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U.S. Department of Commerce
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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 report 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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Burning Behavior of Selected Automotive Parts from a Sports Coupe

Abstract

Selected functional parts from a sports coupe were subjected to a gas flame ignition source and burned in a manner that allowed measurement of the resulting total heat release rate and heat fluxes to the surroundings. This is the second part of a study undertaken to: (1) assess possible means for determining the flammability characteristics of automotive components, (2) obtain data on the range of flammability behavior exhibited by such components and the physical processes underlying that behavior, and (3) obtain insights into the fire behavior seen in related full-scale vehicle fire tests. Most of the vehicle components examined in this study were mounted in isolation on a vehicle buck (a stripped, partial section of the original sports coupe). This led, in some cases, such as with a rear interior trim panel, to a strong influence of the vehicle structure on the behavior seen; it also led to other interactions such as the penetration of the windshield by a front fender fire. Other parts exhibited a wide variety of behaviors influenced not only by their constituent polymer resins but also by their shapes, sizes and internal structures.

1) Introduction

This is the second report of results from Project B.10, "Study of Flammability of Materials," which is being performed as part of a Cooperative Research and Development Agreement (CRADA) between General Motors Corporation and NIST. This study was financed by General Motors pursuant to an agreement between General Motors and the United States Department of Transportation.

Research under this Project will examine the flammability characteristics of automotive engine compartment fluids (other than gasoline) and solid materials from both the vehicle exterior and interior. Efforts will be made to identify or devise cost-effective, less flammable substitutes (with acceptable physical properties) for selected materials.

The present study complements related work (Project B.3) in which a limited number of vehicles selected by General Motors, in consultation with the National Highway Transportation Safety Administration (NHTSA), are being subjected to controlled crash tests. NIST, as part of its CRADA with GM, is participating in subsequent fire initiation/propagation tests on these crashed vehicles. The crash tests involve both rear and frontal impacts. Thus the fire tests involve both under-hood fires and gasoline pool fires under the vehicle. The principal concern in these fire tests is the manner and rate at which such fires grow and spread into the passenger compartment.

For the solid materials in vehicles, the work here is one facet of a collaborative study of the factors affecting their flammability. General Motors is examining such factors as the thermal properties of the constituent polymer formulations[1] and the degradation of these as a function of temperature [1]. Factory Mutual Research Corporation is measuring the flammability behavior of small, isolated portions of these polymer formulations [2].

The focus of the work discussed in this report is on the fire behavior of individual components and, in one case, a sub-assembly of an automobile (the instrument panel). The principal measure of fire behavior that is of interest here is the rate at which the burning process gives off heat (termed the heat release rate); in a fire it is this measure of fire strength which drives heat and toxic gases and thus presents the best measure of fire hazard.

In general, specific parts were selected in this study in an effort to look beyond the range of vehicle components described in the first NIST report [3]. This pointed toward parts with other functions or at least other constituent materials. This tendency was tempered by the need to examine some parts which appeared to be significant participants in the fire paths seen in the full scale tests of this sports coupe in Project B.3 [4].

This study differed from that in Ref. 3 in that it made extensive use of a pair of "test bucks" to mount the parts in their actual usage locations. These bucks were obtained by cutting a sports coupe (of the same type from which the parts tested here were obtained) into two sections at approximately the location of the rear of the front seat (thus forming a front and a rear buck). The engine, drive train and suspension were removed from the vehicle before it was cut. Casters were welded to the frame rails and floor pan of each section so that the height of the test bucks approximated that of the sports coupe equipped with wheels and tires specified by the manufacturer. Combustible materials, other than the component(s) of interest, were removed. Some fiberglass body panels and the windshield could not be removed.

Component orientation with respect to other vehicle components and structures can affect observed fire behavior. Thus, mounting a single component into a buck (i.e., into its intended usage location in a vehicle) can, in many cases, influence its fire behavior. This is a result of the proximity of other inert surfaces which, for example, may block air access to some areas of the component, exchange radiant heat with some surfaces, or, in the case of thermoplastic parts, catch and redistribute polymer melt material. Thus such placement is one step toward more realism but also toward a more narrow specificity of the results. Going the next step beyond this to a component mounted in a fully intact vehicle also implies the presence of many other components, many of which may also be

[1] This phrase is used here to denote the blends of polymer resin plus fillers and additives that are used in vehicle components. The principal polymer resin has been identified in most cases but the other constituents of the formulations have not been identified.

flammable. The interactions among burning components would be expected to result in still different (possibly more severe) fire behavior of the component of interest, especially if surrounding fires supplied substantial amounts of radiation. This last case would be quite costly; the use of a buck offers a substantial degree of realism at lesser cost.

Most of the vehicle components examined here contained (or were composed entirely of) thermoplastic polymer formulations. This means that when subjected to an ignition source they tended to lose their original shape and to sag or flow downward under the influence of gravity. Such flow carries heat from the ignition source and, potentially, flaming material to new locations. This too can have a substantial influence on the observed burning behavior of the component. Ref. 3 includes a more detailed discussion of the potential effects of the pertinent parameters of the constituent polymer formulations, of the particular component in which they are found and of the specific ignition scenario. All of these features can influence the observed burning behavior in a fire test. Thus it should be borne in mind that the results reported here are not unique and do not represent a definitive measure of flammability.

2) Experimental Details

Test Objects Description/Rationale. Table 1, derived from analytical results provided by General Motors (4), lists the components which were tested and gives the polymer resin type in each constituent (where a component had more than one constituent). Note that several of the components may have contained significant amounts of inorganic fillers or fibers but specific data on the amounts are not available at the time of this writing. The total weight of the component is included where this was available.

The components to be tested were chosen in joint consultation among General Motors, NIST and Factory Mutual.

Figures 1 through 14 show photographs of the components as tested. Most were tested individually, mounted in their correct orientation, in one of the bucks when possible. All of the components listed in Table 1 under "Instrument Panel, Gages and Console" were assembled into the unit shown in Figure 12. This assembly was tested in a manner, described below, which was qualitatively similar to the exposure it experienced in a full-scale, post-crash fire test [5].

In general, the fire behavior of an instrument panel is of particular interest since it resides just behind the forward bulkhead separating the engine compartment (where many fires originate) from the passenger compartment. Pre-existing or crash-induced holes in the bulkhead[2] may enable ignition of instrument panel components by fires originating in the engine compartment. The windshield of a vehicle also represents a barrier between the

[2] Designed-in holes through the metal bulkhead are typically covered by a pass-through grommet, a plate or some similar closure device which does not permit the free flow of gases from the engine compartment into the passenger compartment. In a crash, this closure may be displaced.

passenger compartment and fires originating in the engine compartment[3]. Because the polymer layer (termed the "inner-layer") sandwiched between glass layers is flammable, the windshield[4] is of interest here[5]. The air intake grill at the base of the windshield is an intermediate part in the fire path from engine compartment to windshield; it is of interest to determine the extent to which its burning may inflict damage on the windshield itself.

The floor pan drain hole plug was of interest because the floor pan drain hole was one of the fire paths into the passenger compartment observed in a full-scale fire test of this vehicle in Project B.3. This plug was made from EPDM rubber. The drain holes such plugs fill (four in this particular vehicle) are potential paths for ground level fires to penetrate into the passenger compartment, though typically such a fire would have to penetrate not only the plug but also an insulator pad (carpet underlay) and the floor carpet. The plug was tested here only to gain some insight into the conditions in which penetration of the plug would occur. It was mounted in the floor pan of the front buck.

A few components (the power steering fluid reservoir, radiator fan blade, radiator outlet tank) were chosen because parts made from their resin (nylon 6/6) had not been examined in the preceding study. The bumper constituents were chosen because they increasingly comprise, on modern vehicles, substantial fuel masses stretched over a broad lateral expanse; flame spread along that expanse plays a role in their fire behavior. The front fender on this vehicle represents a similar mass but closer to the passenger compartment. Finally there are the materials which form the exposed top surfaces of both the engine and passenger compartments, the hood liner and the passenger compartment head liner. This position makes them highly susceptible to fire exposure due to the buoyancy of flames; the consequences are of interest here. The liners represent two alternative designs for components tested in the preceding study.

Flow Calorimeters. Two measurement devices (basically instrumented hoods which capture the fire plume) were used in nearly all of the tests to measure heat release rates in the study reported here; they are described in more detail in Ref. 3. Both are calorimeters which work on the oxygen consumption principle, i.e., that all common organic materials yield approximately the same heat evolution per unit mass of oxygen consumed in their combustion [Ref. 6]. Thus one can measure the rate of heat release evolved from the burning of an object by capturing the plume of evolved gases and measuring the mass flux deficit of oxygen it carries relative to ambient air.

The variability among common organic compounds with respect to heat evolution per unit mass of oxygen consumed is about ± 5%; this systematic error sets the maximum level of accuracy achievable in oxygen depletion calorimetry when unknown organic polymers are tested. The instrument is calibrated before a major test series, such as that

[3] Federal Motor Vehicle Safety Standard 205 specifies windshield requirements. There is no requirement for resistance to fire penetration.
[4] Other vehicle windows typically do not incorporate a polymeric inner layer and are thus not flammable.
[5] The glass layers in an intact windshield could be broken by thermal stresses induced by an external fire. A crash can also shatter the glass. In either case the inner-layer will hold the glass fragments in place until it starts to sag if heated by an external fire. This exposes the inner-layer.

described here, and then checked each day in a more limited manner (typically at three heat release rate levels). The cumulative calibration data show a small random variation. The combined uncertainty due to these systematic and random errors is about ± 5-7%.[6] A more detailed uncertainty analysis has not been performed because the data presented here are intended only to be indicative of the heat release levels achieved in specific configurations and will not be compared to any mandated performance levels.

One of the calorimeters is rated for fires yielding a peak heat release rate of 100 kW or less; the other is rated for fires yielding a peak heat release rate of 500 kW or less. The former was used for the nylon underhood components, i.e., the power steering fluid reservoir, the radiator fan blade and the radiator outlet tank; the latter was used for all of the other parts (except the windshield segments) and for the instrument panel assembly.

A third facility, the NIST Cone Calorimeter, also a flow calorimeter, was used to examine the ignitability and heat release rate behavior of the windshield segments. This facility has an electrically-heated, cone-shaped radiator with which heat fluxes up to 100 kW/m^2 can be imposed on a test sample.

Ignition Conditions and Burning Configurations. A few components (i.e., the nylon underhood components) were burned in isolation in the same manner as was used extensively in the preceding study [3], i. e., with the object just above a catch surface. These tests were done in the 100 kW flow calorimeter. This configuration tests the potential for a melt/drip fire to interact with the burning of the object itself. The origin of the melt/drip fire lies in the thermoplastic nature of many vehicle components, as mentioned in the Introduction; flaming material tends to flow off of the object and come to rest on the nearest lower surface. In the testing here the potential for interaction between a melt fire and the burning object was emphasized by placing a receiving surface 15 cm below the bottom of the tested component[7]; the surface was composed of fiber-reinforced cement board. The thermal inertia of this material was less than that of typical surfaces likely to be encountered in real post-crash fires (e.g., metal surfaces of the vehicle or an asphalt/concrete road surface); the catch surface used here could thus be expected to heat more rapidly and sustain a melt fire more readily. This makes the tests performed here somewhat more severe than would be the case had the catch surface been steel or concrete.

[6] At the very low end of its heat release range, the smaller calorimeter frequently gave a result of 6 kW for the 7 kW igniter flame; this is noted here but not corrected in the Figures in this report since it is of little consequence. The igniter flame size was held constant by control of its gas flow rate.

[7] A separation distance of 15 cm is a compromise between the relatively short distances likely to be encountered within the engine compartment and the greater distances involved if the flaming melt/drip material flows all the way to a road surface. Separation distance is, in fact, one of the parameters in this problem whose value can be expected to significantly influence the results observed. It was not possible to examine the effects of this parameter in this study. Note that in testing a part in this manner, we are deliberately departing from the specifics of the placement of this part in this vehicle. Instead, we are trying to develop information (admittedly very limited) on whether parts made from nylon 6 are susceptible to interactive melt/drip fires. This is the same approach used for many of the minivan parts tested in Ref. 3.

The tests of this type were implemented as follows. The ignition source, placed below the bottom of the tested component, was a ring burner (10.2 cm ID ring made from 0.635 cm OD stainless steel tubing having 12 equally-spaced holes, 0.132 cm dia.; holes pointing inward/upward at 45°). This burner was operated with a steady propane flow of 5 L/min (measured at normal temperature and pressure, NTP), set and controlled by a parallel pair of Brooks 5850 mass flow controllers, factory-calibrated for propane.[8] This flow corresponds to a heat release rate of 7 kW and yields a conical, essentially laminar fire plume which tapers from a base diameter of approximately 10 cm to a narrow tip at a height of approximately 30-35 cm.[9] This burner was placed 7.6 cm below the lower surface of the tested component; it was left in place and on throughout most of a test. When it was turned off, it was at a point where it was essentially irrelevant to the behavior of the part since no polymeric material remained at or above the height of the burner. Each tested component was in its normal orientation that it would have in a vehicle and was supported in a manner approximating its normal means of support. Note in the Figures that the part is otherwise isolated in space. The catch surface was placed 15.2 cm below the lower surface of the part. That surface was made of a 1.3 cm thick layer of cement fiber board (Durock), 76 cm square. That catch surface was itself located on top of an equal-sized slab of 1.3 cm thick calcium silicate board (Marinite) resting on top of an ATC 6005 weigh cell which allowed measurement of the mass of material collecting on the catch surface (this material typically burned there). The part itself was also being weighed during a test with a pair of Omega LC2 scales. Figure 15 (adapted from Ref. 3) is a generic schematic of the implementation of this test configuration. Note that Figures 3, 4 and 5 show the actual mounting of specific parts.

In these tests a single total heat flux gage was placed close to the test object (Medtherm model 20679) looking horizontally toward it. This was a Schmidt-Boelter type gage cooled with water at approximately 85 °C to prevent condensation on the sensor surface. The gage was calibrated at this coolant temperature with a radiant heat source. The gage was intended only to give a sampling of the level of heat flux the burning object could transmit to surrounding objects. The gage saw radiation only or a combination of radiation and convection if the fire plume on the object leaned toward it and contacted the gage. Note that the radiative fluxes are maximized by close placement of the gage to the burning object. At greater distances they decrease in accord with the view factor between the burning object and the point of measurement.

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[8]Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. 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.

[9]This flow of propane is equivalent in enthalpy release rate (power output) to a liquid gasoline flow of 13 cm^3/min (0.22 mL/s). For reference, Federal Motor Vehicle Safety Standard 301 allows a post-crash liquid gasoline leak rate of up to 35 to 40 cm^3/min (0.58 to 0.67 mL/s; based on an allowed leak of 5 ounces in the first five minutes after the vehicle comes to rest). This is noted only to indicate that the igniter heat release is in a plausible range. The tests done here are not necessarily intended to assess the behavior of parts as subjected to a gasoline leak fire.

The tests were videotaped from two directions, typically at 90°, using Hi-8 camcorders. For these relatively small objects it was usually possible to get enough light on the part so that the flames were not overexposed when the part was properly exposed on the video tape. The tapes provided a visual record of the behavior of the test object and evidence of the extent to which its burning was affected by interaction with its melt/drip pool fire.

Most of the tests (other than those above and the windshield segments described below) were done with the component of interest mounted on the front or rear buck at the proper location. The buck was placed under the hood of the 500 kW flow calorimeter. In this case the only appropriate place to utilize a cement fiberboard catch surface was below the buck (as a simulated road surface). Other metal surfaces of the vehicle did sometimes interact with melt/drip material, as noted below in the Test Results section.

For these tests the igniter was one of four different configurations. The first was the same ring igniter described above, used at the same propane flow rate and placed 7.2 cm below the bottom surface of the part being tested (not necessarily centered on the part). A variant of this, a 5 cm dia. ring igniter, was used in the instrument panel assembly test. Most of the component tests utilized a 15.2 cm long tubular burner providing a narrower flame over a wider area than do the ring burners; this was more appropriate for many of the components given their large lateral extent. Again the propane flow rate was the same as above. Finally, the ignition source for tests of both the head liner and the hood liner was a wider tubular burner, 61 cm across, and the propane flow rate was raised slightly to 6 L/min (8.4 kW). In all tests with the tubular burners, the burner itself was placed up against the lower surface so that the relatively short flames would splay out tangentially across this surface. Flux gages were used in the buck-based tests in a manner that varied from one test to the next, as described in the Test Results section below. These tests were also video-taped from two directions to record the details of the physical behavior that underlay the measured heat release rate. The larger parts could not be illuminated with sufficient intensity to always preclude overexposure of the flames. The apparent opacity of the flames on the video tapes thus sometimes partially obscured some details of the physical behavior.

The windshield comprises a special case. It was of interest to explore the behavior of the glass/polymer sandwich in the condition it often exists in after a crash, i.e., extensively fractured. The fractures provide some limited exposure of the polymer layer (especially where the windshield has been stretched by impact forces). In addition, crash forces cause some fraction (typically small in the vehicles tested in Project B.3) of the glass fragments on the outer surface to fly off, exposing more of the polymer layer. The characterization of interest was of the ignitability and subsequent heat release rate from fractured windshield sections, as a function of the heat flux level on the outer surface. This type of information is provided by the Cone Calorimeter [7] which uses a cone-shaped heater to irradiate the sample surface. Just like the large-scale hoods used for the other parts described above, the Cone Calorimeter captures the fire plume from a 10 cm square sample and infers the heat release rate using oxygen-consumption calorimetry.

It was necessary to cut a windshield into roughly 10 cm square sections for these tests.

This was achieved by scoring the glass on both sides, breaking it along a straight edge and then cutting through the 1 mm thick polymer layer between the glass layers. Several pieces used for these tests had a thin layer of black paint on part of one glass surface (used on the vehicle to obscure the attachment area of the windshield to the vehicle body). This painted side was placed on the bottom in the tests and had no apparent effect on the results here. The windshield sections were then fractured extensively by rolling them around a metal cylinder. This caused a small number of glass fragments to dislodge. A total of approximately 5-10% of the exposed surface had its outer glass layer deliberately removed in patches (roughly 1-2 cm dia. or less) to provide a reasonably consistent level of polymer exposure. Fig.2 shows a typical example of the samples tested. Samples of this type were exposed in replicate tests to radiant fluxes from 15 to 50 kW/m^2; piloted ignition delay time and heat release rate were measured. To assure that the patchy nature of the exposed polymer layer did not lead to erratic ignition results, the piloted ignition source (a small electric spark) was moved around in the smoke plume before ignition.

3) Test Results and Discussion

The test results are presented in the order of increasing complexity of the tests themselves. Thus we begin with the tests on the floor drain plug, then the Cone Calorimeter tests on the windshield, the isolated component tests, the buck-based tests of single components and, finally, the instrument panel assembly.

Floor Pan Drain Hole Plug. This plug fills a hole about 35 mm in diameter in the floor pan. There are four such plugs in the floor of this particular vehicle. It has a large lip on the upper side that would ordinarily preclude its being pushed downward through the hole in the floor pan (see Fig. 1). The central part of the plug, which blocks the hole, is 4 mm thick. As indicated in Table 1, the plug is an ethylene/propylene/butadiene rubber, which is not a thermoplastic material.

The objective of these tests was to expose this plug to heat fluxes comparable to those it might experience in a ground level, fuel-fed fire. Such fluxes can reach 100 kW/m^2 directly above the fire [8]. Here the ring burner with propane as the fuel (5 L/min) gave fluxes from 55 kW/m^2 up to 75 kW/m^2 as measured by inserting a flux gage through the floor pan with its sensor face flush with the lower surface of the metal. (This was done at a location away from the floor plug with the ring burner centered on the flux gage.) Thus the exposure here is representative of that expected somewhat toward the periphery of a fuel-fed fire.

Three tests were conducted on three plugs. Two of the plugs were from the 1995 buck and one was from a 1997 vehicle of the same design. They appeared identical in composition, although this cannot be confirmed. In the first test (plug from 1995 buck) the ring burner was 7.5 cm below the floor pan. The top of the plug was completely open to the atmosphere. In 10 minutes of exposure the plug did not burn through; in fact, its top surface looked largely unchanged, in spite of steady smoke evolution from the plug throughout the exposure. The bottom of the plug was heavily charred. In the second test (plug from 1997 vehicle) the ring burner was moved down to 20 cm below the floor pan to allow more oxygen to mix with the plume; the heat flux level was essentially unchanged. In 15 minutes of exposure the plug did not burn through. A thermocouple (0.5 mm sheath dia., type K) inserted about 1 mm into the top surface reached 435 °C though again the top surface looked largely unchanged. The charred plug was loose in the horizontal floor pan hole.

In the third test (plug from 1995 buck) the top of the plug was covered with the carpet underlay and carpet (from the 1995 buck). This served to insulate the top from radiative and convective heat losses in a manner more representative of a complete vehicle. In this test the burner remained 20 cm below the floor pan. Five minutes into the test the charred plug fell out of the bottom of the hole. By this time the temperature of the steel floor pan near the plug had reached 500 °C (as measured by two 0.020mm type K thermocouples taped to the upper surface of the floor). The insulating layer on top of the plug may have allowed the thermal degradation to proceed all the way though the 4 mm depth of the plug; there was no thermocouple in the plug for this test. Loss of the plug exposed the bottom of the carpet underlay directly to the burner flames. There was no burnthrough even at 20 minutes when the test was ended. The carpet underlay was a high porosity layer of mixed fibers some of which charred; this char formed a protective layer to insulate the thermoplastic carpet from the flames, minimizing damage to the top surface of the carpet. In areas (away from the hole in the floor pan) where the carpet made direct contact with the floor pan, it melted down to a film-like black layer and evolved extensive smoke but did not ignite.

Cone Calorimeter Tests on Windshield Sections. Figure 16 shows the measured dependence of the piloted ignition delay time on the incident radiant heat flux level for windshield sections from this vehicle. The qualitative behavior seen is much like that exhibited by any simple polymeric material. Here the situation was somewhat more complex since the glass was an inert mass whose thermal capacitance slowed the heating of the polymer layer[10]; however, the glass did not preclude the ignition or burning of the sandwiched polymer layer[11]. At high heat fluxes the delay time to ignition was short. As the incident heat flux decreased, the delay time increased. At low fluxes the delay time tended toward infinity as a flux level was approached that could no longer rapidly degrade the polymer layer and cause ignition. Here the flux asymptote (minimum flux for ignition) appears to have been about 13-14 kW/m^2; the exact value would be expected to vary somewhat with the particular rear surface boundary conditions and sample orientation (i.e., angle with respect to gravity). Below we compare this behavior with measured heat fluxes to the windshield of the buck.

[10] The radiation from the Cone heater peaks in the middle infrared where the glass is largely opaque. Thus most of the incident radiation reached the polymer layer via conduction through the outer glass layer. The two layers of glass are non-reactive in this situation and simply add more mass to be heated by the radiation, slowing the eventual ignition of the sandwiched polymer layer.

[11] If the glass were to remain intact (with no cracks or missing chips which expose the polymer layer), it could be expected to preclude polymer ignition. This appears to have happened in some windshield locations in fire tests conducted in Project B.3 [10]. Note, however, that intense, non-uniform heating of the windshield can cause cracks in the glass, as described later in this report.

The heat release behavior from replicate tests for this windshield subsequent to ignition is shown in Figures 17 and 18. As is the case with nearly all materials, the peak rate of heat release increased substantially with an increase in the incident heat flux. The increased flux simply forces a faster gasification and burning of the solid. Note that the low flux curve comes closest to the behavior expected in a vehicle fire since the glass tends to fall away from areas of intense external heating (thus lowering the incident heat flux). The long, slow burning makes it a potential igniter for other flammable materials onto which it may fall.

The reproducibility of the heat release peaks was variable, probably due to sample-to-sample changes in the amount of polymer initially exposed by removal of the upper glass layer. At low fluxes the burning tended to be localized around the areas where the front layer of glass was missing; at higher fluxes the localized flames coalesced into one larger flame covering the top of the sample. At all flux levels the polymer layer appeared to liquefy and flow by capillary action out from between glass fragments to the base of the flames. The total weight loss from the samples varied from 6 to 8 grams, thus the total heat release remained fairly constant regardless of flux level.

Small Components Tested in Isolation. As noted in the Introduction, three components were tested in isolation from the buck in the manner of Ref. 3. These were the radiator outlet tank, the radiator fan and the power steering fluid reservoir. Table 1 shows that all were composed of nylon 6/6 resin, though we have no evidence as to possible variations among the parts in mean molecular weight or additives which could affect melt viscosity. However, all were black. All were mounted approximately in the orientation that they would have in an uncrashed vehicle and from their normal points of suspension.

The radiator outlet tank was clamped in its normal manner onto one vertical end of the aluminum radiator core from the same model of vehicle (with a gasket in place between the parts). This tank is about 55 cm high. The automatic transmission fluid cooler, normally contained within this tank, was removed for this test. The radiator assembly was suspended vertically[12] such that the bottom of the outlet tank was 15 cm above the Durock melt/drip catch surface. It hung from a holder resting on a pair of balances similar to the set-up shown in Fig. 15 (see also Fig. 3). The 10 cm dia. ring burner was 7.5 cm below the bottom center of the outlet tank. It was operated at 5 L/min. of propane. The single, total heat flux gage used was mounted about 8 cm below the top of the radiator tank, looking laterally at the side of the tank from a distance of 5 cm.

Fig. 19 shows the observed fire behavior in terms of the heat release rate, weight behavior and measured heat flux.[13] At time zero the burner flame engulfed the lower half of the tank. The immediate heat flux to the gage is convection from the diluted igniter plume above its visible flame. Although the increasing heat release data in Fig. 19

[12] The radiator (and the cooling fan assembly) in this vehicle normally slopes backward somewhat in the vehicle from which they were extracted.

[13] The plots of heat release rate and heat flux for these and the remaining components are scaled the same as a courtesy to the reader when this was feasible. When a different scaling was used, it is pointed out in the text.

indicate that parts of the tank were burning after about 30 seconds of flame exposure, significant disintegration did not begin until about two minutes into the exposure. The lower portions of the tank wall opened and slowly flowed downward, then dropped piecemeal to the Durock catch surface, where they continued burning. This continued, somewhat irregularly, over the following two minutes or so until nearly all of the mass that could fall downward had done so. During this time the flame spread upward on the inside and outside surfaces of the upper half of the tank. The burner flame was supplemented by flames from the burning mound (ultimately about 20 cm in diameter) of viscous melt on the Durock surface. Enhancement of the burning process by this interaction appeared relatively mild (though we do not have a non-interactive reference case). It did bring flames up past the height of the flux gage; the upward spikes in flux appeared to be due to flame contact with the sensor surface and the lesser flux levels in between to radiation plus limited convection.

Note that the weight loss and weight gain scales in Fig. 19 cover the same range. The weight gain on the pan was always less than the weight loss from the radiator tank. The missing mass by the end of the test was that consumed by the fire. Note that the unburned residue by the end of the test was substantial, as indicated by the 0.23 kg weight remaining on the catch pan. (It was still burning, but quite slowly, when the flames were suppressed 12 minutes after ignition.) During the test there was some underestimate of the weight gain on the catch surface because some falling globs were temporarily partially caught on the burner ring which was supported independently of the weighing system.[14] All such material fell fully to the catch pan level within 10-20 seconds of contacting the ring burner.

In contrast to the several polypropylene components tested in the above manner in Ref. 3, the melt/flow process here was much slower. The melt viscosity of this polymer formulation under the conditions of this test, as evidenced by the flow velocity of material moving downward on the part surfaces, is apparently much higher than that of the polypropylene formulations studied previously. The nylon formulation also appeared to form some char; as noted above, it left an appreciable mass of brittle black material on the Durock at the end of the test. Although we have no direct data for comparison with a similar polypropylene component, the relatively low heat peak heat release rate here (25 kW) probably reflects the lesser flammability of these nylon 6/6 formulations compared to the polypropylene formulations, as reported by Tewarson [8].

The base polymer in the radiator fan blade was also nylon 6/6. Its diameter was about 30 cm. Its qualitative behavior was generally comparable to that seen above for the radiator outlet tank, even though its shape was much more open and extended. Placement of the igniter and of the Durock surface relative to the lower edge of the part were the same as above, as was the igniter power. The single flux gage was at mid-height, looking laterally at the flat surface of a fan blade (from a distance of 4 cm, 10 cm from the rotational axis of the fan blade). Fig. 20 shows the test results. The collapse of the part

[14] In retrospect this effect could have been minimized by supporting the ring burner from the catch pan surface. There would still be some temporary artificial distention of the melt surface which enhances its burning rate.

was more abrupt than was seen above since, when the fan hub collapsed, it took all of the blades down with it. The single highest spike in the heat flux plot appears to have been due to contact between the flux gage surface and the collapsing nylon. The peak heat release rate was very close to that seen with the radiator outlet tank. Although the two parts were comparable in mass, the similar heat release peaks appear to be largely coincidental; the burning surface areas were not likely to have been the same at the peak, nor were the net heat fluxes to the surface. These two parameters have a strong effect on the instantaneous heat release rate from a given material. The weight data at the end of the test may be inaccurate since a portion of the charred mound of fallen melt material remained in contact with both the ring burner and the catch surface below.

The power steering fluid reservoir was also a nylon 6/6-based component. Here, however, an additional factor was included. The reservoir was filled to about one half of its height with power steering fluid (320 g). The goal was to see the extent to which this fluid participated in or influenced the burning behavior of the component. This power steering fluid has an open cup flashpoint of about 220 °C[15] and thus requires extensive heating before it can be expected to burn.[16]

This reservoir had two outlets on its bottom surface. These were closed by clamping a piece of PVC tubing shut over each. To prevent the PVC from readily participating in the fire, it was wrapped with a thin layer of ceramic fiber insulation which was then covered with aluminum foil.

The placement of the ring igniter and the Durock catch pan were the same as in the two previous tests; the burner power was again 7 kW. A single heat flux gage was placed about 2/3 of the way up one side of the reservoir, looking laterally at it from a distance of 5 cm.

Fig. 21 shows the test results. The first point to notice is that it took about 150 seconds to register significant heat release from the test part versus about 30 seconds for the radiator outlet tank. Both had comparable wall thicknesses (3-4 mm) and the same nominal base resin (nylon 6/6). They were exposed to the same heat source in configurations which would give comparable heat fluxes to their outer surfaces. Thus the majority of the difference in early heat release rate responses was most likely due to the mass of fluid within the container slowing the heating of even its outer surfaces. When significant weight loss did begin, a substantial part of it was due to the initiation of a power steering fluid leak; the source of the leak was not evident. The initial leaking fluid dripped to the Durock in flames, where it continued to burn; evidently it flowed slowly enough over the flame-immersed lower portion of the reservoir to reach its ignition temperature. However, as the leak rate increased, the fluid reaching the Durock surface was not flaming; in fact it was cool enough to extinguish most of the initial pool fire. That pool fire was assisted in a small area by the ignition of some small globs of nylon

[15] Measured in an ASTM D-92 type set-up in separate fluid flammability studies in this Project.
[16] The nylon reservoir itself requires even higher temperatures to make it burn but the fluid will tend to resist the heating longer because buoyancy-induced convection currents in it will distribute the incoming heat throughout the entire fluid mass. Nylon 6/6 decomposes above 310 C [11].

resin which had dripped to the Durock surface. When the bulk of the pool fire extinguished, the area immediately around these resin fragments kept burning, probably burning some of the power steering fluid. This process continued while the reservoir largely emptied; the bulk of the fluid flowed on the Durock surface to one side yielding a pool not centered on the burning reservoir. As the fluid flow neared its end (and its flow rate again slowed), it once again dripped flaming from the reservoir and flowed out from under it, extending the flaming portion of the pool 10-15 cm away from the area below the reservoir (to the area under the heat flux gage). The reservoir itself, no longer cooled by any power steering fluid, became heavily involved in flaming and began to collapse onto the Durock surface. The laterally-extended pool fire ended and pulled back to involve principally the molten nylon resin dropping onto the Durock. All of the action in this interval caused the peak in heat release rate seen in Fig. 21, as well as the high heat flux values (when flames engulfed the gage). The fire died down slowly, leaving a mound of black char and what was evident visually as the bulk of the power steering fluid on the Durock surface.

The above sequence makes it clear that a fluid with a flash point well above ambient temperatures (in this case 220 °C) can become involved in the burning of polymeric vehicle components but the path to such involvement may be complex. Circumstances have to be such as to provide the necessary heat to the fluid which, in effect, is trying to flow away. Other physical configurations and flame exposures could lead to greater or lesser involvement. The operating temperature of such fluid in the engine compartment is normally elevated (though not near its fire point)[17]; this would help the fluid become involved in a fire more readily.

All of the remaining tests utilized the buck as a mounting base for the component(s) of interest. The hood was removed from the front buck.

Air inlet screen. The tested component comprised the left (driver's side) half of the air inlet screen. This component sits at the forward base of the windshield, overlapping its bottom front edge slightly. It is principally a plastic component having wire screen over some louvered holes through which fresh air must pass on the way into the passenger compartment. It sits partly atop a metal shelf extending forward from the front edge of the windshield frame. This component is long and narrow and it is, in this sense, unlikely to become fully involved in flaming at one time over its whole area. It is of interest for two reasons. First, its burning would heat the windshield immediately adjacent to it; this could lead to fire penetration of the windshield, especially if the windshield has been fractured in a crash. Second, it is arrayed across the top rear of the engine compartment. A thermoplastic material ignited in one area by a localized engine compartment fire could then undergo lateral flame spread and drip flaming material into other areas of the engine compartment. In this way it could possibly provide a route for growth of a localized engine compartment fire, e.g., across the expanse of the engine.

The igniter used here was a 30 cm wide tubular burner with a line of small gas outlet

[17] For example, tests on another vehicle in Project B.3 gave power steering fluid temperatures of 95 °C at 40 mph in summer weather [12].

holes along its length (1.3 mm dia. at 1.27 mm intervals). It was positioned so as to apply flames on the lower, forward edge of the screen, from below; the flame impingement area began about 14 cm left of the vehicle centerline and continued to about 44 cm left of the centerline. Two heat flux gages were placed on the windshield, 4-5 cm up and back from the rear edge of the inlet screen. One was 18 cm from the vehicle centerline; the other was 53 cm from the centerline. These were Medtherm model GTW 485 gages which are disk-shaped and thus can sit flat on a surface; they looked up and forward, i.e., perpendicular to the windshield surface. Note that since the component was mounted on the buck no weight measurements were made.

Fig. 22 shows the test results. As indicated on the heat release rate plot, flaming melt/drip material began to fall into the engine compartment as soon as ignition of the part occurred. A substantial portion of the air inlet screen in this particular vehicle has no support beneath it, i.e., the metal shelf mentioned above recedes rearward on the vehicle under the area here subjected to the outer ½ to 2/3 of the burner flame. Consequently this portion readily collapsed, flaming, into the engine compartment in the first 1-1/2 minutes of the test. There was no engine upon which it could fall. The flaming material accumulated on any intermediate metal surfaces or on the floor (Durock covered) where it continued to burn. Flaming melt/drip materials fell into the engine compartment over the entire width of this air inlet screen, progressively as the fire spread along it in both directions (toward and away from the vehicle centerline), though never so rapidly as from the unsupported section.

The heat release rate from this component alone never rose much above 30 kW, mainly because it burned slowly and progressively as a consequence of the flame spread along its extended horizontal length, as mentioned above. The early flames in front of the flux gage that was closer to the vehicle centerline, were roughly 30 cm high (corresponding to the early, higher portion of the heat release rate curve). On this particular vehicle the windshield slopes backward at a low angle (ca. 20° above horizontal) and these strongly buoyant flames rose straight upward, not contacting the windshield. The flux to this gage was thus largely due to flame radiation; the flux peaked (twice) at about 10 kW/m^2. Reference to Fig. 16 based on the Cone Calorimeter results for fractured windshield sections, shows that this flux would not be expected to ignite the windshield (even if it had continued much longer than it did) since it was below the minimum flux for ignition of a cracked windshield. It did crack the windshield on its forward base toward the end of this period. The later flames in front of the other flux gage were, in fact, substantially smaller. However, these smaller flames were easily deflected downward close to the windshield by air flow disturbances. This caused the sporadic, spiking flux to the second gage late in the test. The average incident flux to the windshield is hard to assess but it appears to be near or above the minimum flux for ignition seen in the Cone Calorimeter tests for short periods (i.e., not nearly long enough to ignite it). It should be noted that the intact windshield used here would be expected to be more ignition resistant than the extensively fractured sections used in the Cone Calorimeter tests since we began with no exposure of the polymer layer in the windshield.

Front Fender plus Front Wheelhouse Panel Liner. These two items were tested together on the front buck in their normal service positions. Both were mounted on the driver's side of the buck. Table 1 gives the base resins in these two parts. The liner is referred to there as the wheel well liner. Note that the fender was unpainted.

Three flux gages were used in this test; Fig. 7 shows the test layout and the position of two of the flux gages. One measured the heat flux toward the engine compartment. It was in the top of the engine compartment at the height of the top of the fender, immediately opposite the top of the wheel well inlet in the fender (the hood was removed). It was 5 cm away (toward the vehicle centerline) from the top inner edge of the fender. The second gage measured the flux away from the vehicle, in a direction perpendicular to the exterior fender surface (and the vehicle centerline). It was 56 cm above the Durock floor surface, approximately 10 cm to the rear of the longitudinal position of the igniter (see below) and 5 cm away from a fairly broad, uninterrupted area of the fender surface itself. The third flux gage was on the windshield surface, 18 cm up from its forward lower edge and 15 cm in from its outer edge; this placed it approximately 15 cm from the nearest point on the fender which, on this vehicle, slightly overlaps the lower forward corner of the windshield. The ring igniter was placed 7.5 cm below the rear lower edge of the wheel well inlet in the fender so that its flames tended to contact both the curl of the fender into the wheel well and the lower, outer rear edge of the wheel well liner. The igniter was 20 cm above the Durock floor surface. Note that the mounting of the buck (on metal casters) was such as to place the vehicle body at approximately the height above the ground that it would be at if equipped with wheels and tires specified by the manufacturer.

Fig. 23 shows the test results. Note that the ordinate scales in both parts of the Figure differ from those in the previous figures. This heat release rate was small, less than 20 kW, for the first two minutes; it then began to increase rapidly as more material became involved. Most of the initial rapid fire growth appeared to have occurred on the inner surface of the rear portion of the fender. This was aided at first by flames spreading upward on the wheelhouse liner but this factor was lessened quickly as the rear, burning portion of the liner melted and drooped to the floor, beginning at two minutes into the test. Part of the ground-level pool which this created was below the igniter and this fire did supplement the igniter; however, it was relatively far away from the bulk of the growing fire and its contribution to enhancing that growth was thereby diminished. The video results indicate that the primary reason for the rapid fire growth was flame spread on the interior rear section of the fender, followed by flame spread on the exterior of this same section. The fender material was generally not thermoplastic in its behavior in that it did not liquefy sufficiently to flow smoothly to the floor. However, a segment from the lower rear area of the fender did drop to the floor at 210 seconds into the test. This magnified the fire on the ground substantially and yielded the peak in heat release rate at this time. At the heat release peak (near 220 s into the test), only that portion of the fender and wheel well liner to the rear of the top of the wheel well hole were burning.

As the fire grew toward this heat release rate peak, flames began to emerge into the left rear corner of the engine compartment (through a designed-in hole in the left rear corner of the engine compartment[18]), merged with flames from the top, rear portion of the fender, yielding a combined fire plume that passed up over the lower left corner region of the windshield. The heat flux to the windshield climbed to 50 kW/m^2 and above, exceeding 75 kW/m^2 several times in the next 100 s; see Fig. 23. By 240-300 seconds the inner layer material in the windshield appeared to have ignited in this test. The windshield went on to burn until 730 s at which time an extinguisher was applied. While it was burning, it dripped flaming material (inner layer plus glass chunks) onto the top of the instrument panel area in the vehicle interior (where only a fibrous insulation layer was in place). At the end of the test there was a crudely triangular hole in the lower left region of the windshield on the order of 50 cm on a side.

The opacity of the flames impinging on the windshield precluded a determination of the exact time at which the inner layer material first ignited or the manner in which it became exposed. Figure 16 indicates that a fractured windshield subjected to a constant heat flux of 50 kW/m2 would ignite in about 60 seconds. The result in this test is roughly consistent with those results from the Cone Calorimeter. However, it should be noted that two factors prevent an exact comparison. First the windshield in this test was essentially uncracked at the start of the test, especially in its lower left corner. Second, the heat flux imposed on the windshield in this test was strongly time-dependent.

The lack of a tire in the wheel well (and possibly the lack of a front suspension assembly) probably altered the path of this fire. Had a tire been present, the drooping wheelhouse liner would have fallen, flaming, onto its upper surface and stayed closer to the inner surface of the fender, especially near the top of the wheel well inlet in the fender. This could be expected to assist in the forward flame spread along that portion of the fender probably yielding a somewhat higher peak in heat release rate. Ignition of the tire itself would have raised the heat release still further. As it was, the forward portions of the fender and wheelhouse liner were consumed rather slowly (after the above heat release peak) by lateral flame spread in the forward direction.

Rear Bumper Components. Two tests were performed using rear bumper components. The first involved the rear bumper impact bar and the rear bumper fascia energy absorber. The impact bar is reinforced with a heavy, woven roving fiber layer. The energy absorber is comprised of several sections of non-reinforced polyethylene in contiguous honeycomb configurations (see Fig. 8). The two outermost honeycomb sections are separate, attached to the rest of the absorber by thin straps of the same polymer. The energy absorber is attached to the impact bar and the impact bar itself is attached to the frame rails at the rear of the buck. The assembly stretches across nearly the entire rear of the vehicle. Note that this assembly is normally covered on the vehicle by the rear bumper fascia, which was tested separately, as described below.

The 30 cm tubular igniter was placed 2.5 cm under the center of the main central section of the absorber in such a way that it produced a flame that impinged on the bottom

[18] The hole was an approximately 2.5 cm wide slot where the rear upper portion of the inner fender panel merges with the wheelhouse panel. Just above this is a compartment containing part of the windshield wiper arm mechanism.

surface of the energy absorber and then bent upward to play on the lower, outer half of the honeycomb surface that faces to the rear of the vehicle. It was operated at 5 L/min of propane. The bottom of the energy absorber was 38 cm above the Durock surface covering the floor; this is approximately the normal distance for an intact vehicle. Two heat flux gages were used. One viewed (from a distance of 5 cm) an area at mid-height on the main honeycomb section, approximately 38 cm to the driver's side of the vehicle centerline. The other gage was on the vehicle centerline, in the rear compartment (with the rear hatch removed), 4.4 cm above the lip of the rear hatch opening and 5 cm forward of the rearmost edge of this rear hatch opening frame (i.e., it was within the rear compartment). It measured heat flux forward toward the rear compartment.

Fig. 24 shows the test results. The energy absorber comprises a 4.4 kg mass of a polyethylene-based formulation. The heat release rate that developed here was 30 kW or less due to the large separation between the test assembly and the ground surface, coupled with the horizontal orientation of the components. These factors caused the amount of mass burning at any given time to be a small fraction of the total available. The fire progressed up the rear surfaces of the honeycomb above the igniter, melting much of the material which then dripped to the Durock surface. This melt/drip material burned (partially) on the Durock surface but this pool fire had flames which reached less than a quarter of the way up toward the bottom of the energy absorber. Thus the pool fire did not accelerate flame spread on the absorber or the burning of it. When the center of the absorber had melted out of the way, the igniter flame played directly on the impact bar, igniting its resin. It was this portion of the fire which produced the maximum in heat flux toward the rear compartment. The lateral spreading flame fronts on the energy absorber propagated slowly outward in opposite directions from the centerline of the vehicle[19], continuing to send much of the resin onto what eventually became two separate pool fires on the ground. The flame front spreading toward the driver's side caused the lower peak (radiative) flux seen by the second heat flux gage. Eventually the flame front on the impact bar split and spread laterally in the same two-front manner. When the last few lower centimeters of the central honeycomb section remained on each side (ca. 15 minutes into the test), each melted off of its support screws and hung by the straps attached to the two outermost honeycomb sections. One side burned out in this configuration; the other side was extinguished. A substantial amount of unburned resin was left on the Durock.

After the above test, the remains of the two components discussed above were removed and the bumper fascia alone was mounted in its normal manner to the rear of the buck. Its principal means of attachment to the vehicle body was via a small number of screws near the ends of the bumper (which curl around the rear section of the body, all the way to the back of the rear wheel wells). Note that this test arrangement left the volume enclosed by the bumper fascia empty, which is not its normal state in an operational vehicle.

The same igniter (using the same propane flow rate) was placed again below the test

[19] Lateral spread of this type is slow since most of the flame heat is lost going upward with little being used to pre-heat adjacent material and thus spread the flame.

component on the vehicle centerline. This put the igniter below the indent in the fascia for the rear license plate; see Fig. 9. Two heat flux gages were placed similarly though the one in the rear compartment was slightly more rearward, roughly in the plane of the juncture of the top of the bumper with the vehicle body.

Fig. 25 shows the test results; note that the ordinate scales differ from those in most of the previous figures. By 1-1/2 minutes into the test the videos showed little change except that the exterior surface of the license plate indent area was ignited. By two minutes this area was beginning to open up and drop flaming chunks of material onto the Durock; smoke was issuing from nearly the entire top edge of the bumper at its juncture with the vehicle body. The smoke pattern appeared consistent with flames spreading on the interior surface of the fascia. However, flames spread in such an enclosed space would be inhibited by a poor air supply. It is more probable that most of the smoke arose from pyrolysis of this interior surface as the flames in the license indent area neared penetration.

By 2-1/2 minutes the fire in the center of the bumper was large and growing rapidly, aided by a fire on the Durock. This was a low pile of flaming pieces that fell off of the lower central part of the fascia. The fallen pieces behaved as though they had a very high viscosity that allowed little flow and little loss of the shape and surface area of each chunk. This retention of flaming surface area appeared to accelerate the burning of the overall ground fire. By 2 min and 52 s the combined bumper and ground fire had grown laterally to encompass roughly the central 1/3 of the bumper, which then began to split apart vertically in the middle, allowing the resulting two lateral halves to fall downward. The section attached on its outer end to the passenger's side of the vehicle swung well outward, allowing some of its fire plume to escape capture by the calorimeter hood; this implies that the measured heat release rate was lower than the actual value from this time onward. The driver's side half simply dropped downward initially, allowing rapid flame spread up its now sloping surfaces. By 3-1/2 minutes, however, it too swung outward, this time endangering the heat flux measuring equipment. The fire was then extinguished.

Both heat flux gages gave flux peaks normally only seen with immersion in large, sooty fire plumes [8]. The gage in the rear compartment was driven past its 150 kW/m^2 limit and was discarded after this test; its peak value in Fig. 25 is thus in doubt. The results in Ref. 2 show that a flux of 75 kW/m^2 can ignite various polymeric automotive components (from a different vehicle) in times ranging from 8 to 60 seconds, depending on the particular component. The flux toward the rear compartment exceeded this for 40 seconds.

The differing behaviors of the ground-level fires in the above rear bumper component tests appear to be, at least in part, due to the differing melt behaviors observed. The polyethylene resin in the energy absorber formed a very fluid melt which readily carried flaming material to the ground. In the previous study involving smaller components closer to the catch surface (Durock there, as well), this enabled the development of a strongly interacting pool fire that enhanced the overall rate of heat release substantially

[3]. There, however, the separation distance between the object and its pool fire was about 15 cm, as opposed to 38 cm in the above tests. Here the melt pool represented fuel that was nearly removed from the system; it spread out flat on the Durock, lost heat to it, and burned weakly and incompletely. It appears from its behavior that this melt pool needed radiative feedback from the burning object above it in order to burn more vigorously. Here the separation distance between the ground-level fire and the burning objects at bumper level greatly diminished such feedback.

In contrast to this behavior, the bumper fascia, composed of a polyurethane resin, disintegrated into semi-fluid chunks of flaming material which accumulated rapidly on the Durock surface after an extended initial delay. They did not make good contact with the Durock and thus lost minimal heat to it. As noted above, they appeared to tend to retain their shape and thus their burning area which enhanced the net heat release rate from the ground-level fire. This gave it enough flame height to interact strongly with the bumper fascia. This, in turn, enhanced the rate of lateral flame spread on the fascia surfaces, which dropped more material and widened the ground-level fire, etc. This accelerating process was halted by the splitting of the bumper fascia which allowed the bumper segments to swing out away from the ground-level fire.

Hood Liner. This item consisted mainly of a fiberglass pad with a small amount of resin binder. Here it was mounted to the steel engine compartment hood from the front buck. This assembly was tested in isolation. The normal thermoplastic clips holding the liner to the hood were included but these were supplemented with steel screws to preclude detachment of the liner from the hood during the test. This was done to assure that the underside of the liner remained visible during the fire exposure described below. The assembly was mounted at an angle of approximately 30° atop an aluminum surface; the front of the hood was higher than the rear. A 60 cm wide tubular burner (identical in construction to the 30 cm tubular burner used above) was placed centrally across the rear (and in this case, lower) edge of the liner (transverse to the longitudinal centerline of the hood). It was operated at 6 L/min of propane (not the usual 5 L/min) in order to get slightly longer flames out of this wider burner while staying within the limits of the propane flow control system. Across its entire width, the burner sprayed laminar flames over the lower (rearmost) 10-12 cm of the hood liner; any flame spread would be upward along the downward facing, but upwardly-sloped liner surface; see Fig. 10.

In a crash, vehicle fluids may be released into the engine compartment. In some situations, engine coolant can be sprayed onto the hood liner during a crash. Engine coolant is a mixture of water and anti-freeze. Commercial antifreezes are either ethylene or propylene glycol with small amounts of dye and corrosion-inhibiting additives. Most automobile manufacturers recommend a 1:1 mixture of water and anti-freeze.

It was of interest to determine whether this coolant, normally non-flammable, would affect the burning of the hood liner if it were coated on it. Separate preliminary tests indicated that a 50/50 volumetric mixture of ethylene glycol-based coolant plus water would ignite and burn if distilled since the water is the more volatile component. Here 170 grams of a 50/50 mixture were sprayed onto the bottom surface of one half of the hood liner just prior to application of the igniter; 13 grams dripped off, leaving 157 g soaked into the liner. This amounts to approximately 0.03 g/cm^2 of wetted hood liner. It appeared that the porous liner was not near saturation.

One heat flux gage was used. Its axis was perpendicular to the liner surface, 5 cm from it; it was approximately 44 cm up (along the sloped liner surface) from the igniter, viewing a portion of the side having the coolant content; see Fig. 10.

Fig. 26 shows the test results. Virtually the only flame spread seen here was on the side that was sprayed with coolant; there was no indication of ignition or spread on the dry side of the hood liner. On the wetted side, flames spread from the igniter area to the forward (top) end of the hood liner in about 20 seconds after an initial delay of about 20 seconds. No lateral flame spread on either the dry or the sprayed portions of the liner was seen. The flames that resulted from upward spread persisted for about one minute. They were rather weakly luminous, consistent with the oxygenated nature of ethylene glycol. The peak heat release rate was modest (ca. 15 kW/m^2); so also was the peak radiative flux downward from the burning liner (10 kW/m^2). The radiative flux was probably too low and too short-lived to have ignited any solid object in an engine compartment (though it would enhance the burning rate of any already burning object there). The flames themselves probably did not persist for sufficient time to have ignited solid polymeric materials immersed in them, since the expected flux level to them would be 20-30 kW/m^2 [8]. However, it appears likely that had more coolant been sprayed on the liner, the flame would have lasted longer[20] and ignition of other polymeric components, especially those with thin cross-sections, would then be more probable [8]. Coolant is normally at an elevated temperature within the engine; this too would enhance the burning in this type of situation.

The upward spread of flames on the coolant-wetted side of the liner indicates that the coolant in the liner structure was quickly distilled by the igniter flames so as to enrich its ethylene glycol content. Continued spread upward indicates that the glycol flames from lower areas then took over this distilling function on higher areas. The low thermal inertia and extended surface area of the fiberglass mat made this possible. Given this, coolant spills on higher density surfaces would not be expected to become as readily involved in flame spread.

Interior Trim Panel. This was the right quarter interior trim finishing panel. It runs essentially from floor to roof level; see Fig. 11. It is a monolithic molding of polypropylene/polyethylene-based resin which includes an arm rest "shelf" about 1/3 of the way up from floor level. It was mounted in the rear buck in a manner approximating its normal mode of attachment. Just above the half-height level, this panel normally includes a grill behind which an audio speaker is placed. Here the hole for that grill was covered with a perforated piece of aluminum foil; no speaker was present. Aluminum foil was also used to create a surface approximately where the upper half of the rear

[20] Capillary action could be expected to feed more fluid to the exposed surface. On the other hand, if the liner was so heavily saturated with coolant that its porous structure was filled, it would be difficult to ignite in the first place.

compartment lift glass would have been; it was removed for this test. This was done so that the fire plume would not go too readily out through this opening.

It should be noted that the shape of this component was complex as was the body area it covered. There was a variable separation between the trim panel and the body sheet metal (right inner quarter panel). Just beneath the armrest, for example, there was a metal support structure that made contact with the under side of the panel. Elsewhere the separation distance could have been as much as a few centimeters.

Three thermocouples (0.2 mm dia. wire, bare junction, type K) were placed in the space between the rear surface of the test panel and the body sheet metal to help determine whether flames were propagating upward behind the panel. The lowest was just above the armrest support; the middle thermocouple was at the height of the top of the speaker grill, just to the rear of it; the upper thermocouple was roughly 10 cm below the top edge of the test panel. The junctions of all of the thermocouples were near the back surface of the trim panel.

The 30 cm tubular igniter was used at a propane flow rate of 5 L/min. It was placed approximately 10 cm above floor pan level (the floor is uneven in this region) and about 1.3 cm away from the outer surface of the test panel. It sprayed flames on an area of the panel roughly 30 cm wide by 15 cm high.

Two heat flux gages were used. The first, oriented horizontally about 38 cm up from the floor, pointed at the panel area just above the arm rest from a distance of 19 cm. The panel area below the arm rest was laterally closer to the gage, about 8-10 cm away. This gage was intended to measure radiant heat transmitted toward the rear seats of the vehicle (which were removed from the test buck). The second flux gage, with a flat disk configuration, was placed against the interior of the roof of the buck (the headliner was absent). This gage looked downward, perpendicular to the roof plane, in a location about 10 cm inward (toward vehicle center and slightly forward) from the upper rear seatbelt retraction roller. It was intended to sense the heat flux from the fire plume to the roof.

Fig. 27 shows the test results; note the ordinate for the heat release rate plot. The observed behavior was, in large measure, dominated by the thermoplastic behavior of the panel and its interaction with the metal body panels. In the first two minutes, the armrest brace (and the shape of the panel at the armrest height) tended to serve as a temporary inhibitor[21] of what was a mixed process of upward flame spread accompanied by substantial flaming melt/drip/flow downward toward the floor pan. The armrest brace then tended to become a pooling area for flaming melt material. Flames from this pool and from upward moving flames on the melting panel then began to reach upward behind and in front of the upper half of the panel. Both the thermocouples and the video images indicated that the flames moved upward behind the panel more rapidly and extensively than they did in front of it (i.e., on its outer surface), possibly because of a chimney-like

[21] The metal structure blocked the free upward movement of flames, both from the igniter and from burning polymer, as they tried to move up the inside surface of the trim panel.

effect in this space. Much of the upper portion melted and sagged downward onto various lower areas of the metal body panel forming the side of the vehicle (i.e., the inner quarter panel). Again the more horizontal metal surfaces (the armrest brace and the floor pan at the juncture with the sidewall of the vehicle) provided locations for pool fires though flowing melt on more vertical surfaces was flaming as well. The bulk of this flaming melt material gradually moved toward the lowest part of the floor pan, here, principally, the well in which the back of the rear seat cushion normally rests. This last movement put the fire under the lower flux gage so that the highest fluxes it recorded (roughly, about 40 kW/m^2) were due to partial flame immersion, not just radiation. The heat flux to the roof area at the upper gage location was less than this (peaking at ca. 27 kW/m^2). Flames did play on the rear upper corner of the roof area

Headlining Trim Finish Panel. The principal organic material was the fabric-covered polyurethane foam layer that forms the lower surface, facing the passenger compartment. This was bonded to a fiberglass layer that contained a phenolic binder. This item was mounted in an inverted sheet metal box whose length and width were just slightly larger than those of the head liner. Aluminum foil was taped to the upper side of the liner and then brought out over the edges of the box so that buoyant gases would not get into the space above the liner, between it and the metal box. All holes in the liner (for the seat belt anchors, etc.) were similarly covered from the top with foil, for the same reason. The lower edge of the liner was 7 cm above the lower lip of the inverted sheet metal box. The head liner itself is not flat but rather has two elongated domes extending back from above the driver's and front passenger's head areas; these are the highest regions into which hot gases will flow preferentially.

Eight thermocouples (0.2 mm wire dia., bare junction, type K) were inserted through the liner from above in two lines parallel to the longitudinal axis of the liner; their junctions were 4-5 mm below the bottom surface of the liner. The lines were 20 cm to either side of the centerline. The first pair of thermocouples was 19 cm from the front end of the liner; the next three pairs were placed at intervals of 15 cm, progressively further toward the rear of the liner. The thermocouples thus spanned the length of the domes that recessed upward into the headliner.

Two heat flux gages were used. Both looked straight up at the liner from a distance of 5 cm below it. Both were on the same line as the driver's side thermocouples. One was 35 cm from the forward end of the box; the other was 58 cm.

The 60 cm long tubular igniter was used at a propane flow rate of 6 L/min. It was placed against the forward end of the liner, symmetrically, perpendicular to the centerline. It sprayed laminar flames on an area approximately 60 cm wide by 7 cm long.

Fig. 28 shows the test results. The fire lasted about 90 s and fully consumed the fabric-covered foam layer. Within 8 seconds a front representing a visible physical change to the liner fabric (possibly melting) had moved to the location of the third pair of thermocouples, 50 cm from the front of the liner, within the domed (highest) region of the liner on both sides. The thermocouples themselves gave ambiguous indications of the nature of the front. The two pairs closer to the igniter (on both sides) reached 500 °C and above as the front passed. There was no flame luminosity which was visible in the presence of the external lighting being used. Furthermore, as the front reached the third pair of thermocouples out from the igniter, it remained visible but these thermocouples reached only 350-400°C at this time.

At 15 s the liner ignited, almost exactly in the center of the tubular igniter. As the liner ignited in this location it caused flames to extend briefly (for about 6 s) along the underside of the liner out to approximately as far as the front noted above. The thermocouples showed only a weak response to this (the four toward the igniter were already in the 500-700°C range)[22]. Flames then spread rapidly rearward on the passenger's side as the foam (and nylon fabric) layer detached from the fiberglass layer above and drooped down, flaming on its loosely hanging edges. This flame front reached the third thermocouple, 50 cm from the front of the liner, by 25 s into the test. Spread was nearly as fast on the driver's side domed area and again involved flames clinging to the lower hanging edges of the loosened fabric/foam layer. Spread was more erratic after this (it stopped and re-started) but it had essentially consumed the entire foam layer by 90 s into the test. Well before this time, at about 45 s, the igniter flame became erratic, almost certainly because the oxygen around it had been consumed and/or displaced by combustion products. This could have slowed the overall burning progress after it began to happen but, for the most part, the liner material seemed to burn below any oxygen-starved layer because it came loose and drooped downward several centimeters with burning on its lower edges. It may be appropriate, in any future testing of this type, to more closely match the depth of the metal box to the depth that gases can accumulate in a real vehicle.

The peak heat release rate, shown in Fig. 28, was less than 20 kW. However, it is occurring in a space where buoyancy naturally causes heat to accumulate. Heat from any other burning objects in the passenger compartment accumulates just below the headliner, as well. Radiation from this hot gas layer may ignite the tops of the seats, etc., leading to generalized ignition, known as flashover of the compartment. This was the endpoint of some of the vehicle fire tests in Project B.3; these involved multiple burning objects in the passenger compartment.

The heat fluxes seen by the flux gages in this test varied from about 20 (much of the time) to 60 kW/m^2 (in a brief spike)[23]. However, they are somewhat difficult to interpret. The gages were up in the hot gas layer and so were seeing both convection and radiation. At 25-35 s, when the spikes appeared in the gage readings, the gages were making contact with flaming melt/drip material. It did not appear in the test videos that material stuck to the gages but post-test inspection indicated some contamination. Any coating on

[22] Most of the thermocouples stayed in the 400-600°C range until the igniter was turned off at 240 s.
[23] A heat flux downward (typically measured at floor level in the room of a building) of 20 kW/m^2 is one criterion used to assert that flashover has occurred. The average level in Fig. 28 is just below this but it would be lower at greater distances below the liner. The radiation component would decrease least at the height of the seat tops (roughly a factor of two, Ref. 13), given that they are separated least from the expanse of the headliner.

the gages would tend to muffle their response. After the spikes due to material contact, the gages continued to read flux values comparable to those before this contact. The thermocouples did not indicate appreciable gas temperature changes after the material contact, which is consistent with heat flux values remaining largely unchanged as Figure 28 indicates. This heat flux (from gages immersed in the hot gas layer) may be pertinent if all windows in the vehicle are intact and closed. An open window would probably allow some of the hot gas layer to escape so that it might not reach the head level of an occupant. The radiative component of the flux here (which we cannot separate out) would then be the more realistic measure of threat of ignition to other materials in the passenger compartment or of burns to passengers.

The flaming melt/drip material falling from the head liner ranged in size from globs less than a centimeter (the majority) to larger patches of material (one of which was a few hundred cm^2, burning on its periphery). This flaming material fell onto an aluminum plate 1.2 m below the liner and continued to burn. The flaming melt/drip process began 15 s into the test and continued until the fabric/foam layer on the liner was fully consumed.

Instrument Panel Assembly. This assembly (placed in the front buck[24]) comprised all of the components listed in Table 1 under the headings "Instrument Panel, Gages and Console" and "Heater and Ventilation". Included in the assembly as tested was the dash sound barrier, a flexible pad that covers the entire interior surface of the forward bulkhead (with a hole for the HVAC case to penetrate this bulkhead). Also included was a carpet plus underlay taken from our 1995 buck; this is believed to be of the same composition as that shown in Table 1. The carpet was from the rear floor area of the buck and so did not fit fully flat against the front end floor pan. Fig. 12 shows a view of the assembly from the passenger compartment side. There are a few components absent (knee bolster panels, HVAC controls, radio, air bag module) which were remote from the location where the ignition source was applied. Nearly all of the included components were made from thermoplastic resins. One component that does not exhibit melt/drip behavior, however, is the A/C evaporator lower case (Fig. 13), the first component subjected to the igniter flame in the test done here. The resin in this casing was filled with a sufficient percentage of chopped glass fiber as to preclude significant shape change in the heating conditions imposed in this test.

The purpose of this test was to determine the fire development time for an instrument panel subjected to ignition conditions analogous to those used in the Project B.3 test of the same vehicle [5]. Note, however, there were significant differences between the two set-ups. The Project B.3 test was of a vehicle previously subjected to a front end impact with a stationary pole; this yielded varying levels of damage and/or displacement to various components in the fire path. The buck here was from an uncrashed vehicle and all of the parts used were undamaged. Thus the arrangement of components in the two situations differed. In addition, the Project B.3 test involved a growing engine compartment fire which entered the passenger compartment through a crash-induced

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[24] The windshield had a hole from an earlier test; this was covered over with aluminum foil, taped in place, to preclude unrealistic air or smoke flow in this area.

break in the HVAC casing. Such a fire tends to generate a pressure differential between the engine compartment and the passenger compartment which can help push fire gases into the passenger compartment. No generalized pressure gradient like this was imposed in the present test (as it was in Ref. 3). Finally, the igniter placement here (described below) differed somewhat from that in the B.3 test since other materials within the engine compartment which ignited early in the B.3 test were not present here. Given these differences, the test here cannot be expected to duplicate the results seen in the B.3 test.

One aspect of the Project B.3 crash damage was simulated (not duplicated), the hole through the HVAC casing. Figures 13 and 14 show the hole (12 cm high by 1-3/4 cm wide) that was milled into the HVAC casing in a location very close to the break seen in the B.3 crashed vehicle. Any flames that penetrate this hole pass directly into the HVAC module near the heater core on the passenger compartment side of the forward bulkhead.

The igniter used here was a 5 cm diameter ring operated at 5 L/min of propane. As shown in Fig. 14, it was placed in the engine compartment 5 cm below the inner edge of the lower A/C case at a location where its vertical axis was 8-10 cm laterally displaced from the plane of the slot milled in the case. Its flame played on the bottom of the A/C case and on the vertical side where two portions of the sidewall meet at an obtuse angle. It is relevant to note that the upper portion of the A/C case, (which received minimal, intermittent contact with the top of the igniter plume) is made from a polypropylene-based formulation.

In assembling the instrument panel, 13 thermocouples (0.2 mm dia. wire, bare junction, type K) were inserted at various locations along the expected fire path to help in interpreting the progress of the fire. The test was videotaped from both the engine compartment side and from the passenger compartment side. An infrared camera was also used to view the passenger compartment side. One heat flux gage was positioned to view the fire from the passenger compartment side, essentially looking into the hole left by the missing HVAC controls in the center of the instrument panel; it was 7 cm away, looking horizontally.

Fig. 29 shows the heat release and heat flux results; note the ordinate scales. Figs. 30a and 30b show the embedded thermocouple results. Neither the heat release nor the flux curves reveal much more than that a ½ MW fire developed (and its time of development). The fire path was evident to a large extent via the videos and the thermocouple results.

The igniter flame played on the bottom of the HVAC case and a narrow strip of the side, up to about the level where the composition of the case changed to a polypropylene-based material. The exterior of the lower A/C case above the igniter was igniting by 38 s into the test. By 60 s smoke began to emerge from the air intake holes at the base of the windshield; this meant that pyrolysis was occurring in that portion of the interior of the AC evaporator case that protruded into the engine compartment. Thermocouple #6, inside this case passed 600 °C by 100 s into the test, indicating that flames were at its location near the inside of the wall being subjected to the igniter flame[25]. One would not normally expect flames to appear so readily on the rear side of a burning composite wall such as this since there would be no pilot flame to ignite the gases evolving there. Here, however, there was a small pathway to the interior through a water drain hole (2-3 mm dia.) in the bottom of the lower A/C case. The igniter flame played on the area where this hole was; evidently a sufficient flame penetrated this hole so as ignite the gases evolving from the interior of the case wall.

The external fire on the HVAC case grew steadily, beginning to involve the polypropylene-based upper portion by 140 s. Lateral spread of flames on the exterior of the fiber-filled case toward the milled slot was slow but steady; the average lateral spread velocity toward the milled slot was 0.045 cm/s. Occasional flame tips from this fire front were sucked into the top of the milled slot by 160 s; the heating of the A/C case walls created a weak chimney effect within it early in the igniter exposure. However, there were indications in the video images that flames were already inside this area by 160 s; a few flamelets could be seen there. This was even more evident by 200 s when flaming melt/drips were seen inside the milled slot. Only by 270 s were external flames being steadily pulled in through a large part of the milled slot; they were probably being pulled in by the buoyancy of the internal fire. Thus the evidence indicates that the slot played only a minor role in the fire development. Evidently the drainage hole in the bottom of the case was more important, at least in the early development of this fire. The polypropylene-based portion of the A/C case was relevant to this stage of fire development also since it was fully involved by 270 s and undoubtedly was sending flaming melt/drip material into the lower forward portion of the heater case (just inside the plane of the forward bulkhead). This was the only hot area visible to the infrared camera (which was looking from the passenger compartment side) from about 90 s onward.

At 310 s the bottom of the heater case (fully inside of the forward bulkhead) melted through onto the carpet below it; the melt material was flaming. Flames spread slowly on the carpet and on melt/drip plastic, leaving a fire that was spatially close enough to interact with continued flaming in the heater case area.

The placement of the thermocouples embedded in the instrument panel during its assembly was in locations expected to be involved in upward flame spread from the milled slot region. Thermocouple 2 detected flames on the underside of the metallic front plenum chamber[26] at the base of the windshield, above the heater case area, by 330 s. Although one might expect that the fire would naturally follow the available path through the HVAC ducts, it should be borne in mind that these ducts were made of a polypropylene-based material, as was the heater case. In the first 2-3 minutes smoke did tend to emerge from duct outlets in the dash panel (though not exclusively) and as time

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[25] Consistent with the definition adopted in Project B.3, we take a local temperature at a thermocouple of 600 C to indicate that presence there of flames; this is low for a flame temperature but a bare thermocouple tends to read less than the true gas temperature.

[26] This chamber at the base of the windshield is a metal duct through which external air passes on its way to the HVAC unit.

increased it emerged at many locations away from the ducts. The fire was capable of melting holes in these ducts and by 330 s flames were visible out side of the ducts.

The next thermocouple to detect flames was number 8 at 355 s, inside the top of the air distributor case (the next element in the air distribution system, in the driver's side direction from the heater case). Flames persisted here only for about 20-25 seconds before disappearing for another 40 seconds. Between 370 and 390 s flames appeared at three more locations behind and above the HVAC unit , all the way to just under the topper pad. The fire was essentially becoming generalized in the area behind the passenger's side of the dash panel. At 400 s the bottom fell out of the HVAC case (probably due to the weight of the blower motor) and 10 seconds later a fire plume emerged from the topper pad along much of the passenger's side. About 2/3 of the instrument panel was in flames when the fire was suppressed at 450 s because it was overwhelming the calorimeter hood. The pattern of growth of the fire and the fact that it clearly had consumed less than half of the available material indicated that its heat release rate would have gone significantly higher if it had not been extinguished. In an actual vehicle, however, the heat release rate could have been limited to a lesser level than the maximum seen here due to a restricted air supply.

The peak in the measured heat flux occurred during the extinguishment process and thus is unrealistic. Up to near the end of the test, there was little flaming in the area which the gage viewed (the hole in the center of the dash panel). The gage saw only radiation until the suppression process began, at which point the disturbed flames engulfed the gage. Thus the real peak radiative flux was that seen at about 450 s., a value of about 30 kW/m^2.

The absolute time line of this fire is highly specific to the particular set-up tested here. The results illustrate that flames originating in the engine compartment can enter the instrument panel through the HVAC unit in less than 2 minutes, even in the absence of a substantial pressure gradient pushing flame gases though openings in the forward bulkhead. Such a fire can result in extensive involvement of the instrument panel in 7-8 minutes. The fire would have developed more quickly if flames were deliberately introduced into the slot milled in the HVAC case; it would have developed more slowly if flames had not entered through the drain hole in the bottom of the HVAC case. Any such variant would be expected to show the self-accelerating character seen here once a small fire appears within such an openly-structured mass of fuel. That is, the specific physical arrangement of the plastic components matters less to the result than the fact that they are all flammable.

4) Summary and Conclusions

Again it is to be noted that the fire test results here are specific to the particular surroundings in which the component was tested as well as to the igniter size and placement. It is for this reason that quantitative comparisons cannot be made with the tests in Ref. 9 of the polymer resins themselves, of which the components here were made.

Rubber drain plugs, similar (but not necessarily identical in dimensions or composition) to those tested here are fairly common in the floor pan of motor vehicles. They presumably are used to close holes needed during the painting or other surface treatment of the vehicle body. Similar plugs can be found in other parts of some vehicle bodies in holes that may facilitate assembly. The plugs tested here were not thermoplastic and thus were fairly heat resistant to moderately high heat fluxes. However, when tested in a configuration that mimicked the real heat balance conditions to which floor plugs are subjected in a fuel spill ground fire (i.e., insulated on top by carpeting), the plugs used here ceased to block flame penetration after a few minutes.

The three parts based on nylon 6/6 tested here all burned over their entire surface but with relatively low peak rates of heat release (20-30 kW). It is difficult to attribute this comparatively benign behavior to the resin alone since we do not have data on these parts for other resins. In the previous study [3], small parts based on polypropylene were found to give both greater and comparable heat release peaks to those seen here.

In Ref. 9, Tewarson reports two pertinent measures of the flammability of these polymer resins as obtained from the components under study here. The first is termed a heat release parameter and is the ratio of the heat of combustion to the heat of gasification of the material. The reported heat release parameter of the nylon from the present components tended to be less than 2/3 that of polypropylene. Tewarson's second parameter is his fire propagation index which incorporates the heat release parameter and a measure of the ease of ignition. Reported nylon and polypropylene values for this latter parameter were not greatly different. The peak rate of heat release seen in the present experiments was a product, in part, of the processes measured by these indices. If these indices were the only relevant parameters, one would expect nylon-based components to yield a lesser heat release peak than do polypropylene-based components. The heat release rate peak here also depends on the area which is burning at the time of the peak. This, in turn, depends on the initial part shape and the manner in which that shape changes as burning progresses; the latter depends on the flow behavior of the resin formulation and on its thermal stability. As noted previously, the nylon resin formulations tested here flowed very slowly, as compared to the polypropylene-based parts tested in the present study or in Ref. 3. Other results here (notably for the rear bumper fascia) imply that a lack of fluidity in a polymer formulation in fire conditions is a mixed blessing: it precludes a large diameter pool fire but it may preserve the burning area of distinct segments of falling material, enabling an enhanced total burning area by other means. Thus it is ambiguous as to whether nylon would necessarily yield a lower heat release rate than polypropylene if the two resins were compared in the context of a variety of part shapes and ignition configurations.

The fractured windshield sections from this vehicle were seen to behave qualitatively in much the same manner as any polymeric material; the polyvinyl butyral inner layer was ignitable and fully burnable. The ignitability results obtained here provide a reasonable basis for estimating the ignition response of a post-crash windshield given data on the heat flux level being imposed by an external fire. An uncracked windshield is expected to be somewhat more ignition-resistant than that data would indicate, at least on the low heat flux end of the ignition curve.

The air inlet screen, which sits at the base of the windshield in this vehicle imposed a peak heat flux of only 10 kW/m^2; this caused only local cracking. Flames from the air inlet screen made little or no contact with the windshield because of its low slope angle. On the other hand, the burning of the polymer-based front fender yielded extensive flame contact on the left corner region of the windshield and imposed heat fluxes there which exceeded 60 kW/m^2 for several tens of seconds. The Cone Calorimeter ignition data noted above indicate that such a flux load could ignite a fractured windshield. Ignition occurred in the test buck here even though the windshield was not pre-fractured in the ignited area. Subsequent burning left a roughly triangular hole in the windshield 50 cm on a side. Burning windshield fragments fell onto the top of the instrument panel area.

The front fender material did not stand out in Tewarson's tests as having high values for his heat release parameter or fire propagation index, as compared to other parts from this vehicle [9], but it yielded a heat release rate peak of 330 kW in the full scale test in this study. This fire would have been judged large but non-threatening to the passenger compartment had it not penetrated the windshield. The high peak heat release and rapid fire development (220 s to the heat release rate peak) were the product of a moderately flammable polymer formulation and a test configuration favorable to rapid upward fire growth. The latter included the thin (few mm) layer nature of both the fender panel and the wheel house liner, the vertical orientation of much of the material just above the igniter and the particular placement of the igniter such that it was almost immediately supplemented by the ignition of the wheelhouse liner.

The tests of the rear bumper components provided much more contrast in their observed fire behavior than one might have expected from their composition. Tewarson's results did reveal distinct differences in the fire propagation index of the materials. He found that the polyurethane-based bumper fascia had a flame propagation index of 18, a relatively high value among the formulations tested from this vehicle; that for the polyethylene-based energy absorber was 11, a more moderate value [9]. However, the polyethylene material had a substantially higher heat release parameter (33) than did the polyurethane material (23), which could compensate for the flame propagation index differences in circumstances where upward flame spread is less important. In the present tests, the horizontal orientation of the components would be expected to slow flame spread. This was certainly the case for the energy absorber (average lateral flame spread rate of 0.025 cm/s); this part also left much of its fuel content unburned on the ground. The bumper fascia, however, exhibited much more rapid lateral fire growth (roughly 10X faster), strongly aided by heat transfer from the flames of material which sloughed off onto the ground. Again, this ground fire interaction is a factor which influences overall fire intensity (as measured by heat release rate) but is not captured by Tewarson's parameters[27].

[27] While Tewarson's parameters may not incorporate all of the factors which dictate the fire performance of a vehicle component, they are very pertinent to the flammability of the polymer formulation from which the component is made. They thus can provide a guide toward less flammable formulations.

The test of the right quarter interior trim finishing panel yielded a moderately intense fire (peak heat release rate of 125 kW) but it served mainly to show how complex the interaction can be between a thermoplastic component and the adjacent surfaces with which the polymer melt interacts. This fire began its growth as a mix of upward flame spread and downward melt/drip spread. It soon moved into a phase of being a downward flowing fire as the melt covered surfaces from the floor pan to just below the roof. It ended as a pool fire in the lowest area of the floor pan. The extended surface area of the buck coated by the polymer melt contributed to the intensity of the fire simply by providing more area for burning. The fluidity of the melt affected the rate of melt flow downward, but so also did the complex shape of the surface and the heat balance on that surface.

The instrument panel test indicated that a fire can spread from the engine compartment into the interior of the instrument panel by burning through combustible material covering pass-through openings in the forward bulkhead. It also indicated that a complex array of thermoplastic components is vulnerable to rapid fire growth even from a small, localized ignition source; the fire initiated by a 7 kW igniter in the engine compartment grew past 200 kW in 7 minutes. The present design, which places a substantial section of the HVAC system on the engine compartment side of the forward bulkhead was a factor in that fire development time since it exposed material which is open to the passenger compartment to engine compartment flames. Any analysis of what constitutes a potential fire pathway into the passenger compartment must take crash-induced damage into account. Here the pathway (a milled slot) that was deliberately introduced to serve the function of a crash-induced hole proved to be of secondary influence compared to a much smaller designed-in hole in the lower A/C case.

Two tests of the potential participation of vehicle fluids in fires yielded evidence that this can occur. Power steering fluid participated slightly in the burning of the reservoir containing it. This seemed to require circumstances which isolated a portion of the fluid sufficiently so as to allow it to heat to its fire point; the bulk of the fluid did not ignite. Engine coolant burned when sprayed onto the low density, porous surface of the hood liner. Thus engine coolant, despite its high water content, cannot be assumed to be a non-contributor to a post-crash fire.

The results in this report and in Ref. 3, show that: (1) all of the plastic parts burned, (2) some burned more slowly than others, though both materials and configuration played roles in this. The next area in need of examination is the role which less flammable resins can play in slowing the growth of post-crash fires and the development of life threatening heat and/or toxic gas conditions in the passenger compartment. Work along these lines is now underway and will be the subject of the next report in this series.

5) Acknowledgment

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Table 1. Description of Vehicle Components

	Part Location	Part Name	Constituent Parts	Polymer	Total Wgt. (kg)
1	REAR BUMPER	bumper fascia		polyurethane - MDI/poly(2-propylene glycol)	6.2
2		bumper energy absorber		polyethylene	4.44
3		bumper impact bar		polypropylene	
4	BODY FRONT END	front wheel well liner		PP/PE copolymer	
5		air inlet screen	plastic molding	PP/PE copolymer	0.57
6	FRONT FENDER			styrene crosslinked polyester	3.0
7		hood insulator	top skin	polyethylene	
8			insulator pad	glass fiber w/ phenol-formaldehyde binder	.59
9			scrim	Nylon6/PMMA phenolic binder	
10	COOLING AND RADIATOR	radiator inlet/outlet tank		Nylon 6/6	.43
11		engine coolant fan		Nylon 6/6	.40
12	UNDERHOOD PLASTIC ACCESSORIES	power steering fluid reservoir		Nylon 6/6	.27(empty)
13	WINDSHIELD	windshield laminate		polyvinyl butyral/ polyvinyl alcohol blend	
14	INSTRUMENT PANEL, GAGES AND CONSOLE	instrument panel compartment	front door	polypropylene	
15			rear section	PP/PE copolymer	
16		instrument cluster	lens	styrene/acrylonitrile copolymer	
17			housing, black	acrylonitrile/buta-diene/styrene copolymer	
18			housing, white	polystyrene/ phenolic resin	
19		instrument panel cluster trim plate bezel		styrene/acrylonitrile copolymer	
20		instrument panel	cover	acrylonitrile/ butadiene/styrene copolymer	
21			foam		
22			structure	polystyrene	
23					

	Part Location	Part Name	Constituent Parts	Polymer	Total Wgt. (kg)
24		Instrument panel upper trim panel	cover	polycarbonate - *bis*-phenol A	
25		dash sound barrier	top layer	polyethylene	
26			foam insulation	polyurethane - TDI/poly(2-propylene glycol)	
27		windshield defroster nozzle & air distributor		polypropylene	
28		dash panel insulator	plastic	polyethylene	
29			foam	polyurethane - TDI/poly(2-propylene glycol)	
30	HEATER AND VENTILATION	heater module	cover	polypropylene	
31			blower motor housing	polyester - maleic anhydride/poly(2-propylene glycol) styrene cross-linked glass-filled	
32			vent mode valve foam seal	polyurethane TDI/poly(2-propylene glycol)	
33	FLOOR	floor carpet	fiber surface	Nylon 6	
34			media binder	PE / polyethylene terephthalate	
35			backing	polyethylene	
36		floor pan plug		ethylene/propylene/ butadiene	
37	ROOF	headliner trim finish panel assembly		phenolic resins (phenol + formaldehyde w/amine)	
38			foam	polyurethane - TDI/poly(2-propylene glycol)	
39			fabric surface	Nylon 6	
40	REAR QUARTER	quarter inner trim finishing panel		PP/PE Copolymer	1.24

* Bumper fascia is usually made from MDI and polyether, ethylene glycol and diethyltoluenediamine (DETDA) as the chain extender.

Floor Drain Plug

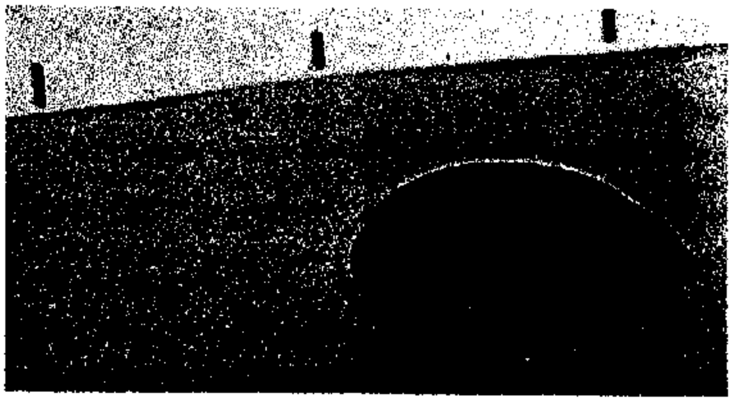


Figure 1. Top view of a floor drain plug for this vehicle; the marks on the label are 5 cm apart.

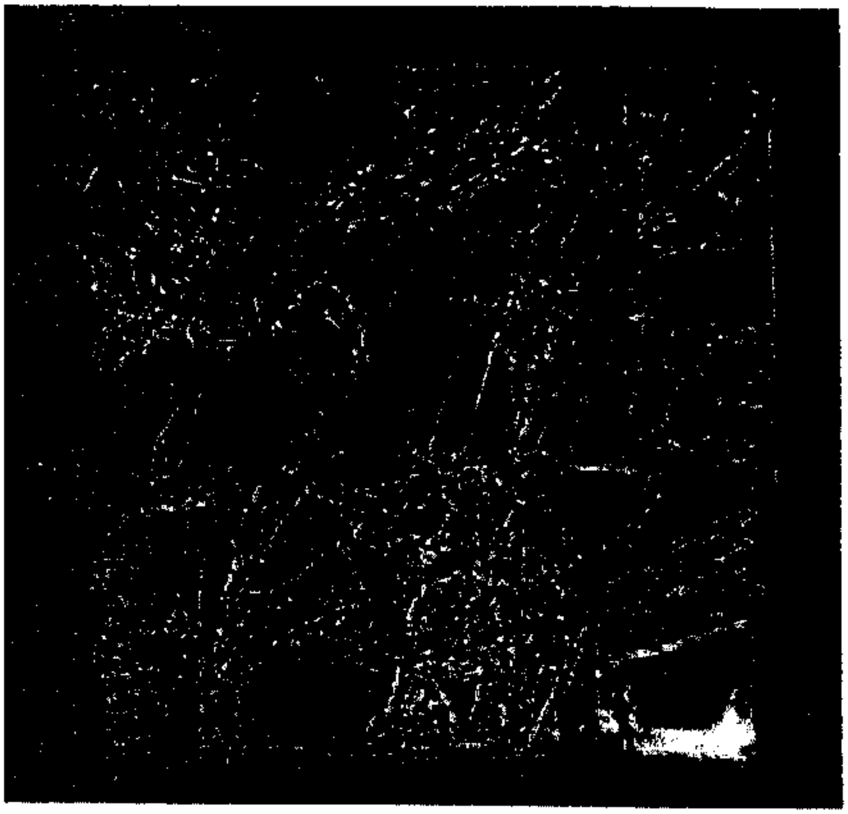


Figure 2. Fractured front window glass as tested in the cone calorimeter (approximately 10 x 10 cm).

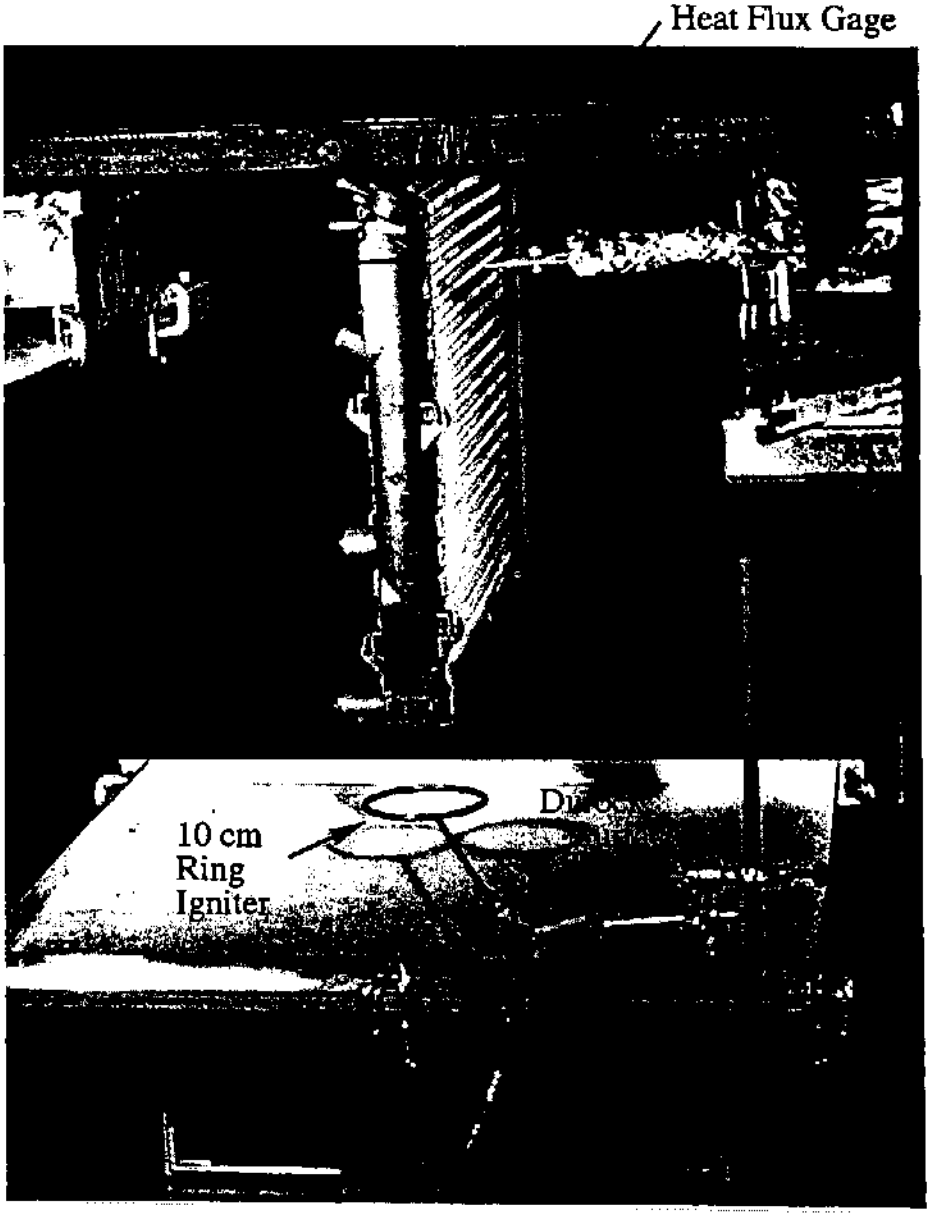


Figure 3. Radiator outlet tank shown in test configuration. Tank is clamped in normal position on end of radiator; assembly is suspended from a pair of scales in upper left and right.

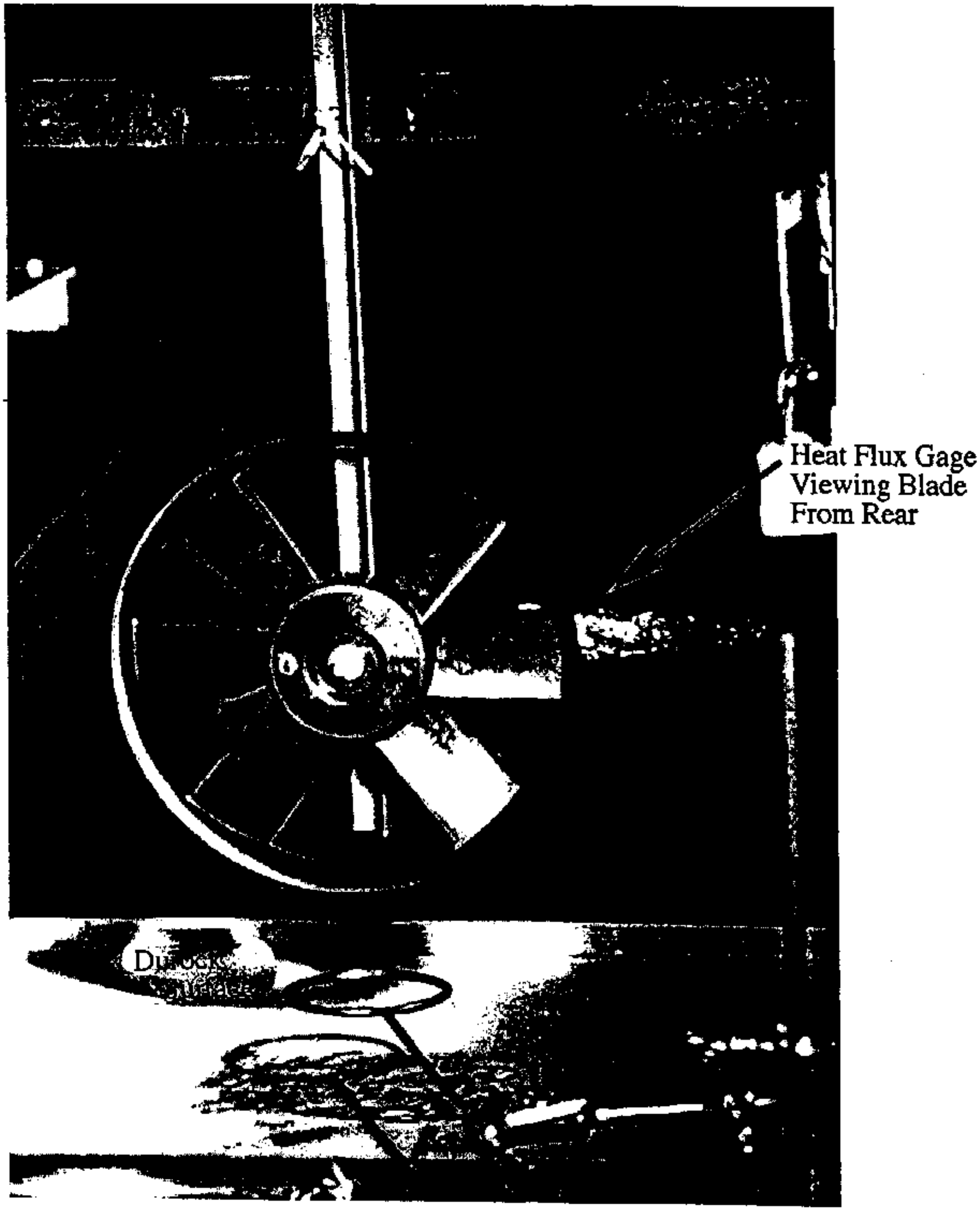


Figure 4. Radiator fan blade in test configuration.
Fan blade is supported from center and suspended from scales (out of view in upper left and right).

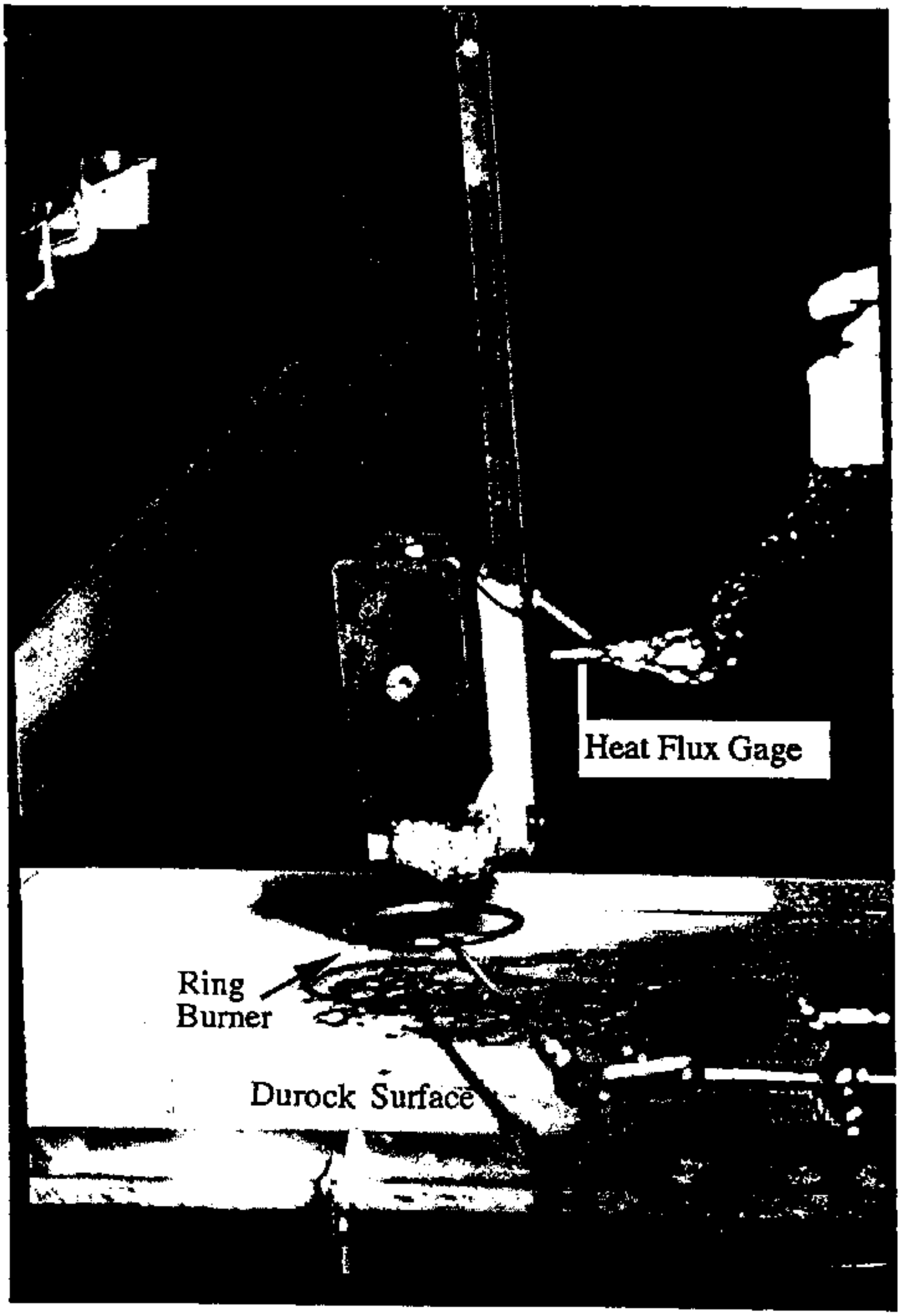


Figure 5. Power steering reservoir in test configuration. Reservoir was approximately half-filled with power steering fluid. Unit is supported by slots in rear as in actual vehicle.

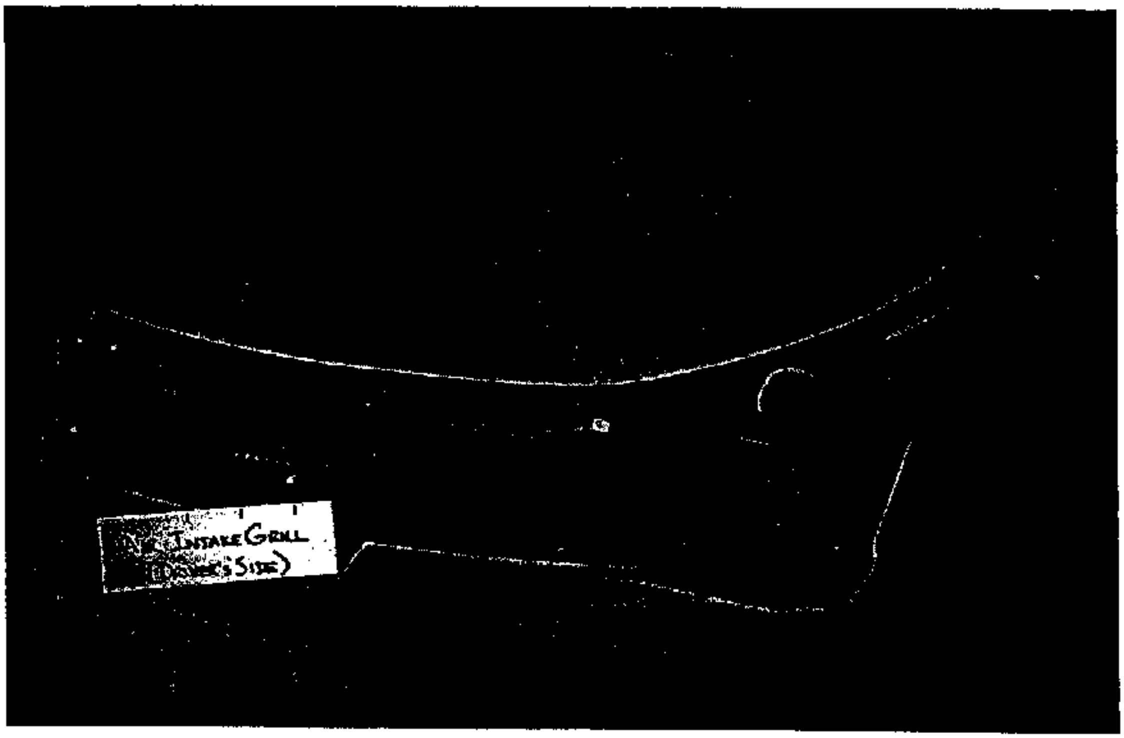


Figure 6 Driver's side half of air intake grill. This component is mounted at the base of the windshield; outside air enters the HVAC system through the slotted grill area on the left. The marks on the label are 5 cm apart.

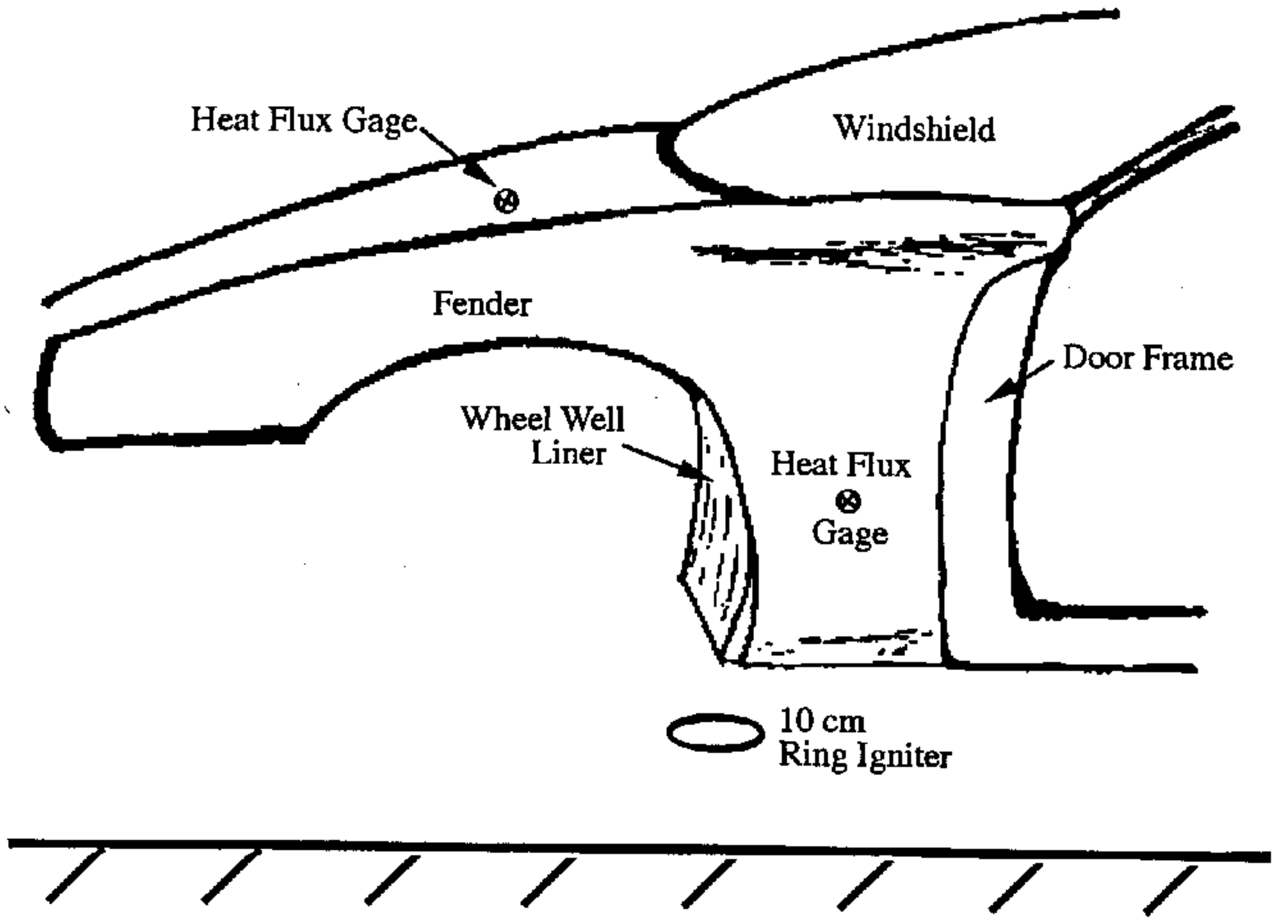


Figure 7. Test configuration for fender plus wheel well liner mounted on front buck.

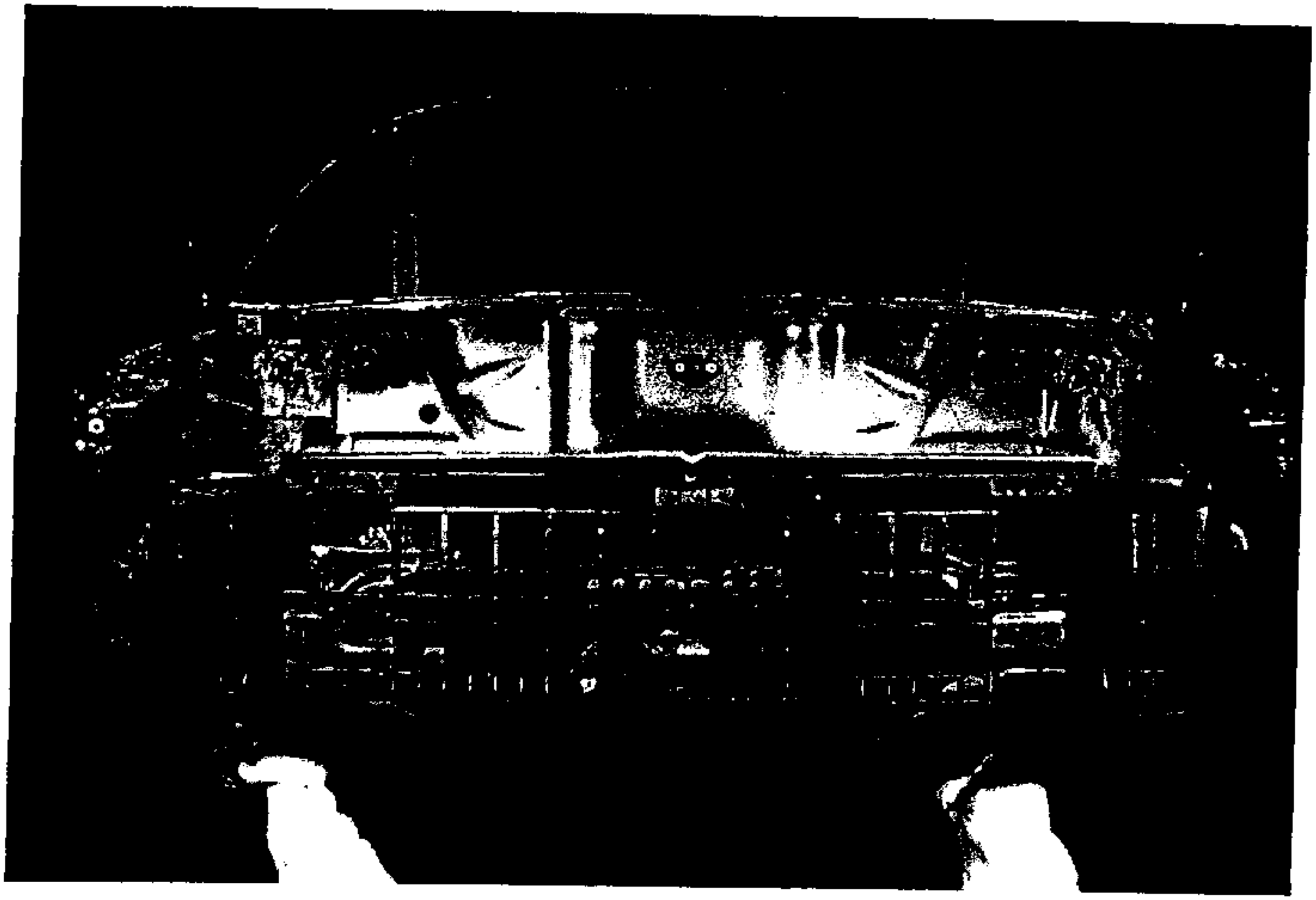


Figure 8. Bumper energy absorber mounted on rear buck for testing. 30 cm tubular burner was placed beneath center of the energy absorber.

Figure 9. Test configuration for rear bumper fascia showing tubular igniter below bottom center of fascia; the latter is mounted on the rear buck in its normal position. Note that the rear hatch of the vehicle is removed.

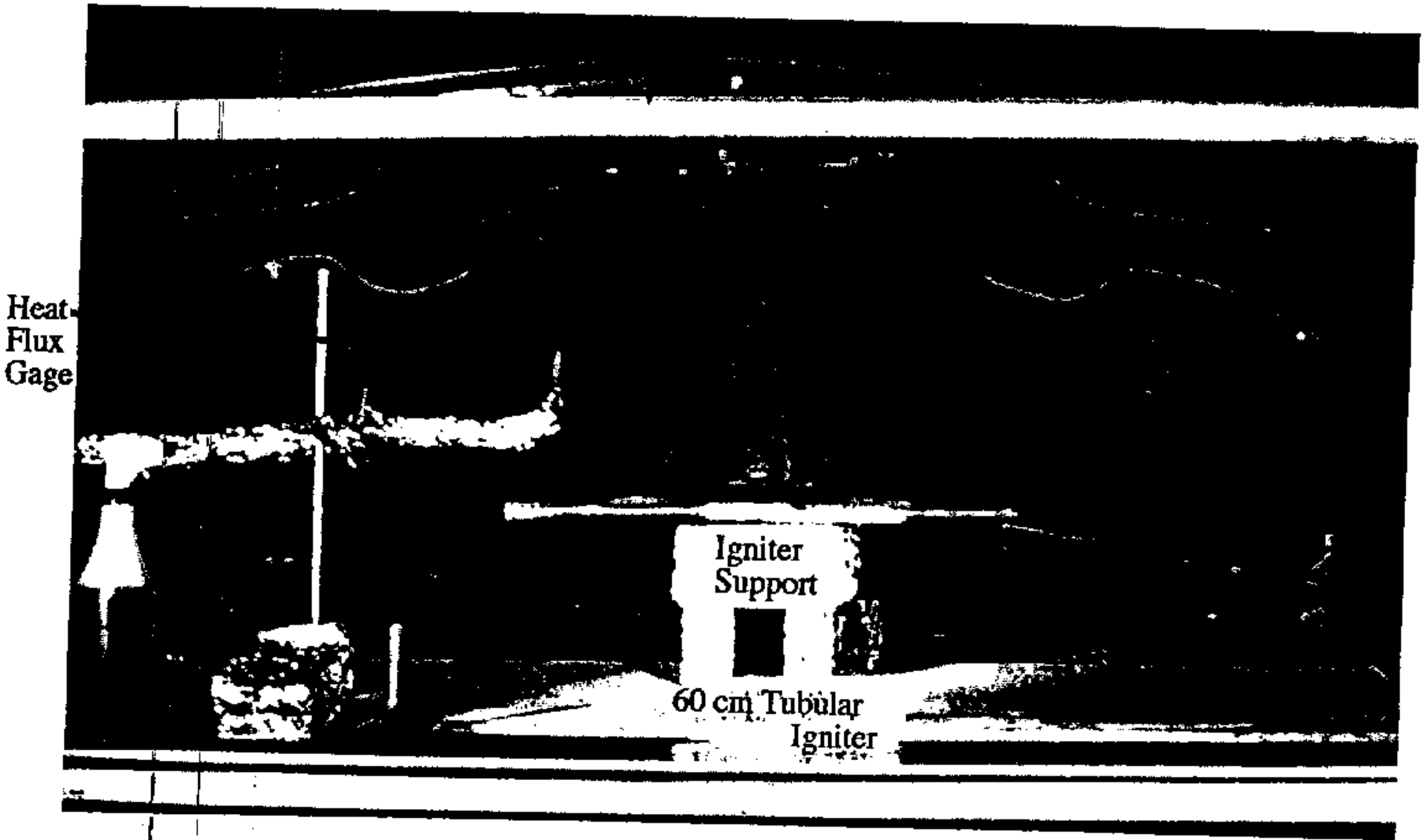


Figure 10. Hoodliner mounted on underside of vehicle hood. Hood itself is isolated from vehicle and propped-up at an angle of approximately 30 degrees. The tape down the centerline of the hoodliner was used to isolate the left side of the hood before it was sprayed with engine coolant; the tape was removed for the fire test.

Figure 11. B-pillar interior trim panel mounted in rear buck before test.

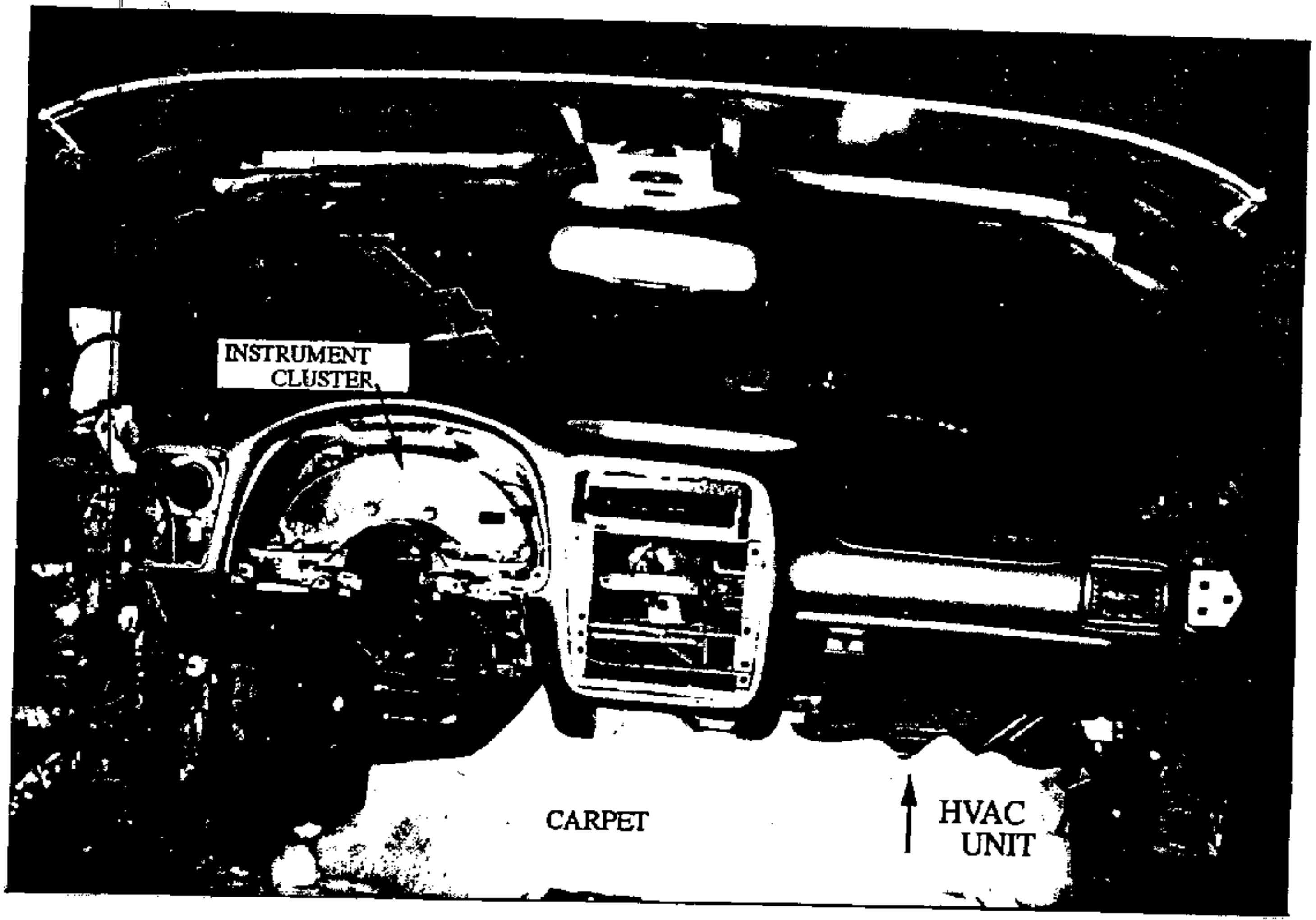


Figure 12. Instrument panel assembly mounted in front buck before test.

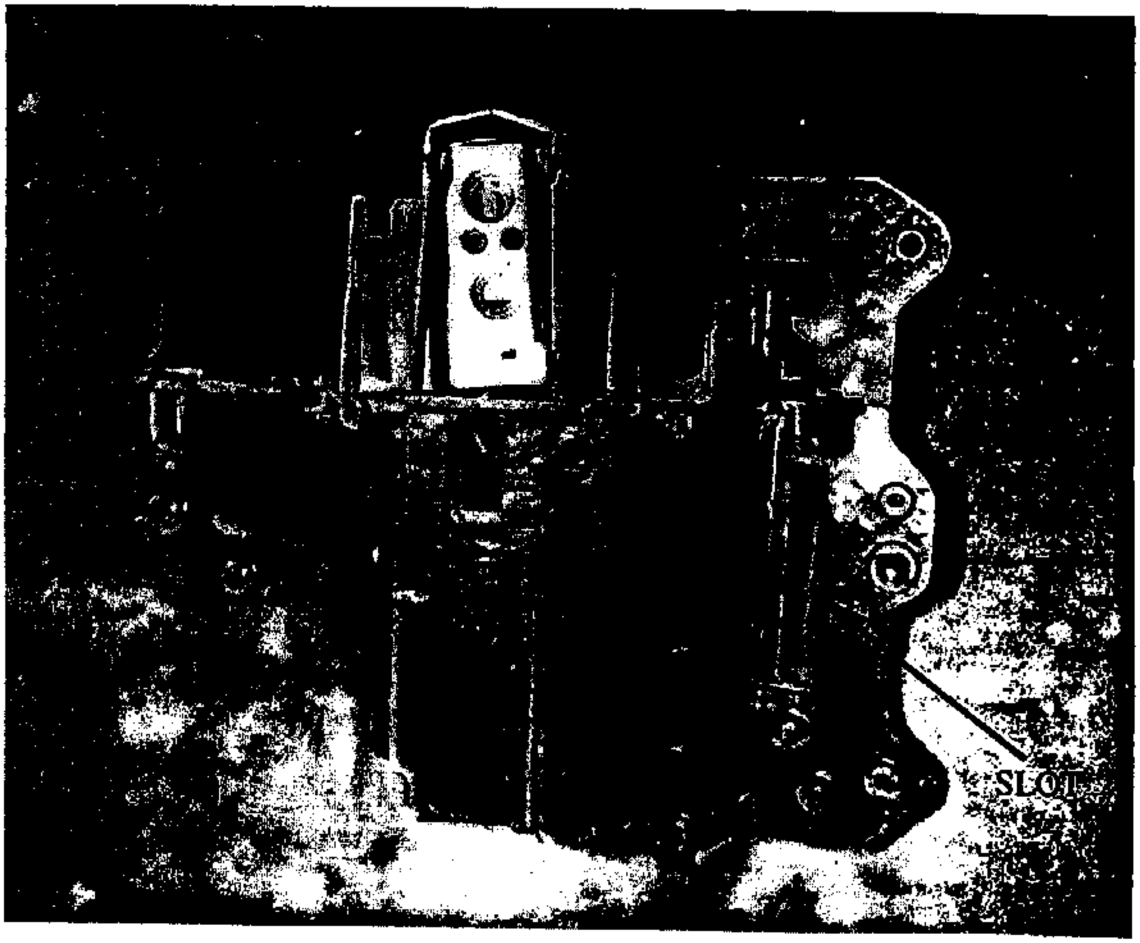


Figure 13. View of engine compartment side of HVAC case, showing 12 cm high x 1.75 cm wide slot.

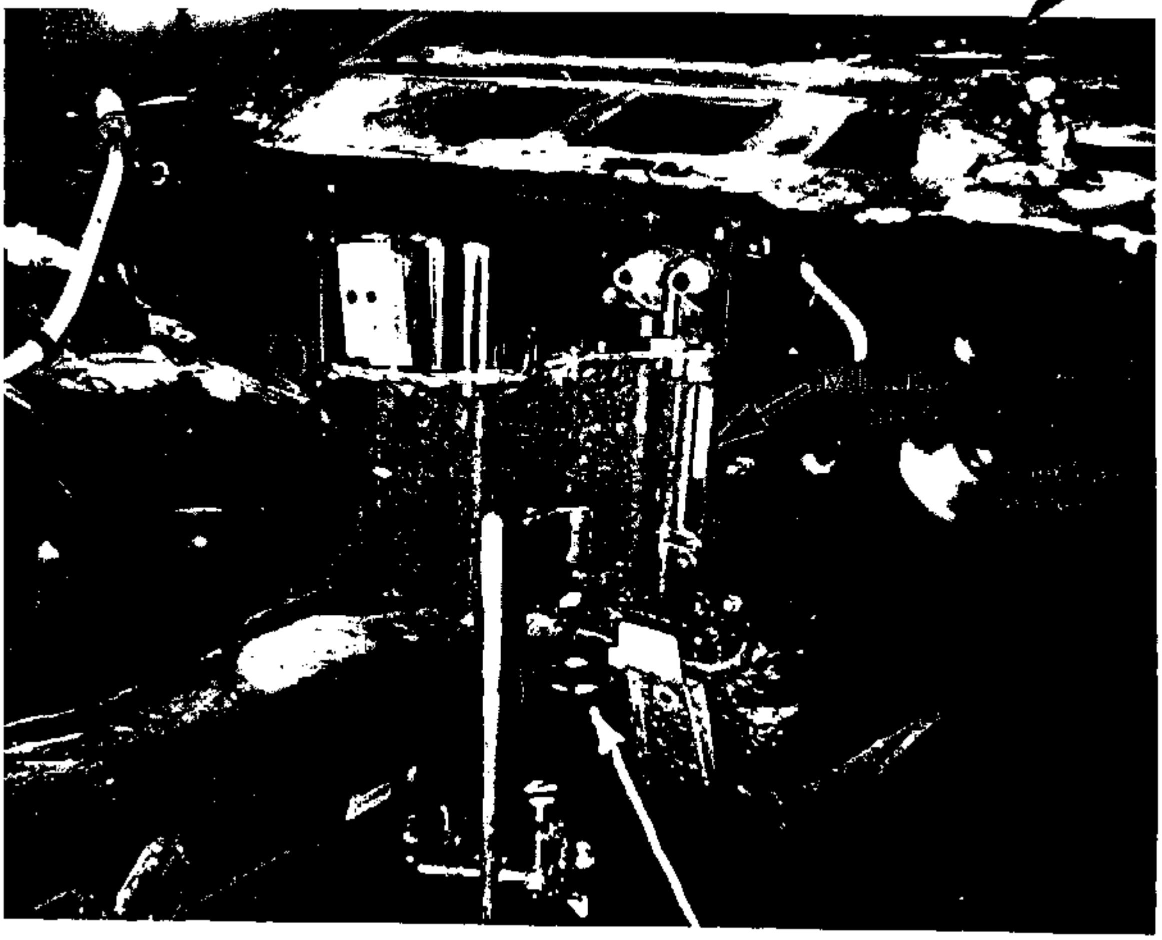
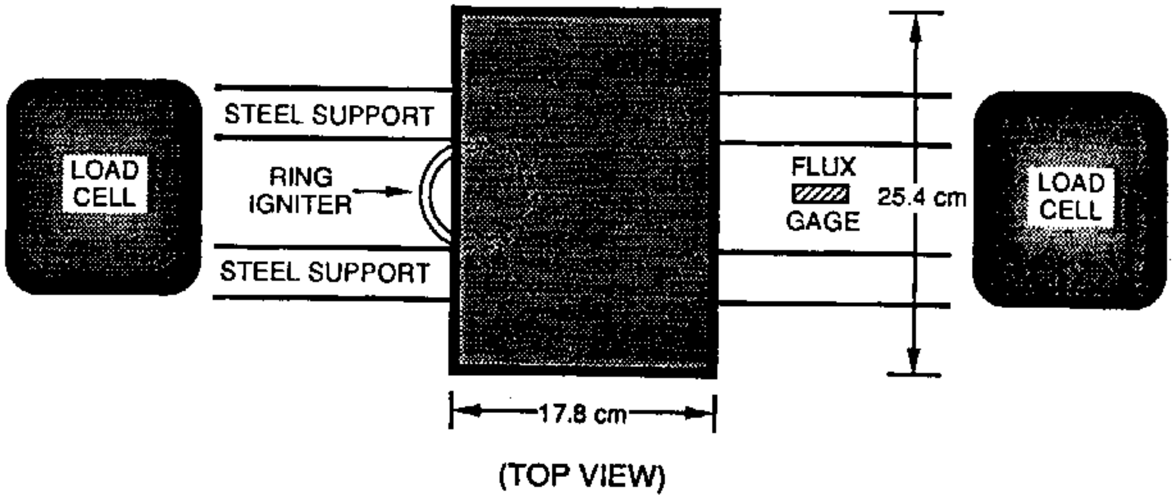


Figure 14. View from the engine compartment of the HVAC unit protruding through the forward bulkhead on the passenger's side. The ring igniter is 5 cm below the bottom of the HVAC case.



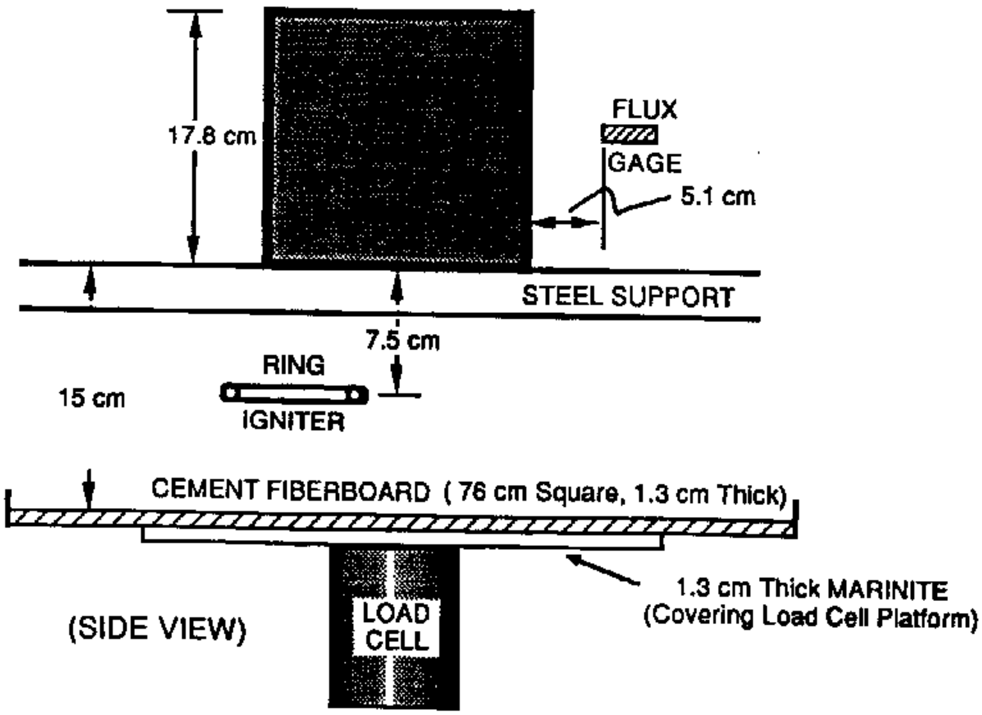


Figure 15. Test configuration for isolated parts, as applied to a generic part.

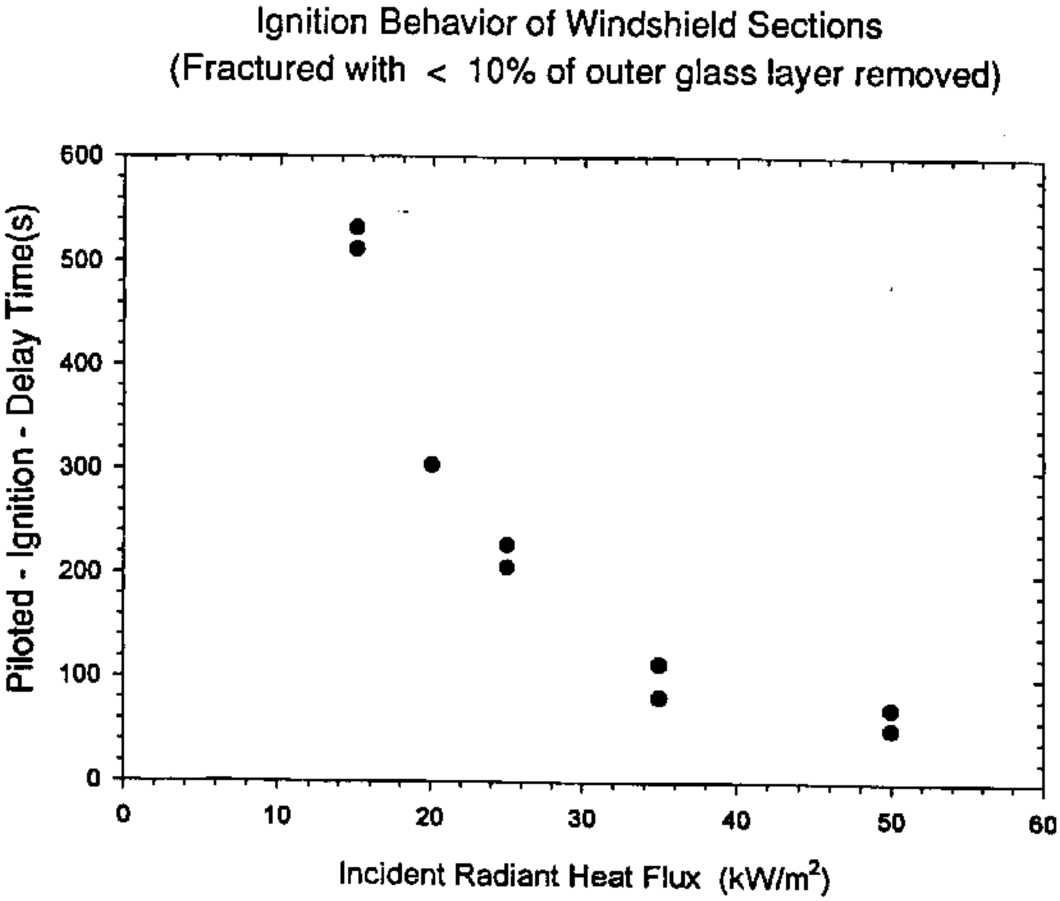


Figure 16. Cone Calorimeter data for windshield sections. Piloted ignition delay time versus incident radiant flux.

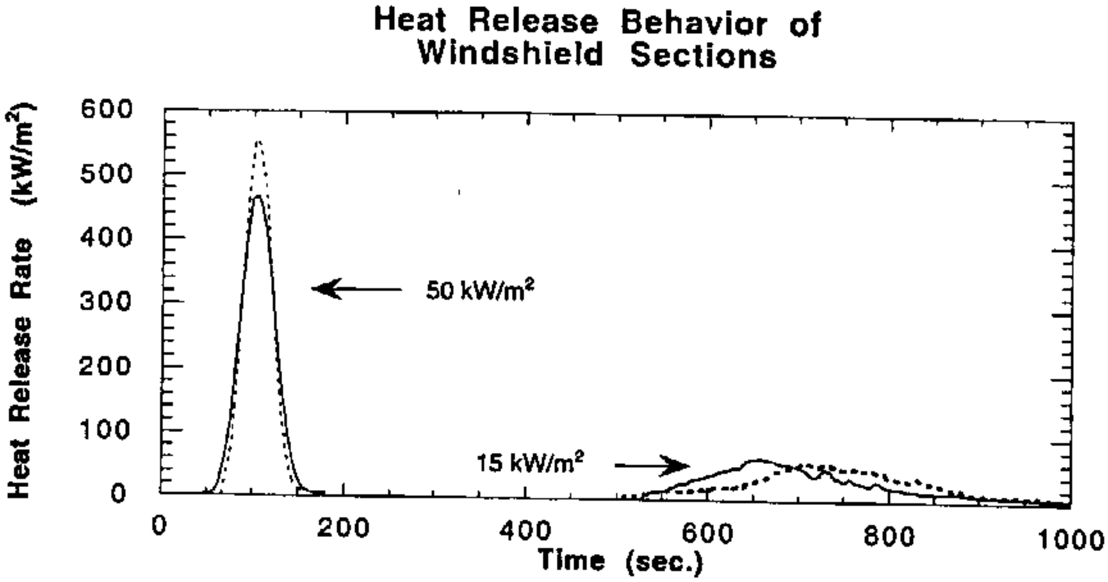


Figure 17. Cone calorimeter test results for windshield sections. Heat release rate history at two heat fluxes. Solid and dotted lines are from separate tests.

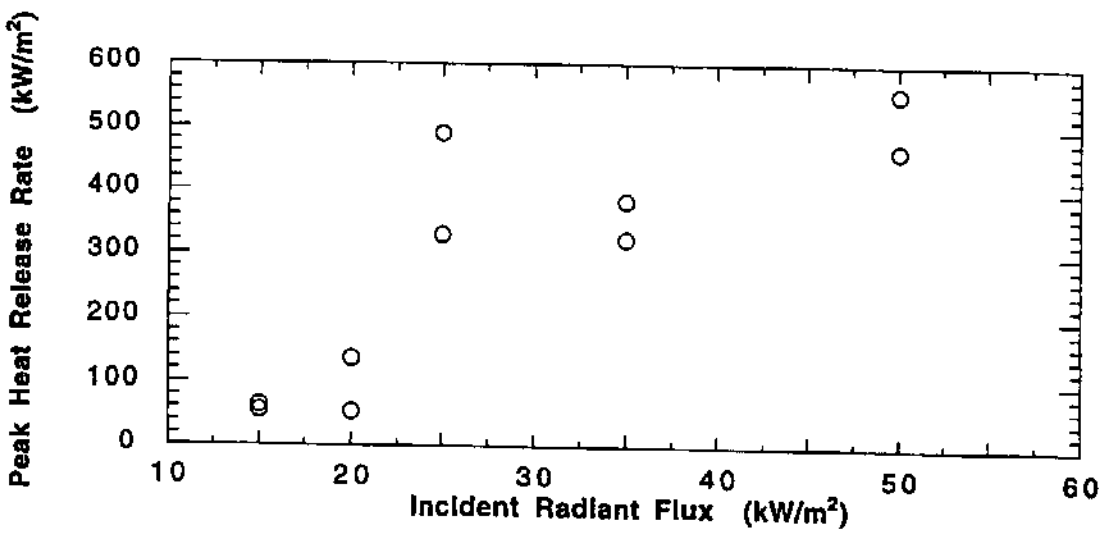


Figure 18. Cone calorimeter test results for windshield sections. Peak heat release rate at five incident heat flux levels.

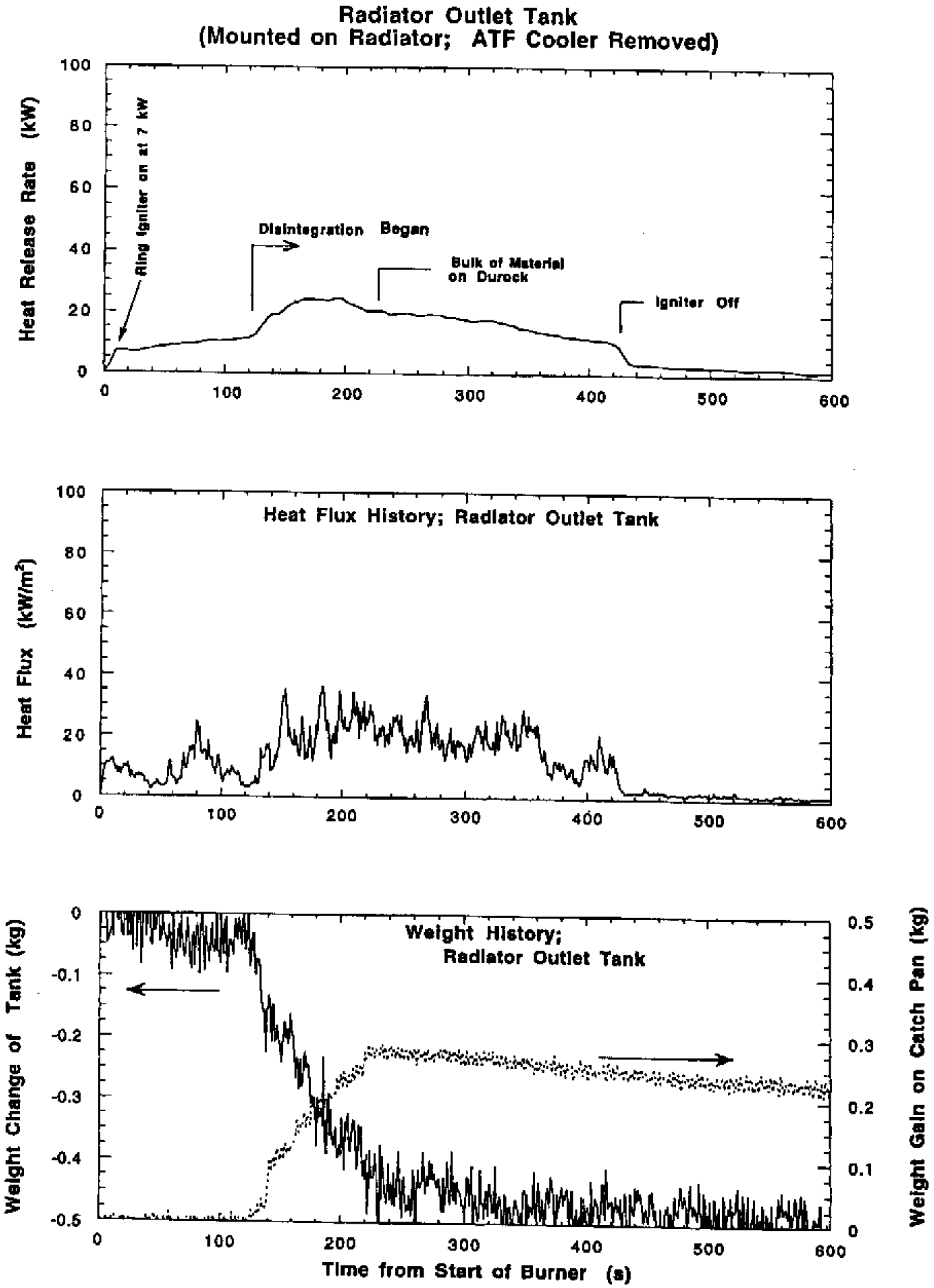


Figure 19. Results from fire test of radiator outlet tank (mounted on end of vertical radiator).

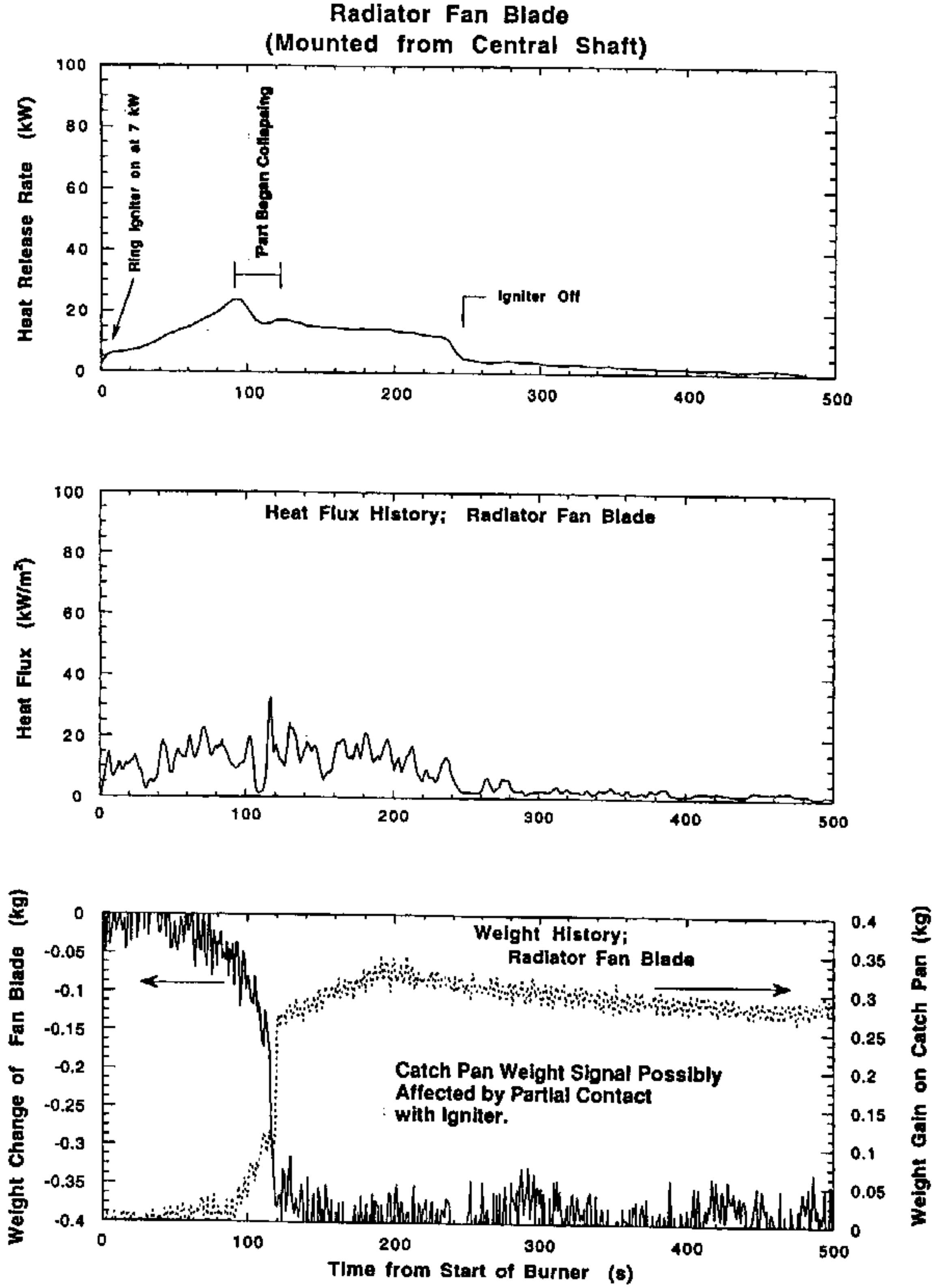


Figure 20. Results from fire test of radiator fan blade (suspended vertically from central shaft).

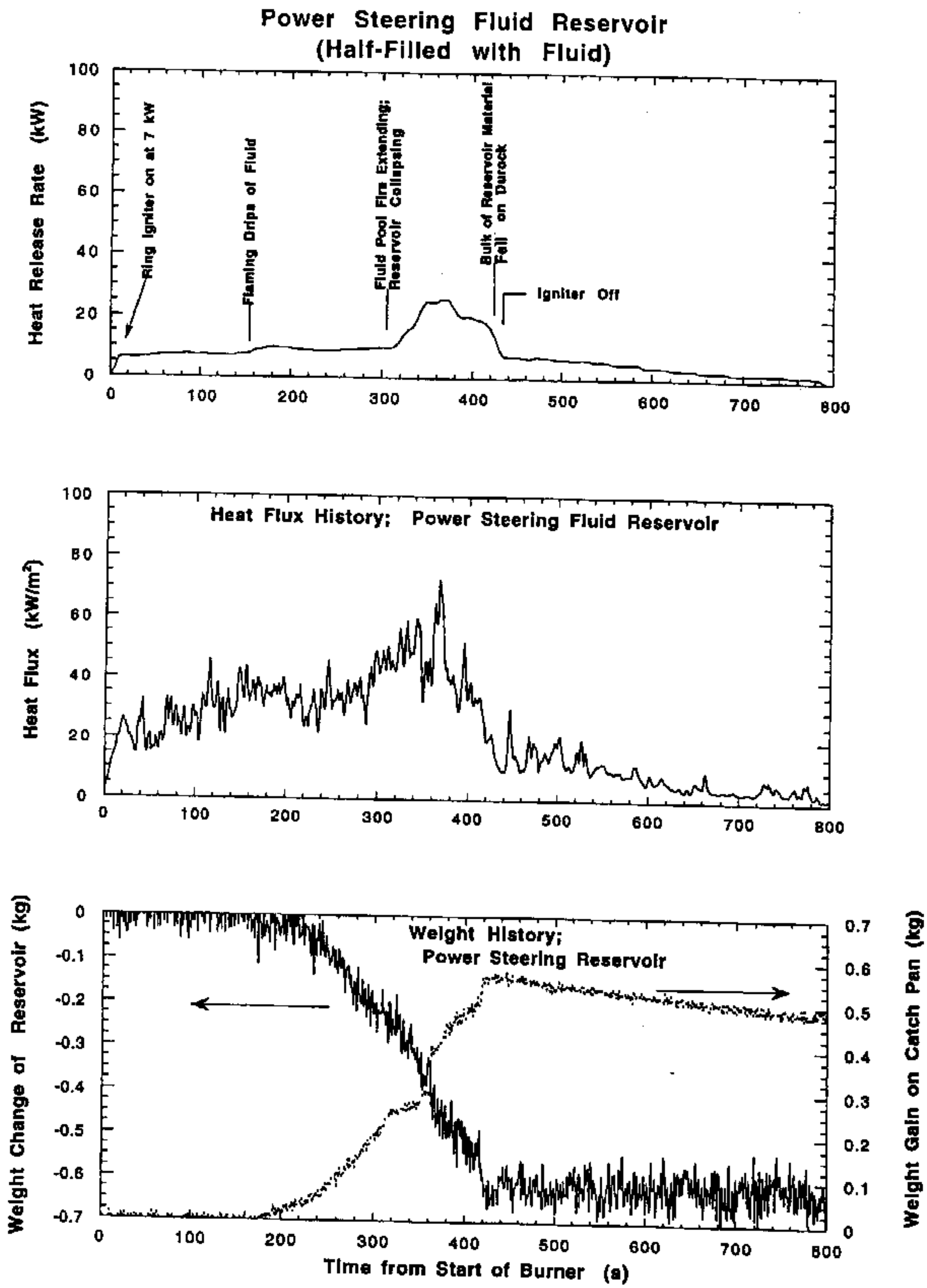


Figure 21. Results from fire test of power steering fluid reservoir (half filled with power steering fluid).

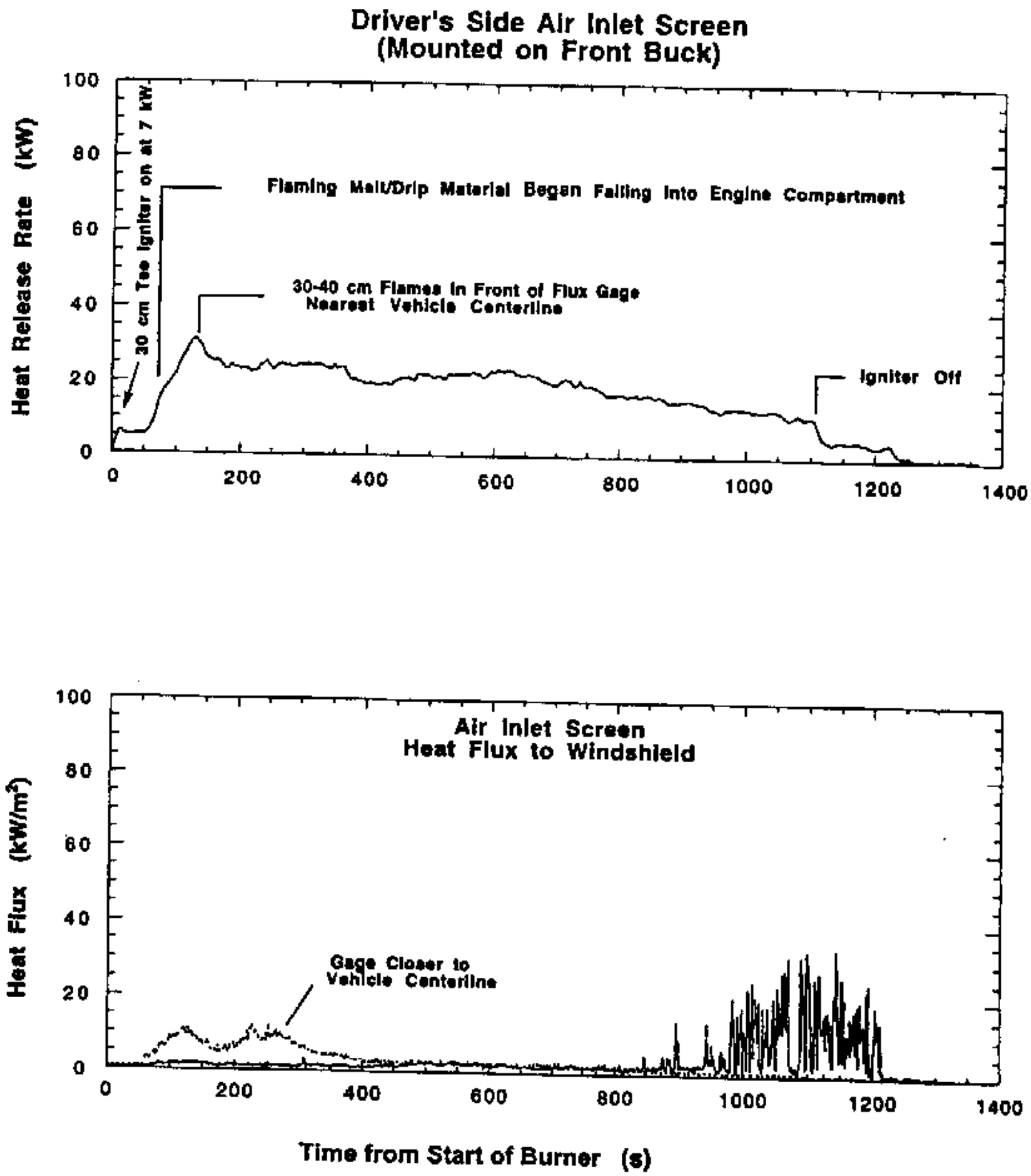


Figure 22. Results from fire test of left half of air inlet screen (mounted on front buck, at base of windshield).

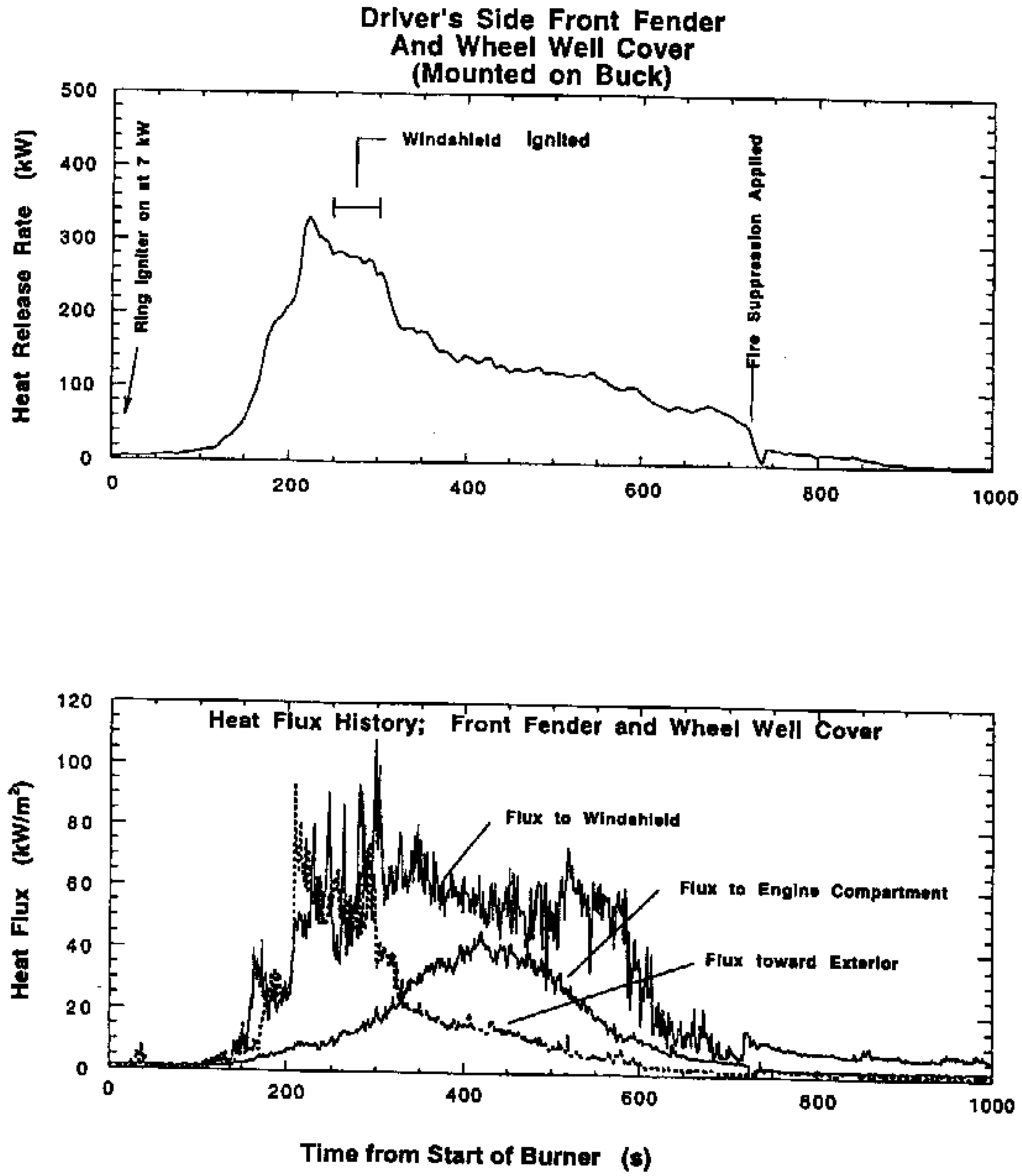


Figure 23. Results from fire test of left front fender and wheel well liner (mounted on buck).

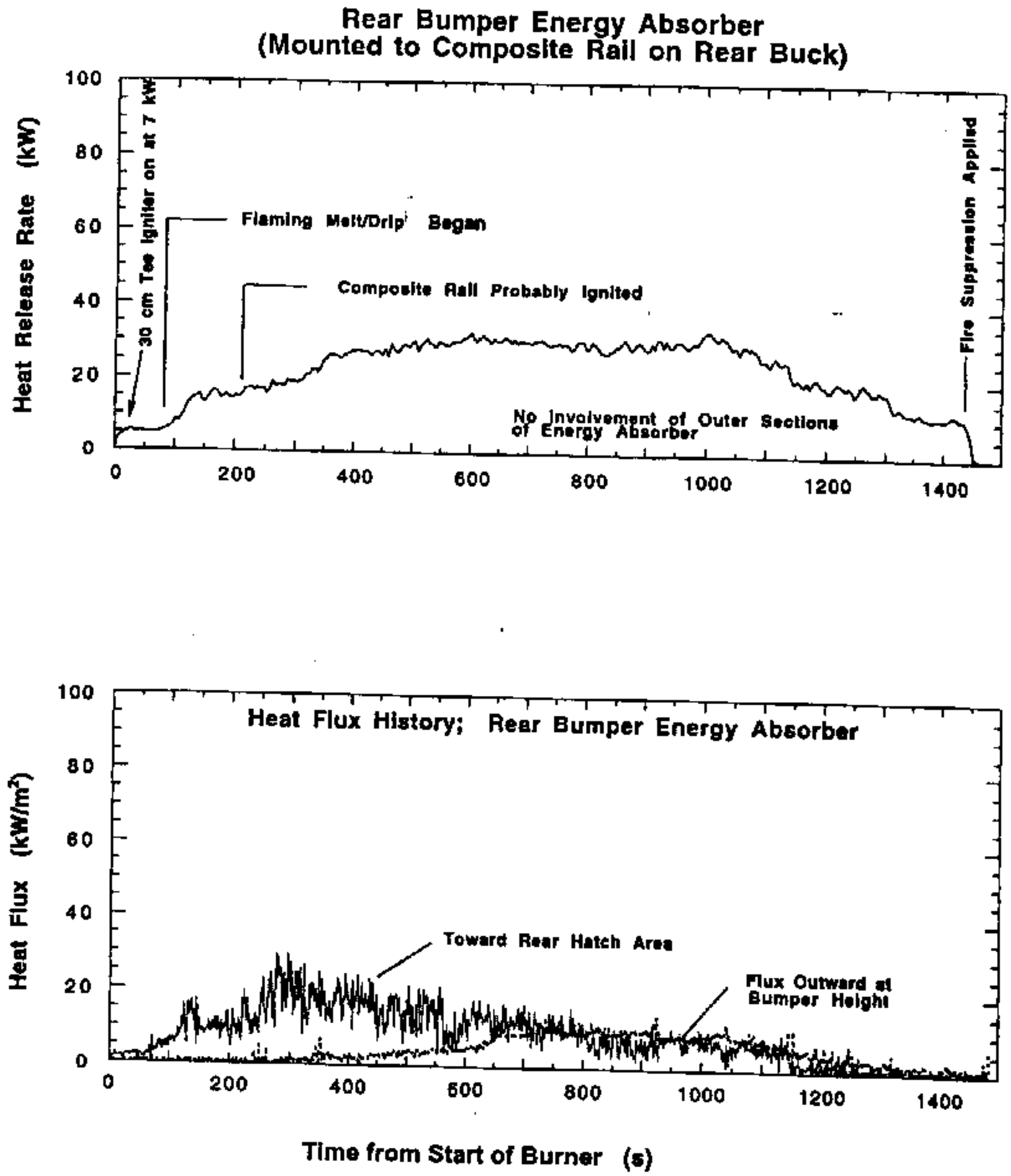


Figure 24. Results from fire test of rear bumper energy absorber (mounted on rear buck; attached to impact bar).

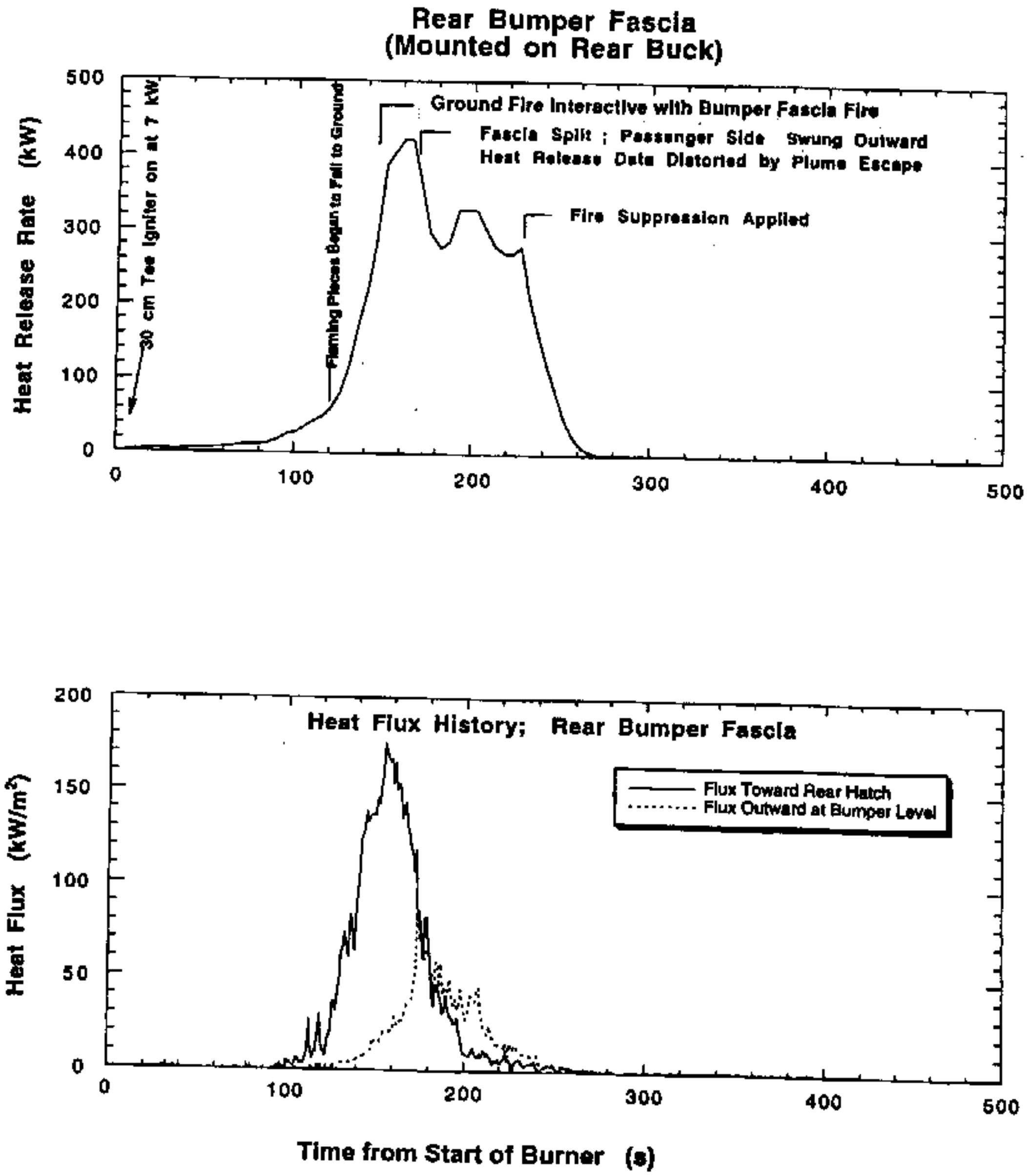


Figure 25. Results from fire test of rear bumper fascia (mounted on rear buck).

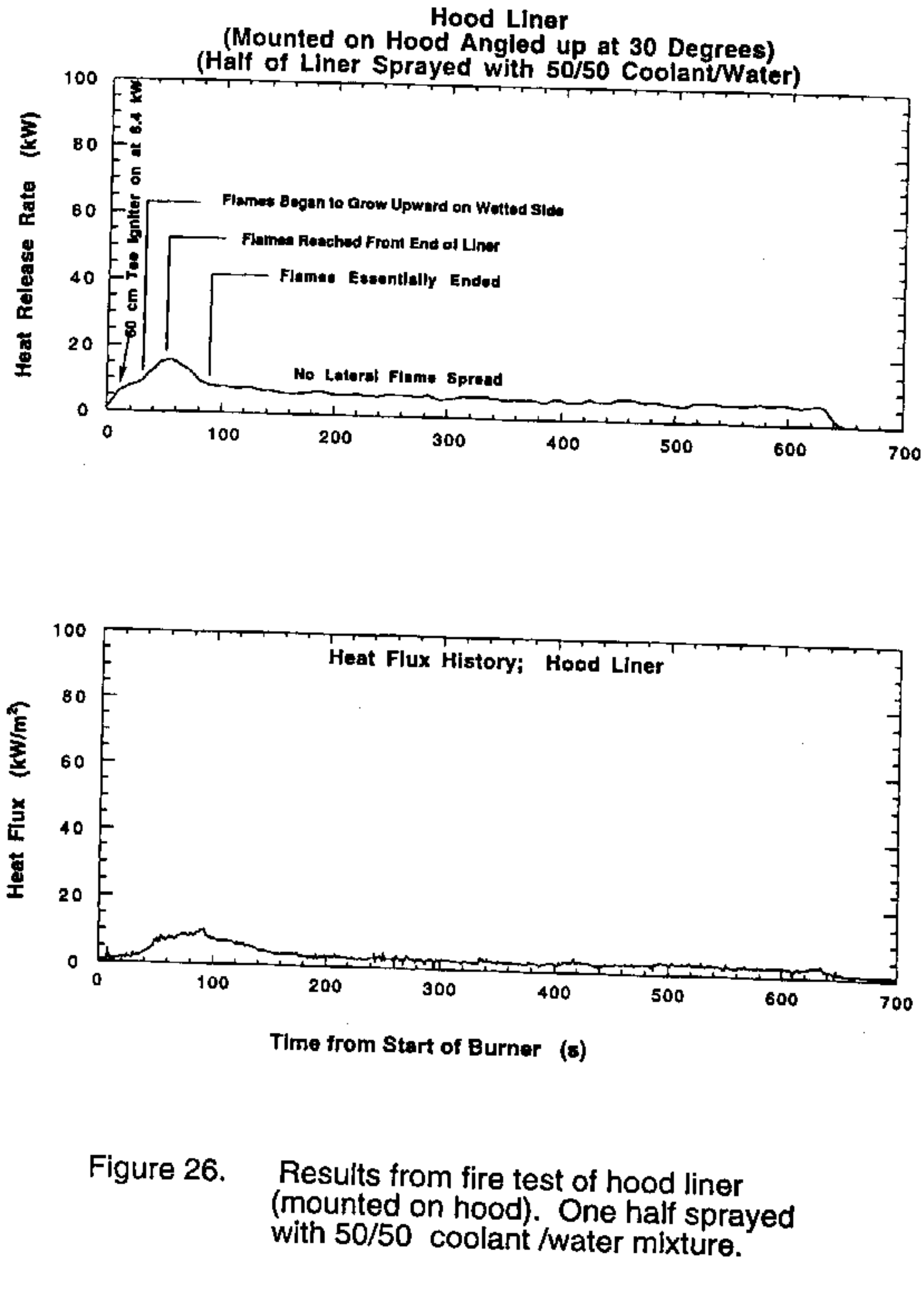


Figure 26. Results from fire test of hood liner (mounted on hood). One half sprayed with 50/50 coolant /water mixture.

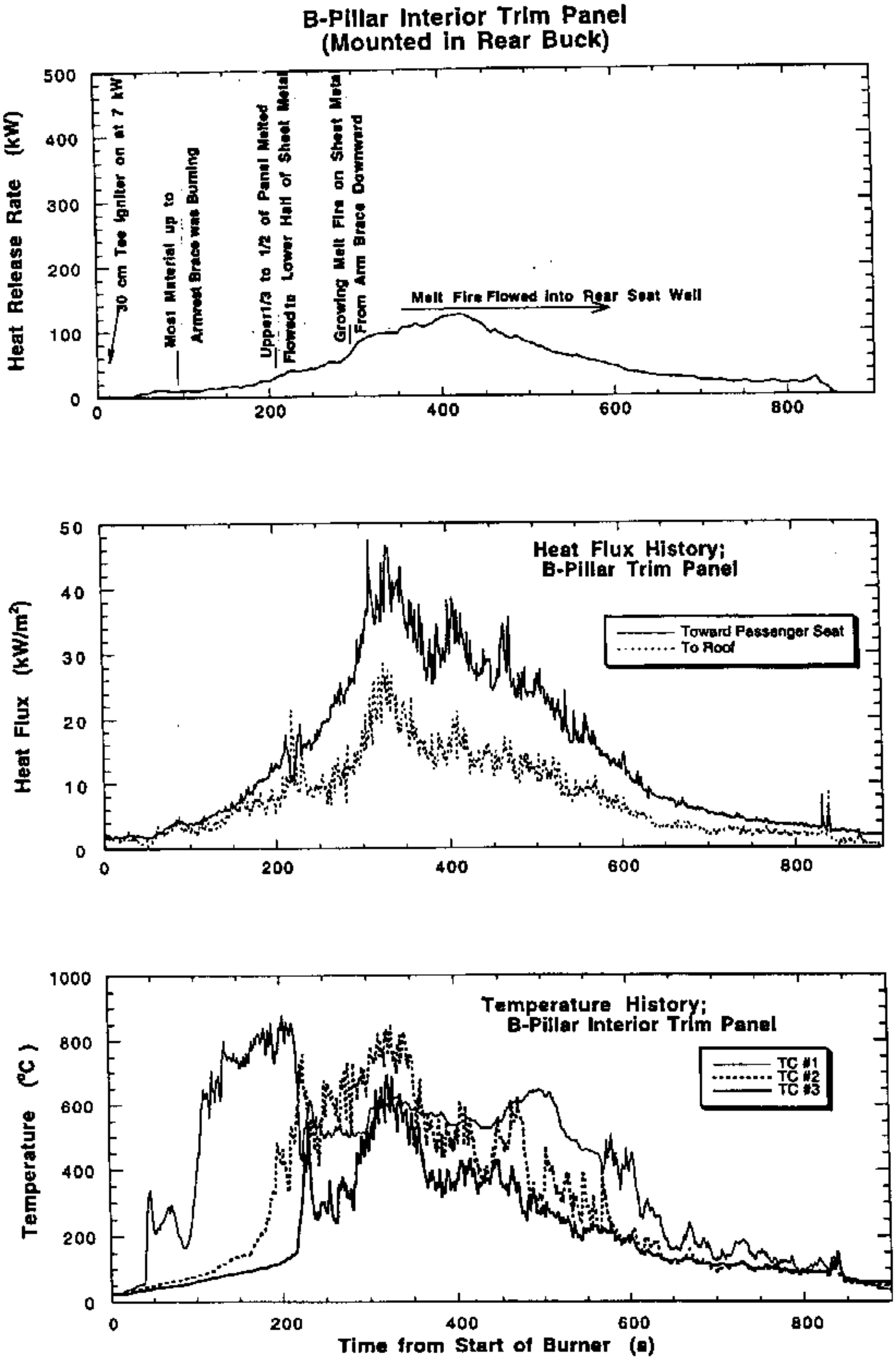
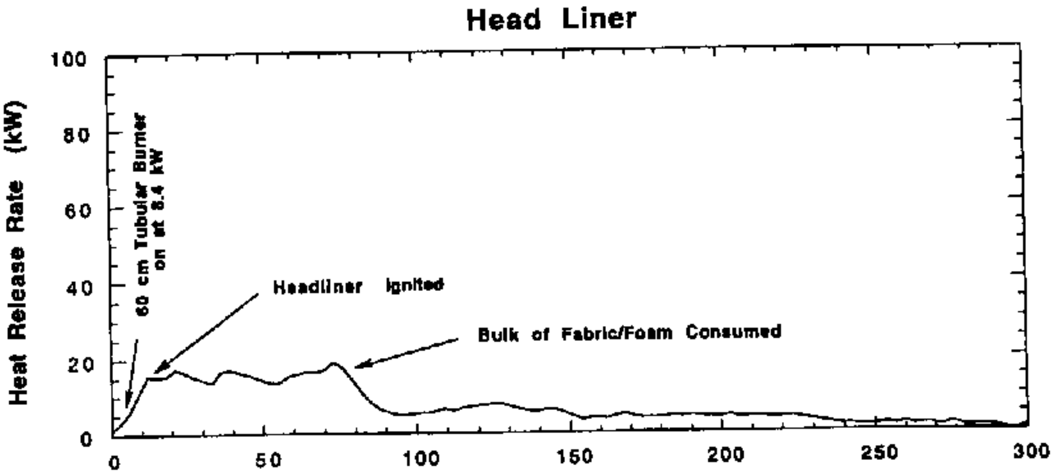


Figure 27. Results from fire test of B-pillar interior trim panel (mounted in rear buck).



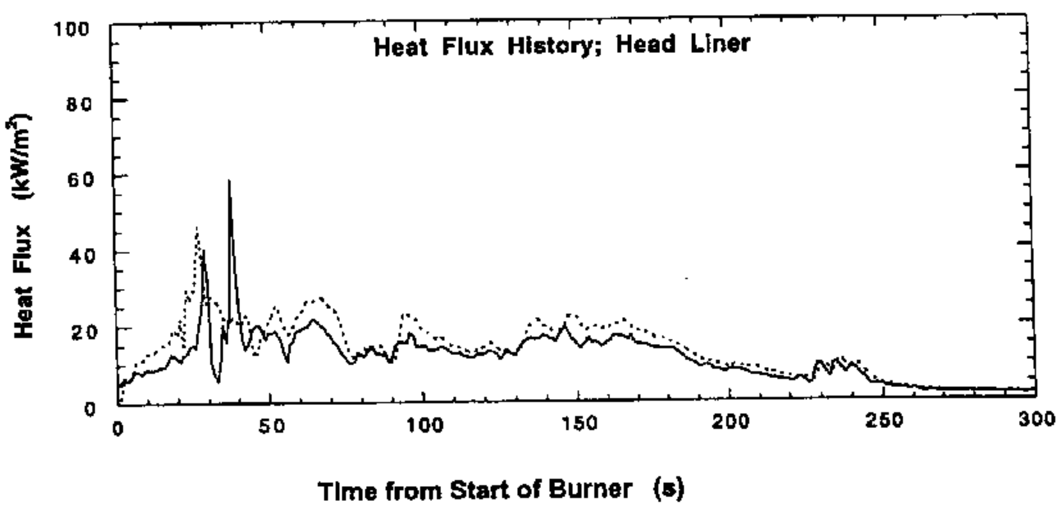


Figure 28. Results from fire test of head liner (mounted in inverted sheet metal pan).

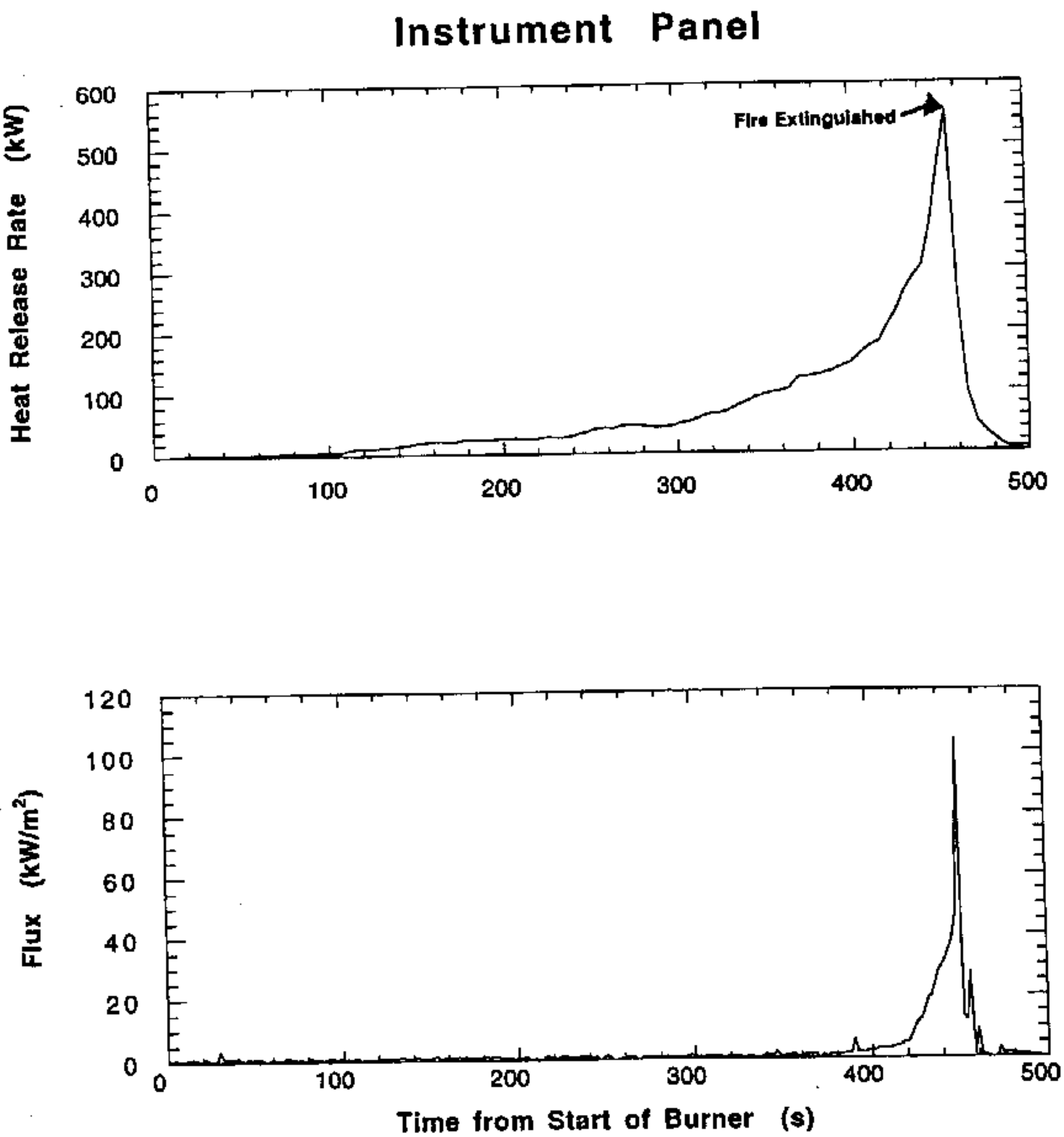


Figure 29. Results from fire test of instrument panel assembly in front buck.

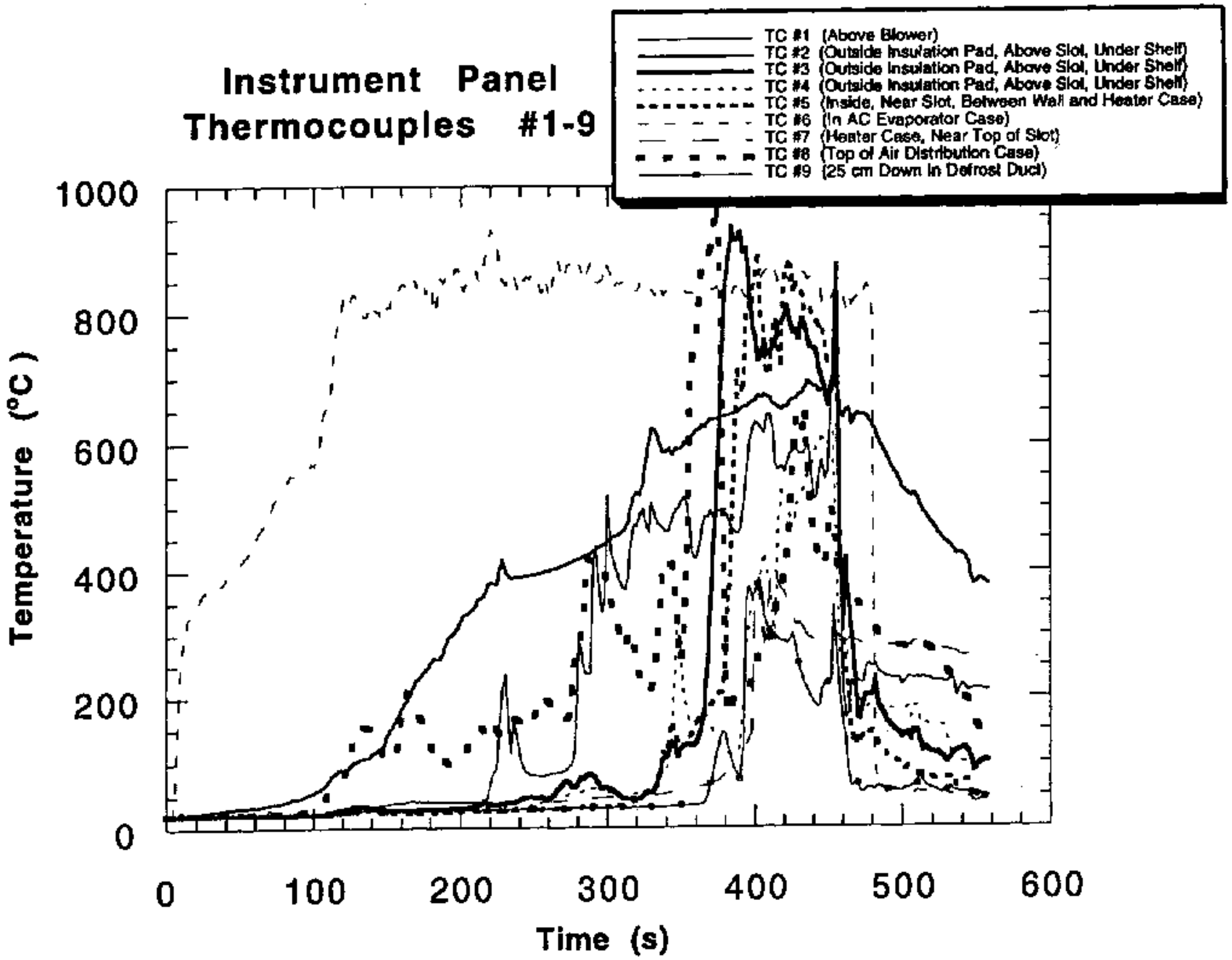


Figure 30a. Results from thermocouples embedded at indicated locations in instrument panel during fire test.

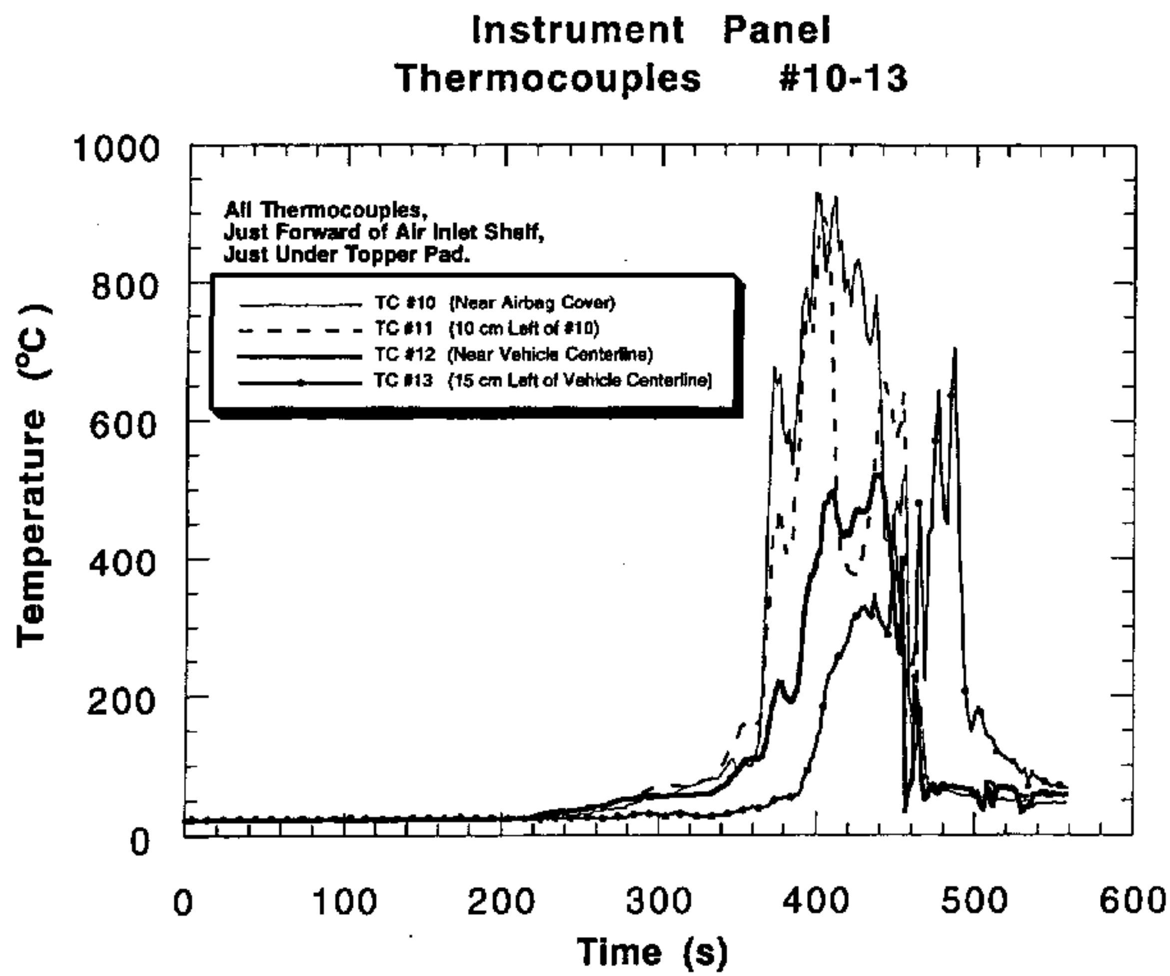


Figure 30b. Results from thermocouples embedded at indicated locations in instrument panel during fire test.