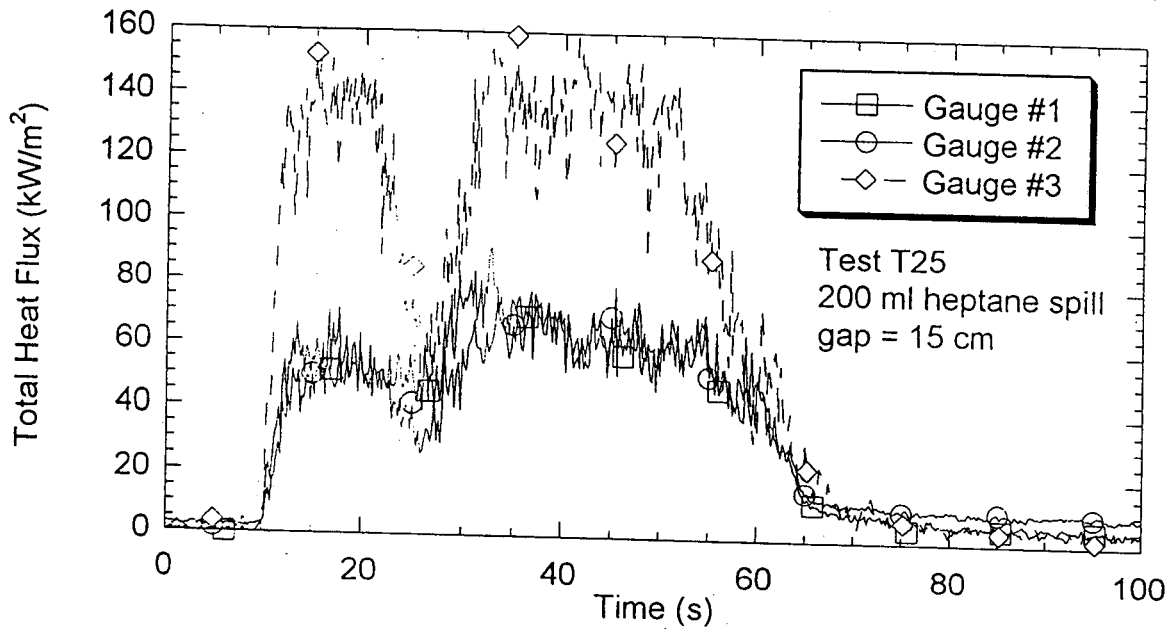


Figure 7. The total heat flux to vertical and horizontal surfaces for a 15 cm gap from a spill of 200 ml of heptane.

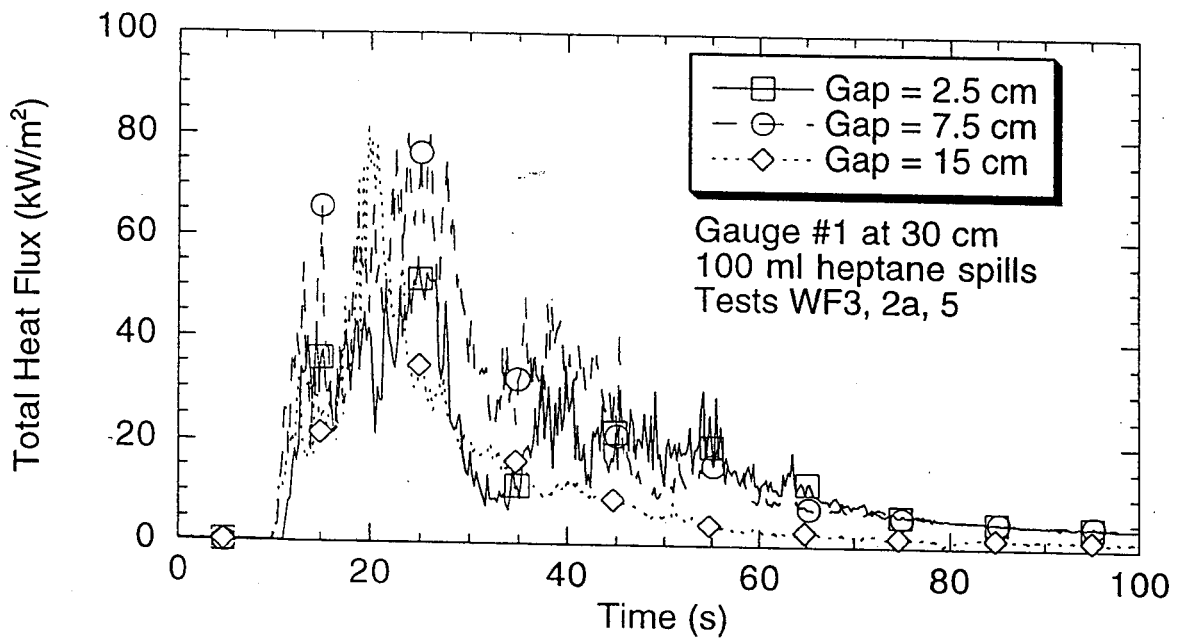


Figure 8. The total heat flux at gauge #1 from a spill of 100 ml of heptane for gap distances of 2.5 cm, 7.5 cm, and 15 cm.

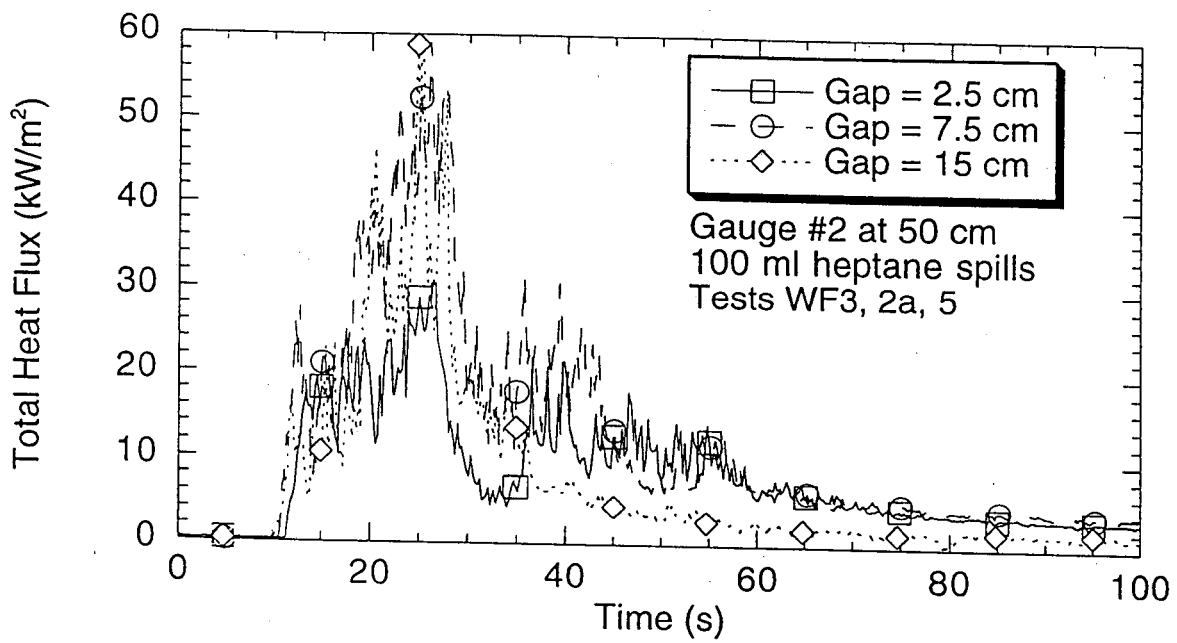


Figure 9. The total heat flux at gauge #2 from a spill of 100 ml of heptane for gap distances of 2.5 cm, 7.5 cm, and 15 cm.

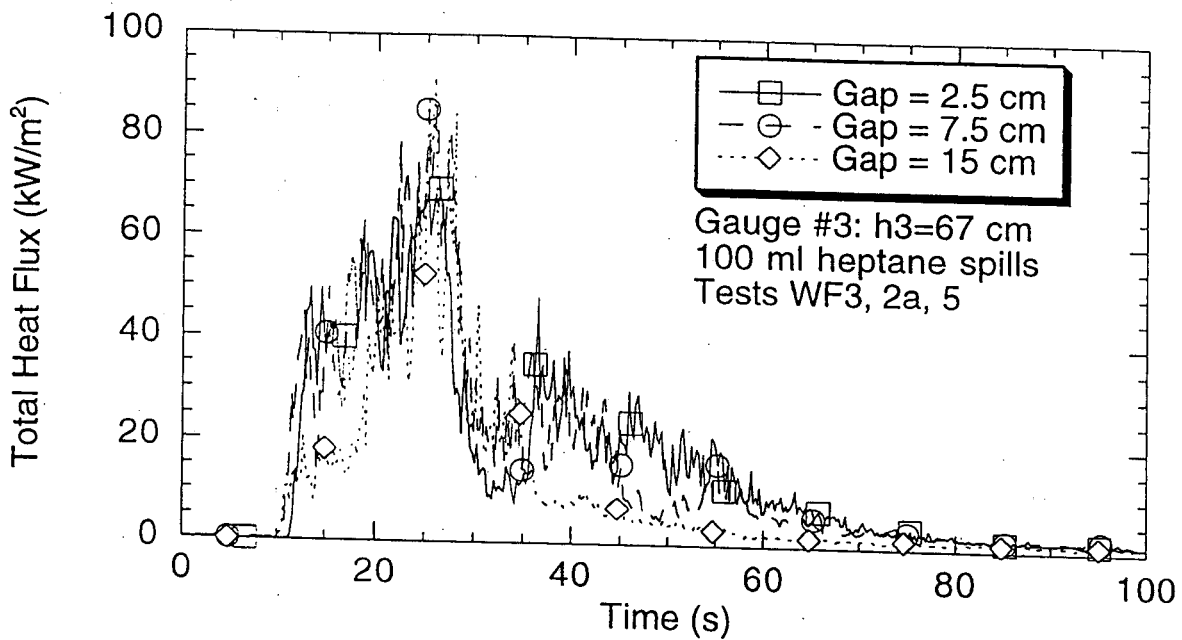


Figure 10. The total heat flux at gauge #3 from a spill of 100 ml of heptane for gap distances of 2.5 cm, 7.5 cm, and 15 cm.

$h=67$ cm (see Figure 2) and gauges 1 and 2 were located at 30 and 50 cm above the cement slab. The peak heat fluxes were lower than those shown in Figures 6 and 7. The peak flux measured for gauge 3 was 70 to 80 kW/m². The flux did not vary as the gap distance changed. A comparison of Figures 7 ($h_3=40$ cm) and 8 ($h_3=67$ cm) shows that the peak heat flux on gauge 3 was higher at locations closer to the cement slab. This was expected for heat transfer in the high temperature regions of a pool fire. Higher in the fire, the plume has been diluted by entrained air and the heat transfer should be less [Baum and McAffrey, 1989]. The peak flux measured by gauges 1 and 2 were 50 kW/m² to 70 kW/m² and 25 kW/m² to 50 kW/m², respectively, with the lower values in those ranges associated with the 2.5 cm gap distance. The fluxes were similar for the 7.5 and 15 cm gap distances. The fluxes measured by gauge 1 were larger than those measured by gauge 2, probably due to convective losses to the metal wall surfaces.

The results in Figures 6 - 10 show that the local total heat flux on a surface is a function of location, gap distance, and volume of fuel spilled. In vehicle fires, although the initial fire may be due to a liquid hydrocarbon, thermoplastic materials are likely to become involved within a few minutes. Fires involving thermoplastics can be expected to yield similar local heat fluxes when compared to the hydrocarbon fires studied here. That is because their flame structures, convective plume enthalpy, and radiative heat fluxes are expected to be similar [Orloff and de Ris, 1982]. Based on this reasoning, a total heat flux of 75 kW/m² was selected for samples oriented horizontally and 50 kW/m² for samples oriented vertically. The effect of the imposed heat flux on the effectiveness of the intumescent coatings is of interest in further studies.

3.2 Heat Penetration into Coated Plates

The 50 kW propane fire was luminous and on average, was approximately 0.9 m tall when unencumbered. When placed under the apparatus shown in Figure 1, luminous flames extended laterally past the edges of the device. The luminosity of the fire prevented observation of the growth of the intumescent layer. Smoke was emitted from the fire and the sample plate was coated with a thin black layer of soot.

Figure 11 compares the back surface temperatures as a function of time during exposure to the fire source for horizontally oriented sample plates from two experiments. One of the plates was coated with 1 mm of Coating 1, whereas the other plate was uncoated. There were two periods that characterize the plate temperature: an early "growth" period and a late "plateau" period. For both experiments, the temperature initially increased rapidly and after ≈ 200 s the rate of temperature rise decreased. Near-steady temperatures were obtained for the uncoated plate after ≈ 600 s of exposure to the fire, whereas the temperature of the coated plate continued to slowly rise (≈ 0.02 °C/s) even after 1800 s of fire exposure. Fire exposures for the coated and uncoated plates were stopped after 1800 s and 1200 s, respectively. A comparison of the temperature profiles after long exposure times (1200 s) shows that the temperature of the coated plate was ≈ 250 °C, which was significantly smaller than

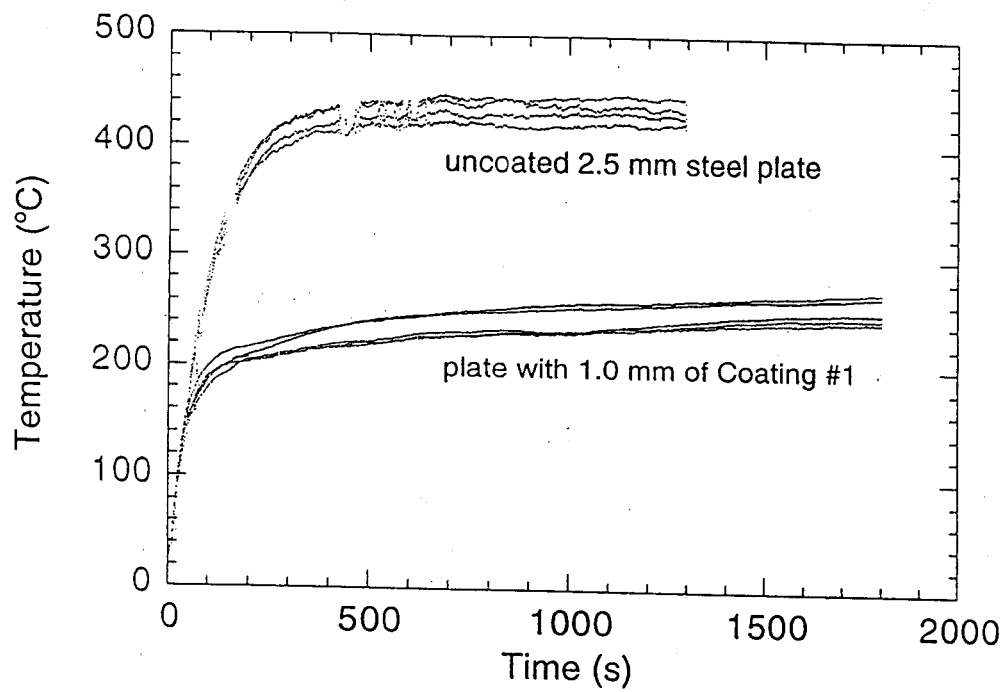


Figure 11. The back surface temperature of horizontally oriented, coated and uncoated 2.5 mm steel plates, as a function of time after exposure to a 50 kW propane fire.

that of the uncoated plate 430 °C. Also, the time to reach the steady temperature was smaller for the coated plate than for the uncoated plate. The spread in the thermocouple readings (thermocouples #1 to #5 in Figure 11) yielded a standard deviation of approximately 20 °C on average. For the other experiments discussed in this report, the average temperature was used.

The effectiveness of the coatings can be compared in a variety of ways. Consideration of the goals of the coating strategy, which was to prevent ignition of combustible components inside of the passenger compartment during a vehicle fire, helps formulate the comparison. Melting and thermoplastic degradation itself will not lead to ignition without an ignition source. Yet, these are the first phases in an ignition scenario and ideally should be avoided. Typical melting and degradation temperatures for many types of thermoplastics common to vehicles occurs between 175 °C and 250 °C [Madorsky, 1964; Abu-Isa et al., 1997]. The final temperature of the back surface of the coated panel is an important characteristic. For example, if that temperature is below the degradation temperature of an adjacent flammable item, then that item will not readily ignite. Because the back surface temperatures on some of the coated materials (see Figure 11) increased even after long exposure times, it was not possible to define an asymptotic temperature value within a reasonable exposure duration. It was not unreasonable, however, to compare the back surface temperatures of the plates after a specific exposure time. In this report a value of 600 s was selected. This value was somewhat arbitrary, but the approach provides a simple indicator of the effectiveness of the coatings for moderate fire exposures. A second important characteristic of a coating is the time duration required to reach the plateau. A longer duration implies increased safety. This can be characterized by considering the slope in Figure 11 as a specific temperature, or alternatively by considering the duration required to attain a specific back surface temperature. In this report, the latter approach was selected with a value of 150 °C. Similar trends are found if a value of 200 °C or 250 °C is used.

Figures 12 and 13 summarize the results for several of the coatings, considering the back surface temperature after a 600 s fire exposure, and the fire exposure time for attainment of 150 °C on the back surface. The initial application thicknesses are denoted in Figures 12 and 13 and are listed in Table 3. Table 3 also lists the coating expansion factor and the percent mass change after a 1800 s exposure for plates oriented horizontally. The expansion factor was defined as the ratio of the average final to the average initial coating thickness. The variation in measured thickness is indicated by the associated standard uncertainty as denoted in the Table. The expansion factor varied from 2 to 56 for the different products tested. The coatings can be characterized by either high (>15), moderate (3 to 15), or low (<3) volume expansion. Coatings 1 and 2 exhibited high expansion, but Figures 12 and 13 show that they were not particularly more effective than the other coatings. In general, there was no apparent correlation of performance with volume expansion. Table 3 shows that the percent reduction in mass was generally greater than 38%, but was as high as 66%. In the

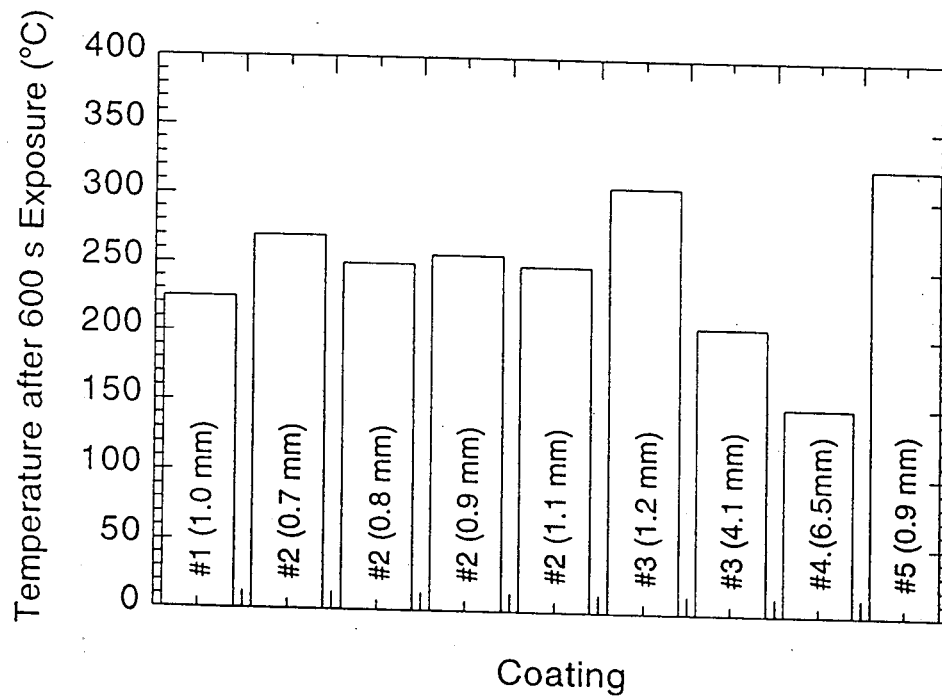


Figure 12. The back surface temperature of coated steel plates after exposure for 600 s to 60 kW/m² produced by a 50 kW propane fire.

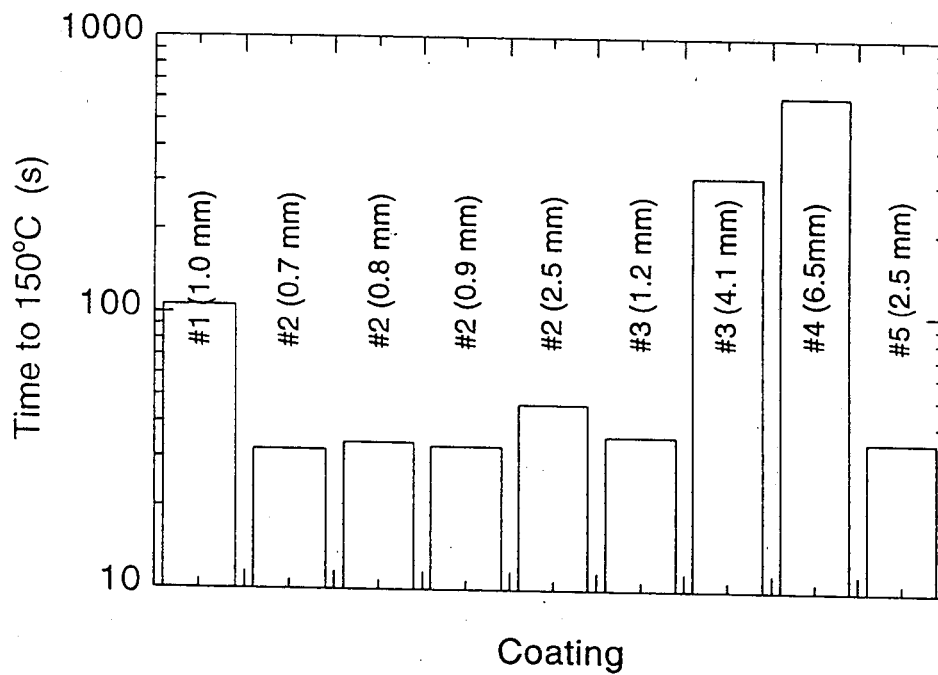


Figure 13. The time for the back surface of coated steel plates to reach 150°C after exposure to the 50 kW propane fire.

Table 3 The initial thickness, volume expansion and percent mass change for the intumescent coatings.

Coating	Initial Thickness (mm)	Expansion Factor	Percent Mass Change
1	1.0 ± 0.4	51 ± 36	-38%
2	0.66 ± 0.07	56 ± 11	-62%
2	0.67 ± 0.08	57 ± 17	-43%
2	0.86 ± 0.08	35 ± 7	-58%
2	1.1 ± 0.2	42 ± 13	-38%
3	1.2 ± 0.2	5.8 ± 1.7	-63%
3	4.1 ± 0.4	8.0 ± 2.4	-50%
4	6.5 ± 0.3	7.9 ± 1.6	-66%
5	0.85 ± 0.07	5.9 ± 1.8	-40%
5	0.92 ± 0.07	5.9 ± 1.8	-62%
6	6.7 ± 0.7	2.5 ± 2.0	-45%
7	5.1 ± 0.4	2.6 ± 0.5	-51%

horizontal orientation, the coatings adhered throughout the fire and the mass loss was attributed to vaporization of the coating.

Figures 12 and 13 show that the most effective coatings in terms of the lowest temperature after 600 s of fire exposure and the longest time to reach 150 °C (Coatings 3 and 4) appeared to be related to the coating thickness. For this reason, the data in Figures 12 and 13 were replotted in Figures 14 and 15 as a function of the initial and final coating thickness, respectively. Figure 14 shows that the plates with a larger initial coating thickness appeared to perform better, with the temperature after 600 s of fire exposure smaller for the thicker coatings. Scatter in the data for small coating thickness was diminished when the same data were replotted as a function of the final intumescent thickness, as shown in Figure 15. For moderate times, insulation by the intumesced coating played an important role. A straight line fit to the data was good except for the two data points representing plates with large initial coating thickness. This suggests that for the same initial coating thickness, the key to thermal protection may be rapid and large expansion. In terms of the time to attain 150 °C, the data scatter was improved when the data were plotted in terms of the initial (see Figure 14), rather than the final coating thickness. This indicates the importance of the heat capacity of the coating for short fire exposure times.

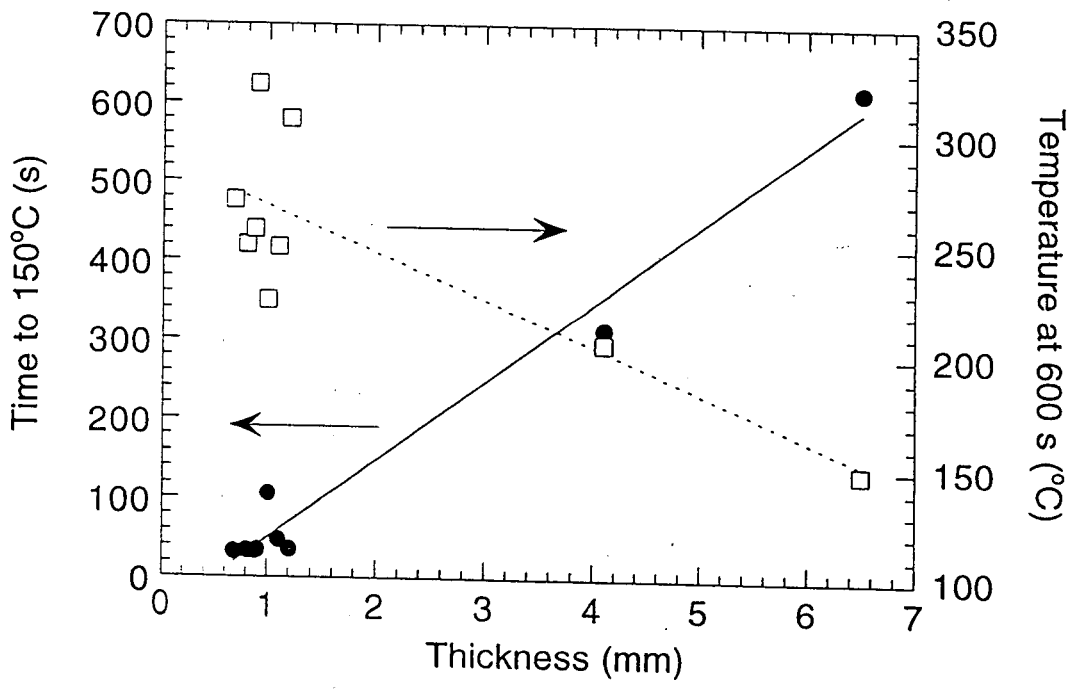


Figure 14. The time to reach 150 °C and the temperature after 600 s for the coated sample plates as a function of the applied coating thickness.

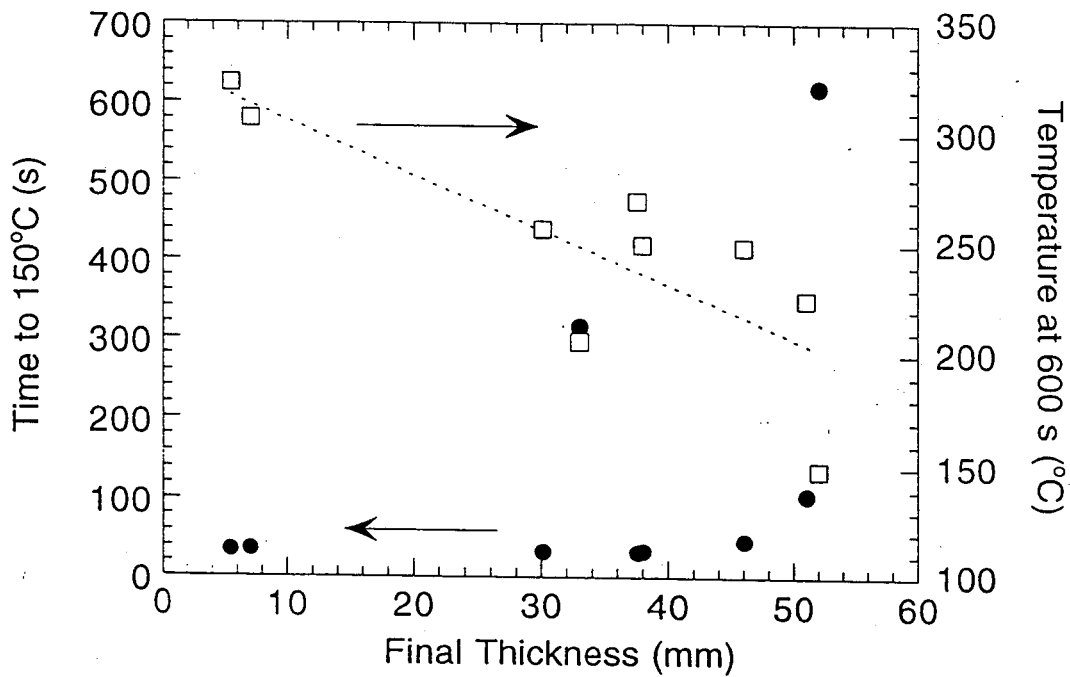


Figure 15. The time to reach 150 °C and the temperature after 600 s for the coated sample plates as a function of the final coating thickness.

Thus, both the initial and final thickness were important parameters. As the initial coating thickness of Coating 3 increased by a factor of 4, Figures 12 and 13 show that the time to reach 150 °C increased by a factor of 10, and the temperature after 600 s decreased by more than 100 °C. Increasing the thickness of Coating 2 by a factor of 2.5 had less of an effect. The time to reach 150 °C increased by a factor of 1.5, whereas there was no significant difference in the temperature after 600 s.

For similar coating thickness, some coatings performed better than others. Coating 1 performed quite well compared to the other coatings, which were applied with a 1 mm thickness. Figures 12 and 13 show that the temperature after 600 s was approximately 90 °C lower for Coating 1 as compared to Coatings 2, 3 and 5 for similar or larger application thicknesses. Difference in the time to reach 150 °C was less significant, as expected for the same initial thickness.

3.3 Effectiveness of the Coatings in Closing Structural Openings

In the second series of experiments, holes were drilled through a number of plates to test the effectiveness of coatings in blocking fire and smoke penetration through a perforated body panel. The coatings were applied to the plate surface, and the inner walls of the holes were not coated. Table 4 lists the initial average coating thickness, the ratio of the final coating thickness to the initial thickness, and the initial and final hole diameters for the test plates. The (standard) uncertainty in the final diameter was 1 mm, whereas the (standard) uncertainty in the initial hole diameter was 0.5 mm. The plates were oriented horizontally and exposed to the fire for 30 min. The smallest holes (1.6 mm) were usually filled, but the thermocouple traces indicated that this typically required more than 5 min. For all of the other coatings, holes equal to or larger than 6.4 mm were not blocked and flames were observed to penetrate during the entire experiment.

Figure 16 shows the total heat flux through a hole measured in experiments similar to those described by Table 4, but performed in a vertical orientation using a 1.0 mm layer of Coating 2 on the front surface of the plate. The gauge was located 0.5 cm behind a 6.4 cm hole in the plate. Although flames were observed to penetrate the hole throughout the entire experiment, the heat flux decreased from 40 kW/m² to approximately 10 kW/m². In the vertical configuration, the leading edge of the coating, closest to the bottom of the plate, disattached from the plate and fell during exposure to the fire. This behavior was repeated in a second experiment. This effect was not observed for the coatings near the edge of the holes, nor was it observed for plates oriented horizontally.

In a third series of experiments, the effectiveness of the intumescent caulks in protecting openings associated with pass through components was considered by coating the inner walls of the 19 mm holes with intumescent caulk. Three wall coating thicknesses were tested, namely 5.0 mm, 3.5 mm, and 2.5 mm. The caulks did little to close these holes. Table 5

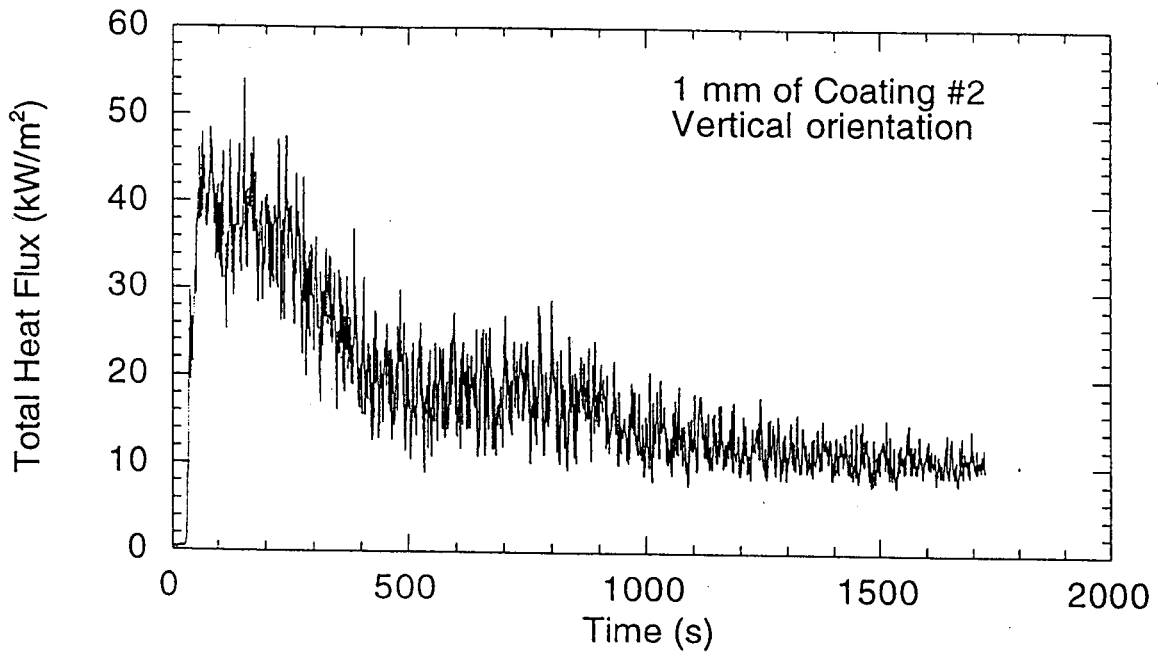


Figure 16. The total heat flux through a 6.4 mm hole for a 1 mm layer of Coating 2 held in a vertical orientation.

Table 4 The effect of intumescent coatings and caulks (applied to the plate surface) in closing holes.

Coating	Initial Thickness (mm)	Expansion Factor	Initial Hole Diameter (mm)	Final Hole Diameter (mm)
2	0.67 ± 0.07	50 ± 10	19.1 ± 0.5	12.7 ± 1
			12.7 ± 0.5	9.5 ± 1
			9.5 ± 0.5	6.5 ± 1
			6.4 ± 0.5	3.2 ± 1
			3.2 ± 0.5	1.6 ± 1
			1.6 ± 0.5	0.0
3	3.0 ± 0.3	8.0 ± 1.6	19.1 ± 0.5	17.8 ± 1
			12.7 ± 0.5	10.2 ± 1
			7.6 ± 0.5	6.4 ± 1
			5.1 ± 0.5	3.8 ± 1
			2.5 ± 0.5	1.0 ± 1
			1.3 ± 0.5	0.0
6	6.7 ± 0.7	2.5 ± 2.0	19.1 ± 0.5	18.0 ± 1
			12.7 ± 0.5	12.0 ± 1
			9.5 ± 0.5	7.0 ± 1
			6.4 ± 0.5	3.0 ± 1
			3.2 ± 0.5	0.0
7	5.1 ± 0.5	2.6 ± 0.5	19.1 ± 0.5	18.0 ± 1
			12.7 ± 0.5	12.0 ± 1
			9.5 ± 0.5	11.0 ± 1
			6.4 ± 0.5	2.0 ± 1
			3.2 ± 0.5	0.0

lists the initial caulk thickness on the inner wall of the hole, the initial hole diameter, and the final hole diameter on the coated sample plates after 30 min of exposure to the 50 kW propane fire. An ideal product would rapidly close an opening completely. Coatings 6 and 8 exhibited similar amounts of expansion, reducing the holes by an average of 2 mm. Flames were observed to penetrate the holes throughout the duration of the experiments. Coating 7 appeared to disintegrate, eventually exposing the entire original hole. Table 5 shows that the initial hole diameter apparently had negligible effect on the intumescent behavior of the coating, as the final size of the hole through the coating had little relation to the initial value. The results show that these intumescent caulks failed to fill holes as small as 9 mm in diameter. Although coating the inner wall of a panel is apparently not an effective strategy for intumescent applications, other orientations may be more effective. The results presented here prompted discussion with technical and marketing representatives of several manufactur-

ers of intumescent products. Through follow-up conversations, it was apparent that none of the manufacturer representatives that we spoke to could produce a solution to the hole-filling problem at this time.

Table 5 Effect of intumescent caulks (applied to inner wall of hole) in closing holes.

Coating	Wall Coating Thickness (mm)	Initial Hole Diameter (mm)	Final Hole Diameter (mm)
5	5.0 ±1	9 ±0.5	6 ±1
	3.5 ±1	12 ±0.5	10 ±1
	2.5 ±1	14 ±0.5	12 ±1
6	5.5 ±1	8 ±0.5	6 ±1
	3.5 ±1	12 ±0.5	11 ±1
	2.5 ±1	14 ±0.5	11 ±1
7	5.0 ±1	9 ±0.5	18 ±0.5
	3.5 ±1	12 ±0.5	18 ±0.5
	2.5 ±1	14 ±0.5	18 ±0.5

3.4 Intumescent Ventilation Grilles

The performance of the intumescent caulks motivated testing of intumescent air transfer grilles. This product is used in the building and construction industry to seal a room and prevent the transport of smoke and toxic gases into a heat and air conditioning system in the event of a fire. The grilles are available in various shapes, sizes, and thicknesses. The grilles were composed of an aluminum frame with intumescent strips fastened to (both sides of) rectangular crosspieces. The crosspieces were approximately 3 cm wide (denoted the x direction) and 30 cm long (y direction) and 1 mm thick (z direction). They were separated in the z direction by a distance of approximately 1.5 cm. The intumescent strips had the same dimensions as the crosspieces, except they were approximately 2 mm thick (z direction).

Experiments were performed with the grilles exposed to the 50 kW propane fire for 60 s in a horizontal orientation in the same manner that the coated steel plates were tested using the apparatus shown in Figure 1. Figure 17 shows a grille after the 60 s time exposure. The gaps between the crosspieces were closed at locations where fire exposure occurred. Also evident are intact gaps, at locations where no fire exposure occurred. Observation of the video record shows that fire penetration through the grill was completely stopped after 60 s of fire exposure.



Figure 17. Photograph of an intumescent grill after a 60 s exposure to the 50 kW propane fire.

In their current form, the grilles are probably not appealing for vehicle body panel applications because they have a large mass, and would be susceptible to collision damage. However, this product does demonstrate that intumescent materials can be effective in closing gaps along a surface when applied in an appropriate manner.

4. Summary and Recommendations for Future Research

Recent burn experiments initiated in the front-end of vehicles as part of Project B.3 have shown that fire spread into the passenger compartment can occur through a number of pathways including a breached forward bulkhead. In the experiments reported here, the application of intumescent coatings on simulated post-collision body panels was considered in an attempt to reduce the heat flux and transport of smoke and toxic gases into the passenger compartment during a post-collision vehicle fire. The following conclusions are made regarding fire intervention in a post-collision vehicle environment.

- Intumescent coatings considerably reduced heat conduction through a non-damaged body panel. The reduction was related to the thickness of material applied.
- When applied in a customary manner, intumescent products as currently formulated do not resolve problems associated with even small openings in a post-collision vehicle body panel. The experiments showed that the coatings failed to close and prevent flames from penetrating even small (6 mm) holes simulating a post-collision vehicle body panel. As new formulations become available, further testing may be useful.
- Further investigation may consider the placement and orientation of intumescent products in an attempt to take advantage of their unique swelling behavior. Judicious application of these materials may lead to beneficial results in post-collision vehicle fires, but the details of such an arrangement need further consideration. For example, application of an intumescent coating on the portions of the surface of a pass-through bulkhead component may warrant experimentation.

5. Acknowledgements

The author is indebted to Roy McLane for building the experimental apparatus, to Renaat Ver Eecke for assisting with the measurements, to Ruddy Mell for numerical computations of heat conduction, and to Tom Ohlemiller and Tom Cleary for many helpful discussions. This report was financed by General Motors pursuant to an agreement between General Motors and the United States Department of Transportation.

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U.S. Department
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**National Highway
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Deputy Administrator

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David A. Collins, Esq.
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Legal Staff
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Detroit, MI 48232

Dear Mr. Collins:

We have received your letter, dated August 21, 1998, enclosing a report entitled "Evaluation of Intumescent Body Panel Coatings in Simulated Post-Accident Vehicle Fires."

The report relates to Project B.4 Evaluation of Potential Fire Intervention Materials and Technologies. It was prepared by Anthony Hamins of the National Institute of Standards and Technology.

The report will be placed in the Department of Transportation Dockets, NHTSA-98-3588, and in Docket No. 96-GMRSRCH-GR in NHTSA's Technical Information Services, formerly Technical Reference Library. Your letter dated August 21, 1998, will be placed in the Department of Transportation Dockets, NHTSA-98-3585.

Thank you for your cooperation. If you have any questions or need assistance, please call Ms. Heidi L. Coleman, Assistant Chief Counsel for General Law, at (202) 366-1834 or Mr. Lou Brown, of NHTSA's Office of Research and Development at (202) 366-5199.

Sincerely,

Philip R. Recht