TECHNICAL REPORT
Project ID 0003018009 VOLUME I

POST COLLISION MOTOR VEHICLE FIRES

By
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Prepared for
Motor Vehicle Fire Research Institute
Attention: Ken Digges, President
1334 Pendleton Court
Charlottesville, VA USA

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Approved by:

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DISCLAIMER

ABSTRACT

Published results from the reports of the research studies sponsored by the General Motor Corporation (GM), National Highway Traffic Safety Administration (NHTSA) and Motor Vehicle Fire Research Institute (MVFRI) have been reviewed to assess the passenger survivability in vehicle crash fires. The results from the review are presented in three reports:

1) Volume I: Post Collision Motor Vehicle Fires;
2) Volume II: Theory and Testing for the Fire Behavior of Materials for the Transportation Industry;
3) Volume III: Thermophysical and Fire Properties of Motor Vehicle Plastic Parts and Engine Compartment Fluids

Most of the vehicle parts made of ordinary plastics ignited and melted easily and burned as high intensity pool fires. The engine compartment fluids tested were mostly based on hydrocarbons and were ignited easily as sprays and burned as high intensity pool fires. The data suggested that pool fires of the engine compartment fluids and molten plastic parts, alone or in combination, are capable of providing enough firepower for flames to penetrate the passenger compartment and create untenable conditions for the passenger, as well as lead to flashover.

The flames penetrated the passenger compartment very rapidly in the rear crashed vehicle burn tests with ignition of the gasoline pool under the vehicle (0.5 to 3.0 minutes), times too short for rescue. Times for flame to penetrate the passenger compartment in the front crashed vehicle burn tests with ignition in the engine compartment, were long (10 to 24 minutes) with a possibility of the rescue of the passenger by the rescue teams as these times are longer than the emergency response time.

On flame penetration into the passenger compartment, times to reach untenable/ flashover conditions were very rapid creating conditions for pain, 2nd and 3rd degree burn, flashover, incapacitation, and lethality in that order. Thus, in order to enhance the survivability of the passengers in vehicle crash fires, it is essential to prevent or delay the penetration of flames into the passenger compartment

The penetration of flames into the passenger compartment can be prevented or delayed significantly by the fire retardant treatment of the plastic parts, intumescent coating of the undercarriage of the vehicle, sealing of utility openings, underhood blanket in the engine compartment and fire suppression in the engine compartment. All these techniques were tested in

the vehicle burn tests, but were found to be ineffective in delaying the flame penetration into the passenger compartment and thus need to be re-examined. All the reports generated in the studies sponsored by GM are listed in the NHTSA web page (www.nhtsa.dot.gov) and studies sponsored by NHTSA, and MVFRI in the MVFRI web page (www.mvfri.org).

ACKNOWLEDGMENTS

Continued encouragements and technical support from Dr. K. H. Digges and Dr. R. R. Stephenson of the Motor Vehicle Fire Research Institute (MVFRI) are gratefully acknowledged. We are also thankful to Ms. Cheryl McGrath and Ms. Lisa Ouellet of FM Global for painstakingly assembling various chapters of the report.

EXECUTIVE SUMMARY

A review of the results of research studies on vehicle burn tests, sponsored by the General Motor Corporation (GM), National Highway Traffic Safety Administration (NHTSA) and Motor Vehicle Fire Research Institute (MVFRI) is presented in this volume[1]. The research studies were performed by GM Research Laboratories, National Institute of Standards and Technology (NIST), and FM Global. In the tests, 11 latest models of vehicles were burned after they were crashed at the GM Proving Ground.

The burn tests were performed separately for the front crashed and rear crashed vehicles. Electrical ignition of the plastic parts and ignition of sprays of the engine compartment fluids were used to initiate the fire in the engine compartment for the front crashed vehicle burn tests. For the rear crashed vehicle burn tests, ignition of the gasoline pool under the vehicle in the rear was used to initiate the fire. The flames penetrated the passenger compartment when the heat release rate was between about 100 to 800 kW.

In the front crashed vehicle burn tests with ignition in the engine compartment, flames were observed to penetrate the passenger compartment in about 10 to 24 minutes through the broken windshield, AC evaporator and condenser-line-pass-through and HVAC air intake. In the rear crashed vehicle burn tests with ignition of spilled gasoline pool under the vehicle, flames were observed to penetrate the passenger compartment in about 0.5 to 3.0 minutes through the split weld seams, gaps between the door and doorframe, and drain and utility holes in the floor panel.

Once flames entered the passenger compartment, fire growth in both cases became very rapid and untenable/flashover conditions reached rapidly. Times to pain, 2nd and 3rd degree burns, flashover, incapacitation and lethality increased in that order as soon flames penetrated the passenger compartment. An examination of the flame penetration and flashover times to emergency response times indicated that rescue of passengers was only possible for front crashed vehicle fires. The flame penetration and flashover times for rear crashed vehicle fires started by gasoline pool fires under the vehicle were significantly lower than the emergency response times.

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[1] All the reports generated in the studies sponsored by GM are listed in the NHTSA web page (www.NHTSA.DOT.gov) and studies sponsored by GM, NHTSA, and MVFRI in the MVFRI web page (www.MVFRI.org).

Effectiveness of several active and passive fire protection systems were evaluated in the vehicle burn tests in order to enhance the survivability of passengers by preventing or delaying the penetration of flames into the passenger compartment. Amongst the passive fire protection techniques evaluated were the fire retardant treatment of polypropylene for the HVAC unit and intumescent coating of the under carriage of the vehicle. Both these techniques were found to be ineffective and suggested that other fire retardant and intumescent coating systems need to be examined.

Amongst the active fire protection systems, a unique pyrotechnic device (solid propellant gas generator) in the engine compartment was found to be ineffective in the suppression of the engine compartment fire during the crash testing of the vehicle as well as for the stationary vehicles by GM. However, Ford Motor Company has developed a fire protection system, where a pyrotechnic gas generator is used to effectively deploy a combination of liquid fire suppressant and surfactant to vehicle fires. The system will be sold commercially soon. University of Maryland has also developed a nitrogen foam fire suppression system to extinguish the engine compartment fire. A powder panel fuel tank or fluid reservoir protection system from fires, which have been used to protect aircraft dry bays from ballistic impact, has also been suggested as a useful fire protection system for vehicle crash fires. All these systems need to be examined.

This volume has been organized in six chapters and two appendices, as follows:

Chapter I.	Introduction;
Chapter II.	Fire Behavior of Motor Vehicle Part Systems;
Chapter III.	Fire Behavior of Crashed Motor Vehicles;
Chapter IV.	Ignition and Flame Spread Associated with Post Collision Vehicle Fires
Chapter V.	Survivability in Vehicle Fires;
Chapter VI.	Conclusions: Fire Safety Issues for Motor Vehicle Post Collision Fires and Possible Solutions
Appendix A.	Selected Data for Post Collision Motor Vehicle Fires
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CHAPTER I

INTRODUCTION

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Vehicle fires are a major component of the fire death problem in the United States of America. As a result, the National Highway Traffic Safety Administration (NHTSA) of the Department of Transportation (DOT) was established in 1966 [1]. NHTSA is authorized to set minimum safety standards for new motor vehicles and motor vehicle equipment and to investigate defects in motor vehicles, including fire hazards [1]. Since 1966, NHTSA has issued two Federal Motor Vehicle Safety Standards (FMVSS) dealing with fires in gasoline fueled vehicles [2]: a) Part 571.301: Fuel System Integrity and b) Part 571.302: Flammability of Interior Materials. Another fire test standard for plastic fuel tanks is that of the United Nations Economic Commission for Europe (UN/ECE), regulation No. 34: Prevention of Fire Risks [3].

The FMVSS 571.301 Standard was issued in 1968 to reduce deaths and injuries occurring from fires that result from fuel spillage during and after motor vehicle crashes and rollovers and from ingestion of fuels during siphoning [2]. For satisfying the requirements of the Standard, motor vehicle crash tests are performed. The Standard regulates only gasoline and diesel fuel leakage in vehicle collision and rollover. Since the issuance of the Standard, many studies have been undertaken to evaluate the effectiveness of this Standard as well as to enhance fire safety in general [4,5,6,7 and references therein].

The FMVSS 571.302 Standard was issued in 1972 to reduce the deaths and injuries to motor vehicle passengers caused by vehicle fires, especially those originating in the interior of the vehicles from sources such as matches or cigarettes [2]. For satisfying the requirements of the Standard, burn tests are performed in a metal cabinet and measurements are made for the rate of flame spread, burning time and distance [2]. The test is described in Volume III of the technical report (Chapter I, Appendix A-3, Section A-3-1). A material is considered to meet the requirement of the Standard if [2]:

- It does not burn nor transmit a flame front across its surface, at a rate of more than 102 mm/min;

- Stops burning before 60 seconds of burn time after ignition and does not burn more than 51-mm from the point where the timing was started.

The following components used in the motor vehicles are required to satisfy the FMVSS 571.302 Standard [2]:

- Seat cushions, seat backs, seat belts;
- Headlining, convertible tops, arm rests, head restraint, sun visors, curtains, shades;
- All trim panels including door, front, rear, and side panels, compartment shelves, floor covering, wheel housing covers;
- Covers for engine compartment and mattress;
- Other interior materials including padding and crash-deployed elements that are designed to absorb energy on contact by occupants in the event of a crash;
- Any portion of a single or composite material which is within 13-mm of the passenger compartment air space;
- Any material that does not adhere to other material(s) at every point of contact;
- Any material that adheres to other materials at every point of contact;

Despite the implementation of the FMVSS 571.301 and 571.302 Standards, fires have continued to be serious safety threats to passengers [8]. Therefore, attempts have been made to upgrade these Standards [8]. A major boost towards the upgrading of both FMVSS 571.301 and 571.302 Standards tests and enhance the passenger survivability in vehicle crash fires was provided on March 7, 1995. On this date, the U.S. DOT and the General Motors Corporation (GM) entered into an administrative agreement, which settled an investigation that was being conducted by NHTSA regarding an alleged defect related to fires in GM C/K pickup trucks [9].

Under the DOT/GM Settlement Agreement, GM agreed to provide support to NHTSA’s effort to upgrade the current FMVSS 571.301 Standard, through public rulemaking process [9]. GM also agreed to spend $51.355 million over five year period to support projects and activities that would further vehicle and highway safety in lieu of a vehicle recall to reduce vehicle vulnerability to post crash fires. Ten million dollars of the funding was devoted to fire safety research [9].

Subsequent to the DOT/GM Settlement Agreement [9], GM agreed to fund an additional $4.1 million over 2001-2004 period in research related to impact induced fires, as part of a judicial settlement [10,11]. This latter research project was included under the terms of a judicial settlement between White, Monson and Cashiola versus General Motors Agreement, dated June 27, 1996 (Judicial District Court 1996) [11]. The project was undertaken by the Motor Vehicle

Fire Research Institute (MVFRI) to provide knowledge to assist reducing the fire vulnerability for all future vehicles [10].

The planning for the GM Research Projects under the DOT/GM Settlement Agreement [9] and the MVFRI Research Project under the White, Monson and Cashiola/General Motors Agreement [11] used the databases on fires in vehicle crashes and motor vehicle accidents. The databases used were the Fatal Analysis Reporting System (FARS), the National Automotive Sampling System (NASS), and the Crashworthiness Data System (CDS) [1,4,5,6,7,10,11 and references therein]. An example of the NASS database is listed in Appendix A in Table A-1, taken from Ref. 4. This database is based on photographs, inspection results, witness statements and investigator experience. An examination of Table A-1 indicates that:

- Majority of the collisions were front ended, where fires were initiated in the engine compartment. For rear and side collisions and rollovers, fires were initiated in the rear end, interior, by pool fires under the passenger compartment, and by hot exhaust systems;
- Fuels for the fires included gasoline and the engine compartment fluids. Plastics in the engine components also acted as fuels for the fires;
- Ignition sources were hot surfaces and electrical or mechanical sparks;
- Times to ignition was immediate to as long as 15 minutes;
- Times for fires to enter the passenger compartment were immediate to as long as 15 minutes. In many collisions, vehicles were fully engulfed by fire in 9 to 10 minutes.

Following is a list of GM Research Topics (each topic had several projects) undertaken to satisfy the DOT/GM Settlement Agreement [12]:

- Topic B.1: Analysis of Motor Vehicle Accident Data;
- Topic B.2: Case Studies of Motor Vehicle Fires;
- Topic B.3: Fire Initiation and Propagation Tests;
- Topic B.4: Evaluation of Potential Fire Intervention Materials and Technologies;
- Topic B.8: Search for Scientific Literature;
- Topic B.10: Study of Flammability of Materials;
- Topic B.11: Study of Component Influence on Vehicle Fires;
- Topic B.14: Demonstration of Enhanced Fire Safety Technology;
- Topic B.15: Theoretical and Experimental Study of Thermal Barriers Separating Automobile Engine and Passenger Compartments.

Following is a list of MVFRI Research Projects undertaken to satisfy the Cashiola/General Motors Agreement [10,11]:

- Project 1: Statistical Analysis of Field Data for Frequency of Fuel Leaks and Fires;
- Project 2: Case by Case Study of Fuel Leaks and Fires in NASS and CDS;

- Project 3: Assessment of the State-of-the-Art Technology to Reduce the Frequency of Fires in Motor Vehicles and/or Delay the Time for Fire Propagation to the Fuel or to the Interior of the Passenger Compartment;
- Project 4: Evaluation of Fuel Tanks Subjected to Fire and Impact;
- Project 5: Development of Test Procedures for the Prevention of Fires in Vehicle Equipped with 42 Volt Electrical Systems;
- Project 6: Toxicity Evaluation of Motor Vehicle Components Used in the Engine Compartment and Under-Hood Applications;
- Project 7: Evaluation of Rescue Times for First Responders from Motor Vehicle Crash Accidents Leading to Fire Propagation into the Passenger Compartment;
- Project 8: Comprehensive Analysis of Data from Studies Sponsored by GM, MVFRI and NHTSA (this report is the product of this project);
- Project 9: Development of an Under-Hood Foam Fire Suppression System;
- Project 10: Failure Evaluation of a Compressed Hydrogen Storage Tank.

In July 2002, NHTSA funded a study for either upgrading the FMVSS 571.302 Standard and/or developing a new small-scale test methodology. The standard test methodology was to rate automotive materials consistent with the actual fire performance in vehicle burns and to establish levels of performance for the test methodology that would significantly alter the fire outcome in terms of injury or survivability [13].

The GM, MVFRI and NHTSA funded research studies have generated valuable data on the motor vehicle crash fires and knowledge of how these fires are initiated and propagate in motor vehicle crashes and what type of fire environments are created. These studies have also generated valuable information on the effectiveness of passive and active fire protection and suppression processes in motor vehicle crashes and on the strengths and weaknesses of small-scale tests including the FMVSS 571.302 Standard test for the fire behaviors of engine compartment fluids and plastics used in motor vehicles. Results from several studies on motor vehicle fires reported in the literature [14,15,16,17,18], have also provided additional information on the ignition and flame spread processes associated with motor vehicle fires.

In this report, results from the GM, MVFRI and NHTSA Research Projects as well as from the literature have been reviewed and an attempt has been made to provide answers to the following questions:

1. <u>Engine Compartment Fluids</u>: What was learned about the fire behavior of engine compartment fluids? How do the fluids ignite in a vehicle crash? Do the thermo-physical properties, such as flash point, autoignition temperature, hot surface ignition temperature, boiling point, and others adequately define the ignition resistance of fluids? Do engine compartment fluids participate in flame spread from the engine compartment to the

passenger compartment? Do engine compartment fluids need to be fire retarded to enhance survivability of passengers in vehicle crash fires? Is there a need for a standard test for ignition resistance of fluids?

2. Motor Vehicle Parts: What was learned about the fire behavior of plastics in motor vehicles? How do plastics ignite and participate in flame spread in a vehicle crash? How effective is the fire retardancy and intumescent painting of the plastics and under carriage in enhancing survivability of passengers in vehicle crash fires? How important is dripping, melting and burning of plastics as pool fires in the transport of the flames into the passenger compartment? How effective is the underhood insulation blanket in preventing spread of flames into the passenger compartment? Is there a need to fire retard the blanket to enhance the passenger survivability? Is there a need for simple engineering tools to assess the resistance of plastics for ignition and flame spread?

3. Flame Spread into the Passenger Compartment: How do flames spread in a motor vehicle crash? Is there a significant difference in times for flames to reach the passenger compartment for the front and rear crashes? Are these times long enough for fire fighting and extrication by a nearby fire department? Does the flame spread rapidly on the "exterior" (outside the passenger compartment, such as the underhood and underbody) or on the "interior" in a crash? Should standards be different for "exterior" and "interior" plastics? How effective is fire suppression in enhancing the survivability of the passengers in the motor vehicle crash fires?

4. Passenger Compartment Environment Created by Motor Vehicle Crash Fires: What was learned about the safety and escape of passengers from fires resulting from the front and rear crashes of motor vehicles? How early do smoke and toxic compounds generate in a vehicle crash? Does the passenger compartment environment become hazardous before flames enter the compartment? Do more people die from toxic gases or burns, which problem is of higher priority? How is passenger survivability affected by the closed or open windows? Should emissions of smoke and toxic compounds from plastics in vehicles be limited to enhance the passenger survivability? Is there a need for a regulatory standard for the release of smoke and toxic compounds? How would the replacement of ordinary glass by safety glass in the side windows affect the survivability of the passengers in motor vehicle crash fires?

5. Regulatory Standards: What are the deficiencies of FMVSS 571.302 Standard? Should the Standard be upgraded, replaced and/or supplemented by a new standard? Is there a need for regulatory standards for engine compartment fluids and exterior plastic materials?

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CHAPTER II

FIRE BEHAVIOR OF MOTOR VEHICLE PART SYSTEMS

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2.1 INTRODUCTION

Many vehicle part systems are made of plastics, which are inherently flammable. Fires involving vehicle part systems in crashes depend not only on the thermophysical and fire properties of the plastics, but also on the shape, size, and orientation of the part systems and the environment. Very little was known about the fire behaviors of the vehicle part systems, thus fire testing of the vehicle part systems was undertaken in the GM and NHTSA sponsored studies. The vehicle part systems were selected from a 1996 Dodge Caravan and a 1997 Chevrolet Camaro.

In the NHTSA sponsored study, vehicle part systems were burned in the ASTM E1623 Standard Intermediate Scale Calorimeter (ICAL) by SwRI [1]. In the GM sponsored studies, part systems from the 1996 Dodge Caravan and the 1997 Chevrolet Camaro and fire retarded and non-fire retarded HVAC units were burned in the 100-kW and 500-kW Calorimeters by NIST [2,3,4]. Fire retarded and non-fire retarded HVAC units for a 1999 Honda were also burned under the Fire Products Collector by FM Global [5,6].

2.2 Vehicle Part Systems Burned in the ASTM E1623 ICAL

In the tests performed by SwRI using the ICAL [1], six plastic part systems from the 1996 Dodge Caravan and the 1997 Chevrolet Camaro were burned. These part systems are listed in Table 2-1. In the tests, part systems were used in their actual configurations in a vertical frame and exposed to external heat flux values ($\dot{\mathbf{q}}_{\mathbf{e}}''$) of 20, 35 and 50 kW/m^2. Figure 2-1 shows an example of a test for the battery cover system. A small propane-air pilot flame was inserted in the stream of the pyrolysis gases at a time that was calculated from the ASTM E1354 Cone Calorimeter ignition data. For catching the burning pieces that fell during testing, a drip pan was used at the bottom of each part. In the tests, measurements were made for

- Time-to-ignition ($\mathbf{t_{ig}}$) in seconds;
- Heat release rate ($\dot{\mathbf{Q}}_{\mathbf{ch}}$) in kW and total heat released ($\mathbf{E_{ch}}$) in MJ;
- Generation rate of CO ($\dot{\mathbf{G}}_{\mathbf{CO}}$) in g/s and total CO generated ($\mathbf{W_{CO}}$) in g;
- Generation rate of smoke ($\dot{\mathbf{G}}_{\mathbf{sm}}$) in m^2/s and total smoke produced ($\mathbf{S_{sm}}$) in m^2;

- Total mass loss ($\mathbf{W_{fuel}}$) in g.

Figure 2-1 Burning of battery cover System in the ASTM E1623 ICAL. Figure is taken from Ref. 1.

Data quantified in the ASTM E1623 ICAL are listed in Table 2-1. Correlations between the heat release rates determined in the ASTM E1623 ICAL for the vehicle part systems and in the ASTM E1354 Cone Calorimeter and the ASTM E2058 Fire Propagation Apparatus (FPA) for the vehicle sample part systems, under similar heat flux exposure conditions, are shown in Fig. 2-2.

The data in Fig. 2.2 indicate that the heat release rate per unit surface area from the Cone Calorimeter is significantly lower than from the ICAL (only 42 % of ICAL). The heat release rate from the ICAL, on the other hand, is significantly lower than from the FPA (only 63% of FPA). These differences appear to be due to the melting behavior of the plastic part systems, as was noted for the differences in the heat release rates from the Cone and FPA (discussed in Volume III, Chapter I). The difference in the heat release rate for the melting type plastics in a horizontal configuration in both the Cone and FPA, is probably due to dripping and melting away of the plastic from the sample dish or the non-uniformity of the heat flux exposure (between the surface layer and bottom layer of the sample) in the Cone.

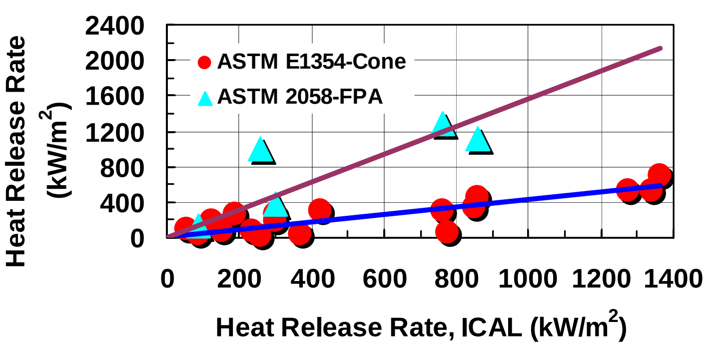

Figure 2.2 Correlation between the heat release rates from the ASTM E1623 ICAL for burning of part systems and from the ASTM E1354 Cone Calorimeter and the ASTM E2058 FPA for burning of samples part systems under similar heat flux conditions.

A similar trend is suggested for the data for $\mathbf{W_{fuel}}$ from the ICAL in Table 2-1. The $\mathbf{W_{fuel}}$ values appear to be low as $\Delta\mathbf{H_{ch}}$ and $\mathbf{y_{co}}$ values calculated from these values are high compared to the fire property data listed in Volume III (Appendix A-4). The low $\mathbf{W_{fuel}}$ values indicate removal of plastics from the burning zone due to dripping and melting away.

Since $\mathbf{W_{fuel}} = \mathbf{E_{ch}}/\Delta\mathbf{H_{ch}}$, it possible to calculate the $\mathbf{W_{fuel}}$ values from $\mathbf{E_{ch}}$ values listed in Table 2-1 and $\Delta\mathbf{H_{ch}}$ values from the fire property data (Volume III, Appendix A-4). The calculated $\mathbf{W_{fuel}}$ values are listed in Table 2-2., which are 1.1 to 2.3 times higher than the values listed in Table 2-1. Table 2-2 also lists the $\mathbf{y_{co}}$ and $\mathbf{y_{sm}}$ values based on the calculated $\mathbf{W_{fuel}}$ values. The $\mathbf{y_{sm}}$ values are obtained from $\mathbf{S_{sm}}$ in m^2 from Table 2-1 and the conversion relationship from Ref. 7. The $\mathbf{y_{co}}$ and $\mathbf{y_{sm}}$ values obtained in this fashion are in general agreement with the fire property data (Volume III, Appendix A-4).

These results indicate that burning of smaller samples of vehicle plastic parts provides as realistic results as obtained by burning the actual part systems. However, there is a need to be careful in testing, especially to avoid loss of sample by dripping for the melting plastics and lack of uniformity of the heat flux exposure of the regressing sample surface.

2.3 Vehicle Part Systems Burned in the "100-kW" and "500-kW" Calorimeters

The tests were performed by NIST in the "100-kW" and "500-kW" Calorimeters shown in Fig. 2-3 [2,3,4]. The hood of the "100-kW" Calorimeter was 1.22-m wide and was attached to a 0.23-m duct via a mixing section. The hood of the "500-kW" Calorimeter was 3.05-m wide and was attached to a 0.46-m duct via a mixing section of the same design as the "100-kW" Calorimeter. In both the Calorimeters, products were sampled twelve-duct diameters downstream of the mixing section (for uniformity and well-developed turbulent flow profile).

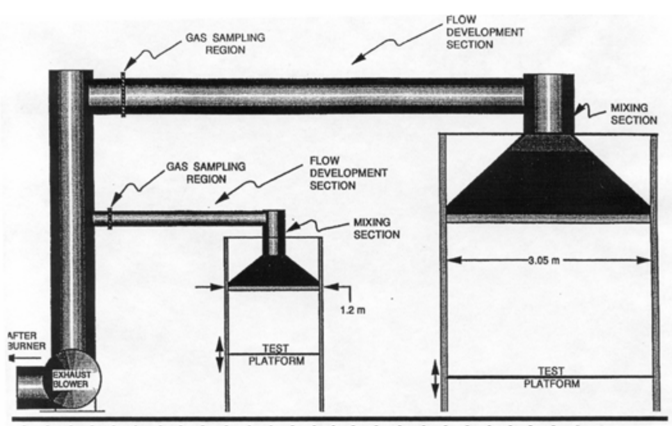

Figure 2-3 The "100-kW" and "500-kW"-Scale Calorimeters, described in detail in Ref. 2.

Table 2-1. Burning Test Data from the ASTM E1623 ICAL for Part Systems of 1996 Dodge Caravan and 1997 Chevrolet Camaro [1]

Part System	Plastic	Area (m^2)	$\dot{q}''_e$ (kW/m^2)	t_{ig} (s)	$\dot{Q}_{ch}$ (kW)	E_{ch} (MJ)	$\dot{G}_{sm}$ (m^2/s)	S_{sm} (m^2)	$\dot{G}_{co}$ (g/s)	Wco (g)	W_{fuel} (g)
1996 Dodge Caravan											
Battery Cover	PP	0.779	20	55	200	16	0.9	51	0.49	133	365
			35	19	288	16	2.1	92	0.76	383	401
			50	6	603	21	3.4	86	0.86	155	394
Air Ducts	PE or PP	0.520	20	123	447	132	8.4	1949	0.96	923	3027
			35	42	664	125	9.2	1880	0.92	989	2940
			50	21	709	123	11.1	1748	1.25	2025	2846
Sound Reduction Foam	PS	0.533	20	4	159	19	3.3	199	0.64	131	417
			35	7	159	14	7.7	290	1.05	157	397
			50	3	226	16	13.8	399	1.15	170	422
Hood Liner Face	PET	0.559	20	22	48	12	1.4	148	1.53	635	867
			35	10	84	16	5	133	1.66	590	887
			50	5	132	22	7.8	91	1.69	612	877
1997 Chevrolet Camaro											
Front Wheel Well Liner	PE, PP	0.393	20	115	161	50	2.3	555	0.65	429	1041
			35	40	495	51	6.3	691	1.24	468	1158
			50	20	802	55	9.7	530	1.2	345	1074
Windshield-laminate	Polyvinyl butyral	0.788	20	300	43	32	0.2	108	0.4	539	675
			35	120	100	32	0.7	110	0.82	1144	692
			50	66	148	45	1	171	0.8	1150	814

Table 2-2. Modified Burning Test Data from ICAL for 1996 Dodge Caravan and 1997 Chevrolet Camaro Part Systems

Part System	Plastic	Area (m^2)	$\dot{q}''_e$ kW/m^2	W_f (Calculated) g	W_{co} g	W_{sm} g	$\dot{Q}''_{ch}$ kW/m^2	y_{co} g/g	y_{sm} g/g
Battery Cover	PP	0.779	20	444	133	5.1	257	0.030	0.011
			35	444	383	9.1	370	0.086	0.021
			50	583	155	8.5	774	0.027	0.015
Air Ducts	PE, PP	0.520	20	3657	923	193.7	860	0.025	0.053
			35	3463	989	186.9	1277	0.029	0.054
			50	3407	2025	173.8	1363	0.059	0.051
Sound Reduction Foam	PS	0.533	20	722	131	19.8	298	0.018	0.027
			35	532	157	28.8	298	0.029	0.054
			50	608	170	39.7	424	0.028	0.065
Hood Liner Face	PET	0.559	20	909	635	14.7	86	0.070	0.016
			35	1212	590	13.2	150	0.049	0.011
			50	1667	612	9.0	236	0.037	0.005
1997 Chevrolet Camaro									
Front Wheel Well Liner	PE, PP	0.393	20	1613	429	55.2	410	0.027	0.034
			35	1645	468	68.7	1260	0.028	0.042
			50	1774	345	52.7	2041	0.019	0.030
Windshield Laminate	Polyvinyl butyral	0.788	20	1328	539	10.7	55	0.041	0.008
			35	1328	1144	10.9	127	0.086	0.008
			50	1867	1150	17.0	188	0.062	0.009

In the tests, each vehicle part system was burned in its normal orientation that it would have in a vehicle. The part system was supported in a manner approximating its normal means of support in the vehicle. For igniting the part system, a 10-cm diameter propane ring burner was used. The propane flow through the burner was set for a heat release rate of 7-W with a flame height of about 30-35-cm and was left on throughout the test. The ignition burner was placed 7.6-cm below the lower surface of the part system under test. A pan was placed 15-cm below the lower surface of the part system. The pan was made of 1.3-cm thick layer of cement fiberboard inside a 61-cm diameter steel pan placed on top of a load cell to measure the melting weight of the part system. The weight of the part system itself was also measured by a separate load cell.

For the assessment of heat flux (convective and radiative) transferred by the burning part system to the surrounding in a vehicle fire, three water-cooled total heat flux gages were used in each test. One heat flux gage was placed above and two gages on the side of the part system under test. In the tests, measurements were made for the total mass flow rate through the duct and mass oxygen depletion rate to determine the heat release rate, flame spread, flame heat flux, and rate of melting and vaporization of the plastic part system. The following 1996 Dodge Caravan and 1997 Chevrolet Camaro part system systems, listed Volume III (Appendix A-1), were tested by NIST [2,3,4]:

<u>1996 Dodge Caravan Part Systems</u>

1. Headliner (whole system, GJ42SK4);
2. Instrument panel (whole system, JF48SK);
3. Instrument panel shelf (whole system, PL98SX8);
4. Resonator (whole system, 4612512);
5. Air ducts (4678345);
6. Break fluid reservoir (whole system, 4683264);
7. Wire harness tube (4707580);
8. Windshield wiper structure (4716051);
9. Fender insulation, low and high density foams for sound reduction (4716345);
10. Hood liner (whole system, 4716832);
11. Wheel well cover, fuel tank shield (4716895);
12. HVAC unit door (whole system, 4734025, 4734033, 4734039, 4734041);
13. HVAC unit door (whole system, 4734042);
14. HVAC unit door cover (whole system, 4734063, 4734067);
15. HVAC unit (whole system, 4734071to 74, 80, and 81; 4734225, 4734367, 70, and 96; 4734650 and 51; 4734724);
16. Fuel tank (whole system, 4883140);
17. Headlights (4857041).

<u>1997 Chevrolet Camaro Part Systems</u>

1. Bumper: rear bumper fascia (10231299), energy absorber (16514312), and impact bar (20294219);
2. Body Front End: front wheelhouse panel liner (10296526), air inlet screen (10246204); front fender (10284967), hood insulator (10278015);
3. Cooling and Radiator: radiator inlet/outlet tank (52465340); engine coolant 22098787);
4. Underhood Plastic Accessories: power steering fluid reservoir (26024352);
5. Windshield: windshield laminate (10132027), defroster nozzle and air distributor (10277446);
6. Instrument Panel, Gages and Console: front door rear section (17997632), cluster (16215781), upper trim panel (10269102), trim panel (10274341), dash sound barrier (10282257), housing (16215781); dash panel insulator (10270975)
7. HVAC: 52458712 and 13, 52458713, 52458898, 52458938, 52458941, 52458960, 52458916, 52458965,72 and 76, 52461468, and 52464968;
8. Floor: carpet (10290204), drain plug (10208798);
9. Roof: headliner trim finish panel assembly, foam, fabric surface etc, 1027277772);
10. Rear quarter: inner trim finishing panel (10253673).

The measured data for the part systems are listed in Tables 2-3 and 2-4. These data indicate that there is a rapid-fire growth during the burning of the vehicle part systems accompanied by rapid melting. Thus, heat release rates appear to be mainly due to pool fires of molten plastics. In vehicle crash fires, pool diameters can be significantly larger than listed in Table 2-3 and thus the part systems could release heat in the MW range rather than the kW range listed in Table 2-3.

The effects of fire retardancy of plastic resins on the fire behavior of vehicle part systems were also examined in the "100-kW" and "500-kW" Calorimeters [4]. The fire retardant plastics[1] were the same as used in the mini-scale and small-scale tests (Volume III, Appendix A-2 and A-4)

[1] Plastic: PP/PE copolymer, untreated and treated with fire retardant (decabromodiphenylene oxide, antimony trioxide and zinc compounds). The fire-retarded part systems weigh 34 % more than the untreated part systems; 510 g versus 380 g. Fire retardants for nylon 66 parts were not known. The retarded nylon 66 weighed 19% more than the untreated nylon 66 (588 g versus 493 g).

Table 2-3. Fire Test Data for 1996 Dodge Caravan Part Systems [2]

Part System	Description	Rapid Melting Period (s)	Rapid Fire Growth Period (s)	Peak $\dot{Q}_{ch}$ (kW)	Pool diameter (cm)	Mass Loss (kg)	Melt weight (kg)
Battery PE/PP and PP	Isolated	1350-1800	1300-1420	21	15-16	1.2	0.2
	Plus cover		20-500	53	37-38		
	In heated box		30-310	88	30-35		
Air intake, PE, PP		193-200	100-200	85	40	0.9	0.9
Front headlamp, PC	Assembly	195-200	150-200	23		2.0	0.1
Master Cylinder		150-520	20-500	10		0.12	0.06
Wiper tray half, SMC	Driver's side		70-240	53			
	Passenger side		100-200	58			
Hood liner, half, PET	Driver's side		20-580	25			
	Passenger side		20-620	16			
Rear wheel, PP	Well liner	100-300	100-270	85	60	1.3	0.3
Fuel tank, PE	Empty	500-600	450-600	500		11.0	2.0
Instrument Panel, PC			340-430	670			
Seat (front)	Single passenger		120-200	540		8.0	
Head liner, nylon 6	Rear half		20-660	3			
	Front half		250-1150	14			

Table 2-4. Fire Test Data for 1997 Chevrolet Camaro Part Systems [3]

Part system	**Description**	**Rapid Fire Growth (s)**	$\dot{Q}_{ch}$ **(kW)**	**Observations**
Radiator, nylon 6,6	Outlet tank	120-180	18	Melting
	Fan belt	20-90	14	Melting
Power steering fluid reservoir, PE, PP	Half filled with the fluid	100-200	18	Fluid pool fire
Air inlet screen	Driver's side	50-125	23	Flaming, melt/drip
Front fender and wheel well cover, PE/PP	Driver's side	150-220	315	
Rear bumper	Energy absorber, EVA	70-400	28	Flaming melt/drip
	Facia, PU	80-160	440	
Hood liner, phenol/formaldehyde/fiber glass	Half sprayed with 50/50 coolant/water	20-60	12	
Interior Trim panel, PE/PP		100-400	118	Melt fire
Head liner		10-20	12	
Instrument panel	PS, ABS, SA	400-450	>580	

Table 2-5. Burning Data for the Treated and Untreated PE/PP and Nylon [4]

Plastic	**Untreated PE/PP**									**FR PE/PP**		**FR Nylon 66**	
Configuration	1		2		3	4		5		3		3	
Test[a]	1	2	1	2	1	1	2	1	2	1	2	1	2
Flaming melt/drip (s)	23		28		19	28	16	30	30	48	53		
Time-to-peak HRR (s)	120	120	120	110	100	120	110	650		160	190	150	150
Start of Pool fire (s)	400	350	220	220	380	300	350	400	300^b;650^b				
Pool fire diameter (cm)	25							60	30^b; 50^b				
Peak HRR (kW)	15	16	15	17	18	16	17	110	60^b; 95^b	6	5	11	13

HRR: heat release rate; **a**: repeat tests; **b**: test data at earlier and later stages of the pool fire

The treated and untreated PE/PP and nylon resins were molded into standard part systems[2] with concave and convex surfaces with a wall thickness of 2 to 3-mm. A pan was provided at the bottom so that any burning plastic melt that flows off the part systems might still contribute to fire growth on them. A 6.2-cm diameter ring burner was used to ignite the simulated part systems. Five burning configurations[3] were tested with isolated non-fire retarded PP part systems. The measured data are listed in Table 2-5.

Data in Table 2-5 indicate that the effects of the fire retardant on PE/PP are to reduce flaming melting/dripping behavior, reduce the fire growth (time to reach the peak heat release rate) and reduce the burning intensity (heat release rate). Burning of untreated PE/PP in the first four configurations provided similar results. In the fifth configuration, three part systems were used and thus the exposed surface areas were significantly larger than the first four configurations. The large surface areas resulted in large pool fires and high heat release rates, although flaming and dripping time and time to start of pool fire were comparable, but time to reach peak heat release rate was much longer.

The effects of flame retardant treatment of resins on the burning behavior of heating, ventilating and air conditioning (HVAC) units in a 1997 Chevrolet Camaro model were also examined [4]. Three HVAC units were burned, the non-fiber filled shells of the two units contained fire-retarded polypropylene and one contained non-fire retarded polypropylene. Slots were cut in the units to approximate the damage that might occur in a crash. In the test, the unit was slowly heated radiatively by a propane burner at 11 kW for first 5-minutes and then at higher radiant flux of 17-kW for the remainder of the test. At ten minutes of preheating, the HVAC unit was subjected to direct flame exposure from a 4-kW propane burner. The following results were observed:

---

[2] The standard part simulated the lower portion of a container from the engine compartment of a model sedan. It simulated the part that sits horizontally, opening upward, on top of the right front inner wheelhouse panel in the engine compartment. The standard part consisted of two separable sub-part systems, the double container section and a roughly U-shaped leg section. The leg section was attached to the bottom of the deeper container by two rivets. At the top, the maximum dimensions of the roughly rectangular top opening were 0.21-m x 0.24-m (8-in x 9-in) with a maximum depth of 0.10-m (4-in).

[3] First Configuration: igniter flame (2.4-kW) on both sides of the deeper container portion of the part. Second Configuration: igniter flame (2.4-kW) on a deep cleft in the part structure separating its two containers; Third and Fourth Configurations: a metal plate functioned as a substitute for the non-combustible sub-part systems within or associated with some vehicle components. Plastic melt was retained on the metal plate. Igniter flame was 2.4-kW in intensity; Fifth Configuration: three part systems packed within an enclosure 941-cm square, 64-cm high with 5-cm gap at the top and bottom) and ignited by a 6-kW burner.

- <u>HVAC unit made of untreated PP</u>: flames were visible within the portion of the unit rearward of the forward bulkhead (inside the passenger compartment) within 135 seconds of the start of the igniter. The heat release rate from the overall fire reached 200 kW before being terminated at 283 seconds after ignition.
- <u>Two HVAC units made of fire retarded PP</u>: there was no evidence of flames in the passenger compartment and fire growth within the units was confined to the engine compartment components. The heat release rates from the two HVAC units made of fire retarded PP was less than about 5 kW. Thus, the fire retardant treatment was effective.

2.4 Fire Retarded and Non-Fire Retarded HVAC Units Burned in the Fire Products Collector

Tests were performed by FM Global in the Fire Products Collector, shown in Fig. 2-4 (right side in the back) [5,6]. The FPC has a fire products collection funnel 6.1-m in diameter, a 0.9-m diameter orifice plate, and a vertical stainless steel sampling duct with a diameter of 1.5 m. The sampling duct is connected to the air pollution control system of the Burn Laboratory at the Research Campus of FM Global. The blower of the air pollution control system induces the airflow through the sampling duct. Air enters the sampling duct via the orifice plate.

Figure 2-4 The Fire Products Collectors at FM Global. Collector in the back right side was used in the tests. Details are described in Ref. 5.

The heat and products generated during the test are captured in the sampling duct of the FPC, where measurements are made for the temperature, linear velocity, optical transmission, and chemical composition of the product-air mixture about six duct diameters from the orifice plate. These measurements are used to calculate the heat release rate and generation rates of fire products including smoke.

Three HVAC units for a 1999 Honda were examined in the FPC tests: one control and two HVAC units treated with different fire retardants, identified as TFCTYA2 and SFCTAE.

Each HVAC unit was 9 kg in weight and was about 1.5-ft (0.46-m) wide and 3.5-ft (1.1-m) long. Each unit was ignited by 1450-ml of heptane contained in a 9 square inch (230-mm square) and 1-in (45-mm) deep pan, that burned for about 11 minutes with a heat release rate of 80-kW. In the tests, heat release rate and generation rates of CO, CO_2, hydrocarbons, and smoke were measured. From the load cell data, mass loss rate was derived. The data from these tests are plotted in Figs. 2-5 and 2-6.

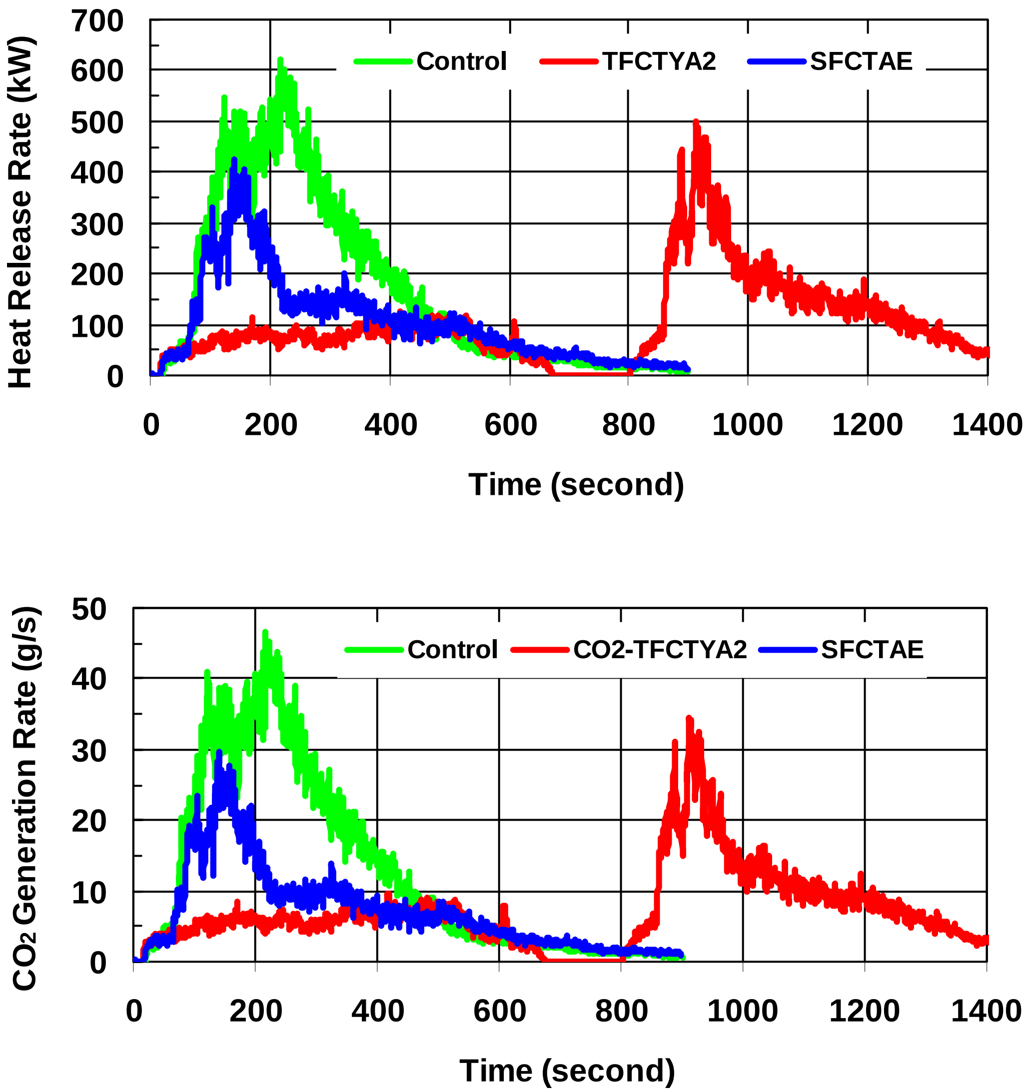

Figure 2-5 Heat release rate and generation rate of CO_2 in the burning of non-fire retarded (control) and fire retarded (TFCTYA2 and SFCTAE) HVAC units for a 1999 Honda in the Fire Products Collector.

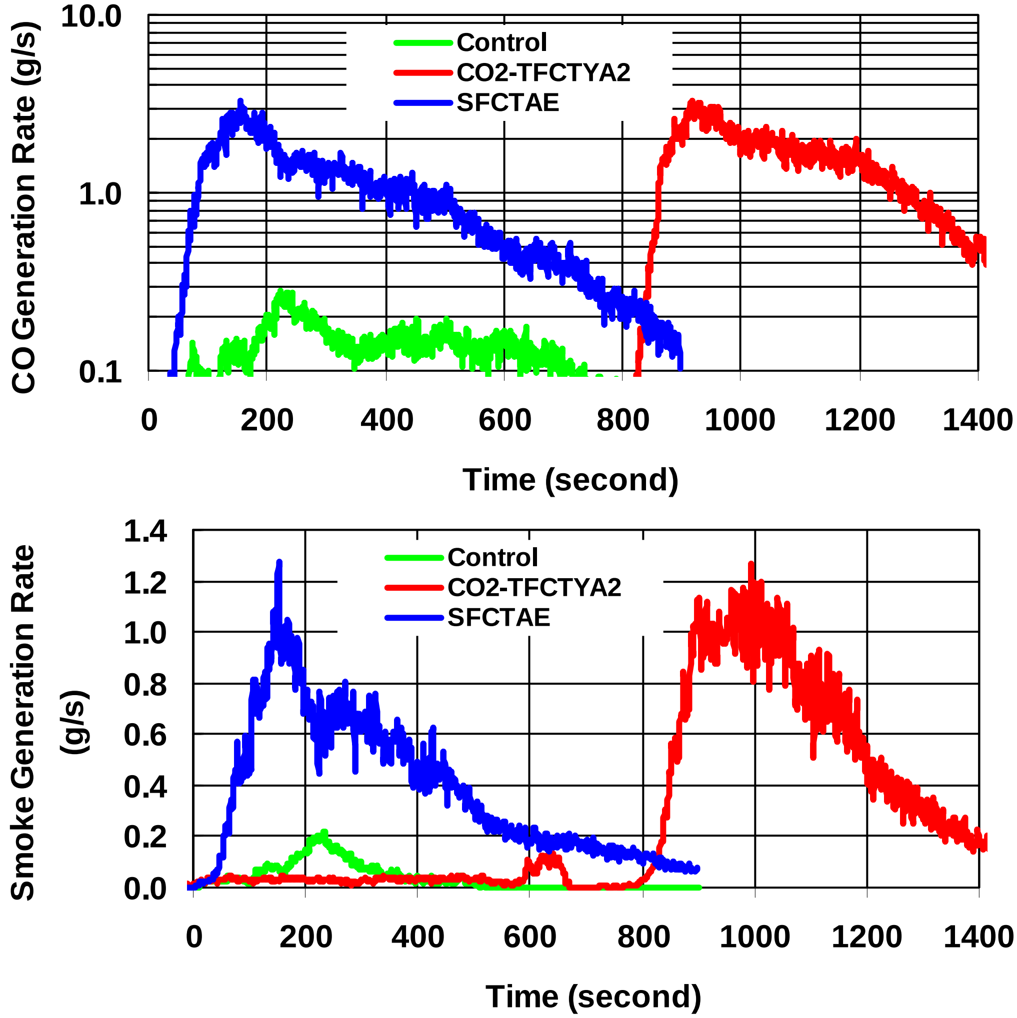

Figure 2-6 Generation rates of CO and smoke in the burning of a non-fire retarded (control) and a fire retarded (TFCTYA2 and SFCTAE) HVAC unit for a 1999 Honda in the Fire Products Collector.

Data in Figs. 2-5 and 2-6 show that:

- Heat release rate and generation rate of CO_2 are reduced slightly by the fire-retardant treatments of the HVAC units. Fire growth for the TFCTYA2 treated HVAC unit is reduced significantly;
- Release rates of CO and smoke are increased significantly by the fire-retardant treatments of the HVAC units.

The fire-retardant treatments of the HVAC units appear to be effective in reducing the fire growth; however, the peak burning intensity is reduced only slightly and thus in a crash fire, it will not be able to resist the penetration of flame into the passenger compartment.

NOMENCLATURE

$\mathbf{E_{ch}}$	Total heat released (MJ)
$\dot{\mathbf{G}}_{\mathbf{j}}^{''}$	Generation rate of product j per unit plastic surface area (g/m^2-s)
$\dot{\mathbf{q}}_{\mathbf{e}}^{''}$	External heat flux per unit surface area of the plastic (kW/m^2)
$\dot{\mathbf{q}}_{\mathbf{n}}^{''}$	Net heat flux to the plastic surface (kW/m^2)
$\dot{\mathbf{Q}}_{\mathbf{ch}}^{''}$	Chemical heat release rate per unit surface area of the plastic (kW/m^2)
$\mathbf{S_{sm}}$	Total; smoke produced (m^2)
$\mathbf{t_{ig}}$	Time to ignition (seconds)
$\mathbf{W_f}$	Total mass loss (g)
$\mathbf{W_i}$	Total mass of product j (g)

Subscripts

ch	Chemical
ig	Ignition
j	Product
sm	Smoke

Superscripts

.	per unit of time (1/s)
“	per unit area (1/m^2)

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CHAPTER III

FIRE BEHAVIOR OF CRASHED MOTOR VEHICLES

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3.1 INTRODUCTION

The fire behavior of crashed motor vehicles was examined by performing vehicle burn tests after the vehicle crash tests. The Following is the list of the vehicle burn tests (each test is described in Appendix B):

1. 1996 Dodge Caravan (13-Nov-1996)-front crash and ignition [1];
2. 1996 Plymouth Voyager (15-Nov-1996)-rear crash and ignition [2];
3. 1997 Chevrolet Camaro (30-Sept-1997)-rear crash and ignition [3];
4. 1997 Chevrolet Camaro (01-Oct-1997)-front crash and ignition [4];
5. 1998 Ford Explorer (09-June-1998)-rear crash and ignition [5];
6. 1998 Ford Explorer (11-June-1998)- front crash and rear ignition [6];
7. 1998 Honda Accord (23-Feb-1999)-front crash and ignition; [7];
8. 1998 Honda Accord (25-Feb-1999)-rear crash and ignition [8];
9. 1999 Chevrolet Camaro-Control (17-Feb-2000)-front crash and ignition [9];
10. 1999 Chevrolet Camaro-FR HVAC (21-Feb-2000) [9];
11. 1999 Ford Explorer-intumescent paint coated underbody (February 23, 2000) [10].
12. 1999 Honda- fire suppression systems (August 10, 1999) [11];

The following fire behaviors were examined in the burn tests:

1) Ignition and flame spread characteristics for flames to penetrate the passenger compartment and create untenable conditions;
2) Effectiveness of fire retardant treatments of the HVAC units as a blocker for flames to penetrate from the engine compartment to the passenger compartment;
3) Effectiveness of intumescent painting of underbody of a vehicle for blocking the flames to penetrate from the underbody to the passenger compartment;
4) Fire suppression.

The vehicle crash tests were performed at the GM Proving Ground and the crashed vehicle burn tests were performed at FM Global using the Fire Products Collector (FPC), shown in Fig. 3-1 [1-10]. The FPC consists of a fire products collection funnel 6.1-m in diameter, a 0.9-m diameter orifice plate, and a vertical stainless steel sampling duct with a diameter of 1.5 m. The sampling duct is connected to the air pollution control system. The blower of the air pollution control system induces the airflow through the sampling duct. Air enters the sampling duct via the orifice plate.

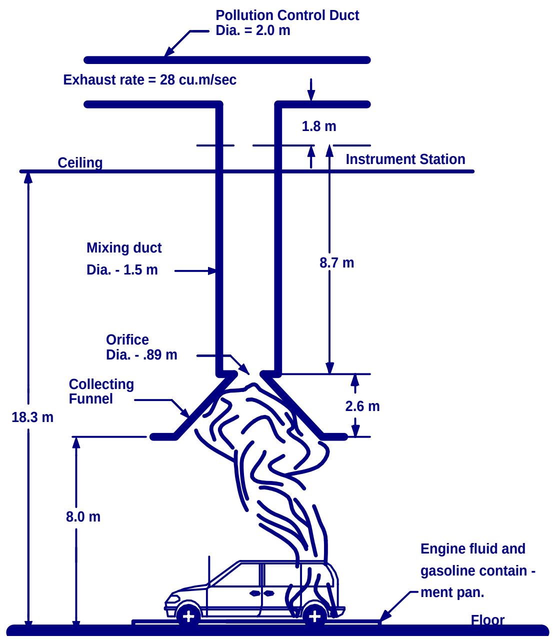

Figure 3-1. Schematic diagram of a large-scale vehicle burn test initiated by gasoline pool fire in the rare of the vehicle under the Fire Products Collector.

In the test, the crashed vehicle was placed in a 7.6-m long, 4.6-m wide and 0.10-m deep steel fluid containment pan under the FPC. The pan was fabricated from two sheets of carbon steel[1]. The bottom of the pan was lined with concrete landscaping paving blocks on a level bed of sand[1]. The pan was placed on top of a load cell. For each vehicle, two tests were performed, one for the front crashed vehicle and the other for the rear crashed vehicle. The fire was started artificially simulating three typical ignition processes that could occur in vehicle crashes:

1) Shorting of the battery and ignition of the plastic parts of the battery in the front crash tests;
2) Sprays of engine compartment fluids touching hot metal parts of the engine and igniting, pooling and burning of the fluids under the engine in the front crash tests;
3) Gasoline pool fires burning under the vehicle in rear crash tests.

The burn tests were terminated at a time at which untenable conditions[2] were reached in the passenger compartment.

[1] This is only a general description of the fluid containment pan. For exact description, original references should be consulted.
[2] The untenable conditions were defined as [1-10]: 1) air temperature between the front seats at the height of an adult occupant exceeding 200 °C and rising rapidly in the passenger compartment, or 2) CO concentration in the passenger compartment exceeding 1 % and rising rapidly, or 3) flames visibly impinging on one or both front seats, or 4) the head-liner is flaming over the forward occupant position, or 5) flashover in the passenger compartment is imminent.

In the crash tests, observations were made for the possible mode of ignition and location so that they could be simulated in the crashed vehicle burn tests. In the vehicle burn tests, detailed records were obtained by the video cameras located both inside and outside the test vehicle. Thermal radiation signatures from the burning vehicle were measured using the infrared imaging systems (IR cameras), also located inside and outside the test vehicle. Flame spread in areas not visible to the video or IR cameras, such as the instrument panel, was tracked by thermocouples and heat flux transducers installed in the test vehicle before the test. The air temperature in the passenger compartment was measured by the aspirated thermocouple probe assemblies containing six shielded thermocouples. Pressure measurements were made to determine the pressure gradient across the dash panel and airflow through the driver's side window[3] during the test. Heat transfer to six locations in the passenger compartment was measured using differential flame thermometers. The gaseous combustion products in the passenger compartment were measured by the FTIR gas analysis of products, sampled continuously from the passenger compartment during the test and by the GC/MS analysis of the grab-samples acquired from the passenger compartment during the test. Weight of smoke was determined by using the filter paper weighing technique [4-10].

All the heat and products generated during the test were captured in the sampling duct of the FPC, where measurements were made for the temperature, linear velocity, optical transmission, and chemical composition of the product-air mixture about six duct diameters from the orifice plate. These measurements were used to determine the release rates of chemical and convective heat, CO, CO_2, hydrocarbons, and smoke. Release rate of fuel vapors were determined from the load cell data that were measured during some of the tests [1-10].

Measurements for the temperature, gas concentrations, heat flux, and velocity were used to estimate hazards to the passengers. Estimations for thermal hazards (skin burn) were made using "BURNSIM"- a burn hazard assessment model [12]. Estimations for the non-thermal hazards (incapacitation and lethality) were made using FAA's Combined Hazards Survival Model [13] and Purser's hazard model [14]. In addition, CFD modeling was performed for the characterization of the hazard posed by heat and exposure to toxic agents associated with the post-crash vehicle fire in a minivan [15].

[3] Windows that were broken or opened during the crash tests were not replaced (see details for each test in Appendix B).

3.2 VEHICLE BURN TEST DATA

3.2.1 Test #1: Propagation of Engine Compartment Fire (1996 Dodge Caravan)

The test information is listed in Appendix B, Section B-1 [1]. The test was performed on November 13, 1996. Following were observed for the penetration of the flame into the passenger compartment in the test [1]:

1. About 270 Seconds Post Ignition: a triangular section of the windshield fell onto the top of the instrument panel, leaving a roughly 15-cm wide hole in the windshield in front of the steering wheel. The size of the hole increased horizontally by a factor of about three and vertically by a factor of about two as several pieces of windshield fell inward over the next 120 seconds;
2. About 360 to 420 Seconds Post Ignition: the instrument panel ignited and flames spread laterally to the right and to the left and downward to the underlying defroster duct assembly over next several seconds. The hot gases were drawn out of the passenger compartment through the windshield hole reducing the flame spread rate in the passenger compartment. Smoke from the engine compartment entered the passenger compartment through the openings in the forward bulkhead;
3. About 420 to 480 Seconds Post Ignition: pieces of flaming windshield fell into the right side of the passenger compartment, igniting the top of the instrument panel, the carpet in front of the passenger seat, the deployed passenger airbag, and in the inboard armrest of the passenger seat. The air temperature between the driver and the passenger in the front, 2.5-cm below the headliner increased from about 50 ^{o}C to > 100 ^{o}C, whereas the temperature 41-cm below the headliner was only 32 ^{o}C. The gas concentrations measured 15-cm below the headliner, also between the driver and the passenger in the front, started to increase;
4. About 540 to 630 Seconds Post Ignition: the vapors in the passenger compartment ignited and flames began to emerge from the driver's door window stating at 600 seconds. Rapid expansion of gases in the burning zone led to an efflux of gases through the top of the window opening in the driver's door and inflow of air through the bottom of the window opening;

5. About 645 to 660 Seconds Post Ignition: interior of the vehicle was approaching the flashover stage when the test was ended.

Data measured in the test are summarized in Table 3-1 for the concentrations of products in the passenger compartment and release rates of heat and products (and their concentrations) in the fire plume just before time to untenable/flashover[4] (**$t_{u,fl}$**) conditions. The **$t_{u,fl}$** value is estimated to be 645 seconds (see Chapters IV and V for details of the **$t_{u,fl}$** estimation).

Table 3-1. Concentrations of Products and Release Rates of Heat and Products Just Before Time to Untenable/Flashover Conditions for Test #1

Measurement		Passenger Compartment	Fire Plume
Concentration	CO (ppm)	1,370	41
	CO_2 (ppm)	20,770	2,831
	CH_4 (ppm)	165	
	C_2H_4(ppm)	230	
	C_2H_2(ppm)	145	
	HCN(ppm)	52	
	NO(ppm)	25	
	HCl(ppm)		
	Smoke (mg/m^3)		
Generation Rate	Heat (MW)		1.25
	CO (g/s)		0.99
	CO_2 (g/s)		93
	Smoke (g/s)		

3.2.2 Test #2: Propagation of Underbody Gasoline Pool Fire (1996 Plymouth Voyager)

The test information is listed in Appendix B, Section B-2 [2]. The test was performed on November 15, 1996. Following were observed for the penetration of the flame into the passenger compartment in the test [2]:

1. Between 10 and 15 Seconds Post Ignition: flames began to emerge in the wheelhouse, impinging directly upon the wheelhouse splash shield;
2. About 60 Seconds Post Ignition: polypropylene was observed dripping from the splash shield (2-mm thick polypropylene + 2% inorganic filler with a melting point of 166 ^oC);

[4] The vehicle burn tests were terminated just before the occurrence of the flashover and thus in many burn tests, actual flashover was not observed.

3. About 60 to 90 Seconds Post Ignition: the splash shield sagged onto the left rear tire. Flames began to fill the left rear wheelhouse. A fire plume was observed outside the left rear wheelhouse. Hot gases started to enter the weld-seams around the left rear wheelhouse, heating the upper left corner of the back panel of the second bench seat cover and left edge of the window opening in the liftgate;
4. About 80 to 120 Seconds Post Ignition: flames spread from the splash shield to the left rear tire and igniting it. The height of the fire plume emerging from the wheelhouse also increased. The top of the flames reached the lower edge of the quarter vent glass. Flames entered the passenger compartment through the split weld-seams around the left rear wheelhouse and through the left quarter vent. The flames ignited the second bench seat and the left quarter trim panel. A thick gray plume of smoke started to emerge from inside of the test vehicle. The density of smoke column increased over the next 20 to 25 seconds;
5. By about 130 Seconds Post Ignition: flames along the interior surface of the vent glass sporadically reached the top of the quarter vent. The angled glass appeared to direct a portion of the fire plume into the passenger compartment through the left quarter vent;
6. Between 135 to 140 Seconds Post Ignition: flames were visible through the left side of the liftgate;
7. About 150 Seconds Post Ignition: some plastics inside the passenger compartment had ignited;
8. By about 155 Seconds Post Ignition: the tops of the flames were consistently above the top of the test vehicle and flames appeared to enter the left quarter vent continuously;
9. Between about 170 and 180 Seconds Post Ignition: flames started to spread laterally to the right across the rear of the headlining;
10. By about 190 Seconds Post Ignition: the flame front had moved forward along the headlining to a line above the backs of the front seats;
11. Between 180 and 195 Seconds Post-Ignition: flames moved from the left to the right side of the headlining. Flames had disappeared from the left side of the headlining by 195 seconds. Most of the combustible plastics in the headlining were consumed in about 20 to 30 seconds after its ignition.
12. About 210 Seconds Post Ignition: manual fire suppression using a water spray and a dry powder fire suppressant was started.

Data measured in the test are summarized in Table 3-2 for the concentrations of products in the passenger compartment and release rates of heat and products (and their concentrations) in the fire plume just before time to untenable/flashover[5] (**$t_{u,fl}$**) conditions. The **$t_{u,fl}$** value is estimated to be 210 seconds (see Chapters IV and V for details of the **$t_{u,fl}$** estimation).

Table 3-2. Concentrations of Products and Release Rates of Heat and Products Just Before Time to Untenable/Flashover Conditions for Test #2

Measurement		Passenger Compartment	Fire Plume
Concentration	CO (ppm)	4,244	109
	CO_2 (ppm)	122,500	2,927
	CH_4 (ppm)	602	
	C_2H_4(ppm)	784	
	C_2H_2(ppm)	827	
	HCN(ppm)	103	
	NO(ppm)	66	
	HCl(ppm)		
	Smoke (mg/m^3)		45
Generation Rate	Heat (MW)		1.89
	CO (g/s)		3.23
	CO_2 (g/s)		139
	Smoke (g/s)		1.12

3.2.3 Test #3: Propagation of Underbody Gasoline Pool Fire (1997 Chevrolet Camaro)

The test information is listed in Appendix B, Section B-3 [3]. The test was performed on September 30, 1997. Following were observed for the penetration of the flame into the passenger compartment in the test [3]:

1. Flames into the passenger compartment propagated simultaneously along three pathways due to elongated shape and location of the gasoline pool fire under the vehicle :

   a) Through the crash-induced seam openings between the rear floor pan panel and left rear inner quarter panel;

   b) Through a gap between the back of the driver's door and the door frame that was created by damage to the vehicle sustained during the crash test and

[5] The vehicle burn tests were terminated just before the occurrence of the flashover and thus in many burn tests, actual flashover was not observed.

c) Through a drain hole in the floor panel;

2. Between 10 and 20 seconds post ignition, flames entered the passenger compartment in the area behind the displaced left quarter interior trim finishing panel. By 30 seconds post ignition, flames had reached the left rear corner of the headlining panel and had started to spread forward and to the right along its lower surface;
3. Between 155 and 170 seconds post ignition, left rear floor pan drain-hole plug burned through. Heated gases and flames that entered the drain-hole under the left rear seat cushion. Flames spread between the carpet and the floor pan to the right and upward along the vertical section of the pan behind the rear seat back;
4. Between 160 and 170 seconds post ignition, flames were observed behind the left interior quarter trim finishing panel;
5. By 180 seconds post ignition, flames were visible between the front of the left interior quarter trim finishing panel and the driver's seat back;
6. By 190 seconds post ignition, flames started to spread forward and to the right along the headlining panel;
7. Between about 185 and 200 seconds, flames were visible in front of the middle of the rear seat back as flames had burned through a drain-hole plug in the front floor pan panel;
8. At about 199 seconds, fire suppression was started.

Data measured in the test are summarized in Table 3-3 for the concentrations of products in the passenger compartment and in the fire plume and release rates of heat and products just before just before time to untenable/flashover[6] ($\mathbf{t_{u,fl}}$) conditions. The $\mathbf{t_{u,fl}}$ value is estimated to be 199 seconds (see Chapters IV and V for details of the $\mathbf{t_{u,fl}}$ estimation).

[6] The vehicle burn tests were terminated just before the occurrence of the flashover and thus in many burn tests, actual flashover was not observed.

Table 3-3. Concentrations of Products and Release Rates of Heat and Products Just Before Untenable/Flashover Conditions for Test #3

Measurement		Passenger Compartment	Fire Plume
Concentration	CO (ppm)	4,797	45
	CO_2 (ppm)	123,100	1,776
	CH_4 (ppm)	464	
	C_2H_4(ppm)	2,221	
	C_2H_2(ppm)	2,198	
	HCN(ppm)	64	
	NO(ppm)	48	
	HCl(ppm)		
	Smoke (mg/m^3)		24
Generation Rate	Heat (MW)		0.98
	CO (g/s)		1.20
	CO_2 (g/s)		63
	Smoke (g/s)		0.55

3.2.4 Test #4: Propagation of Engine Compartment Fire (1997 Chevrolet Camaro)

The test information is listed in Appendix B, Section B-4 [4]. The test was performed on October 1, 1997. Following were observed for the penetration of the flame into the passenger compartment in the test [4]:

1. Flame spread into the passenger compartment progressed along two pathways simultaneously: a) through the windshield and b) through the HVAC module in the dash panel, both of which were broken in the crash test. Flame spread was observed for the fluids under the vehicle, into the passenger compartment through the windshield and the dash panel;
2. Between 180 and 240 seconds post ignition, flames began to contact the windshield, when flames emerged from the engine compartment along the rear edge of the deformed hood. Increase in the temperature of the exterior surface of the windshield caused softening and stretching of the inner layer of the windshield;
3. Between 665 and 670 seconds post ignition, lower portion of the windshield sagged onto the instrument panel top cover. Pieces of broken windshield continued to fall into the passenger compartment until the test was ended. The instrument panel, the deployed passenger airbag and the front passenger seat cushion were charred, where pieces of the windshield fell onto these objects;

4. Between 720 and 780 seconds post ignition, flames spread rearward on the top of the right side of the instrument panel;
5. At about 895 seconds post ignition, flames emerge through the defroster outlet in the instrument panel trim panel;
6. The test was ended at 950 seconds post ignition.

Data measured in the test are summarized in Table 3-4 for the concentrations of products in the passenger compartment and in fire plume and release rates of heat and products just before the time to untenable/flashover ($\mathbf{t_{u,fl}}$) conditions. The $\mathbf{t_{u,fl}}$ value is estimated to be 950 seconds (see Chapters IV and V for details of the $\mathbf{t_{u,fl}}$ estimation).

Table 3-4. Concentrations of Products and Release Rates of Heat and Products Just Before Time to Untenable/Flashover Conditions for Test #4

Measurement		**Passenger Compartment**	**Fire Plume**
Concentration	CO (ppm)	1,100	32
	CO_2 (ppm)	3,500	1,512
	CH_4 (ppm)	262	
	C_2H_4(ppm)	353	
	C_2H_2(ppm)	281	
	HCN(ppm)	11	
	NO(ppm)	5	
	HCl(ppm)		
	Smoke (mg/m^3)	67	19
Generation Rate	Heat (MW)		0.89
	CO (g/s)		0.85
	CO_2 (g/s)		66
	Smoke (g/s)		0.45

3.2.5 Test #5: Propagation of Underbody Gasoline Pool Fire (1998 Ford Explorer)

The test information is listed in Appendix B, Section B-5 [5]. The test was performed on June 9, 1998. Following were observed for the simultaneous penetration of flames into the passenger compartment along a number of pathways in the test [5]:

1. By 25 seconds post ignition, heated gases started to accumulate along the roof trim panel in the rear compartment. Flames burned through two drain holes, covered with ethylene-

propylene-butadiene rubber plugs, in the floor panel in the rear compartment of the test vehicle;

2. By 100 to 200 seconds post ignition, temperatures above the broken left quarter trim panel were greater than 150 ^oC;
3. By about 125 seconds post ignition, flames were first observed on the headliner in the space above the left rear quarter wheelhouse;
4. Between about 140 and 160 seconds, flames spread into the rear compartment through a crash induced seam opening between the rear-compartment floor panel and left wheelhouse panel. Flames were observed above the left rear wheelhouse at this time.
5. Between 150 and 157 seconds post ignition, flames first contacted the headliner in the rear left corner of the headliner with flames spreading along the headliner to the right side of the rear compartment and forward to above the rear seats;
6. The test was ended at 170 seconds post ignition.

Data measured in the test are summarized in Table 3-5 for the concentrations of products in the passenger compartment and in fire plume and release rates of heat and products just before the time to untenable/flashover ($\mathbf{t_{u,fl}}$) conditions. The $\mathbf{t_{u,fl}}$ value is estimated to be 170 seconds (see Chapters IV and V for details of the $\mathbf{t_{u,fl}}$ estimation).

Table 3-5. Concentrations of Products and Release Rates of Heat and Products Just Before Time to Untenable/Flashover Conditions for Test #5

Measurement		Passenger Compartment	Fire Plume
Concentration	CO (ppm)	2,500	87
	CO_2 (ppm)	40,000	2,407
	CH_4 (ppm)	400	
	C_2H_4(ppm)	800	
	C_2H_2(ppm)	500	
	HCN(ppm)	NR	
	NO(ppm)	10	
	HCl(ppm)		
	Smoke (mg/m^3)	1,548	27
Generation Rate	Heat (MW)		1.19
	CO (g/s)		2.31
	CO_2 (g/s)		88
	Smoke (g/s)		0.88

3.2.6 Test #6: Propagation of Mid-Underbody Gasoline Pool Fire (1998 Ford Explorer)

The test information is listed in Appendix B-6 [6]. The test was performed on June 11, 1998. Flame spread into the passenger compartment occurred through a number of openings in the floor panel: a) through the electrical pass-through openings in the floor panel under the left front seat and 2) through the drain holes in the floor panel and heat conduction through the floor panel. Following were observed during the penetration of the flame into the passenger compartment in Test #6:

1. From about 10 to 185 seconds post ignition, flame was present under the floor carpet under the left front seat that had burned, charred, and consumed by the fire. Flames entered the electrical pass-through opening where the grommet had dislodged during the crash test. At about 75 seconds post ignition, flames burned through the grommet that was not dislodged from the electrical pass-through under the left front seat. At about 205 seconds post ignition, flames had burned through the carpet above this pass-through opening;
2. Between about 190 and 195 seconds post ignition, a fire plume was observed between the inboard side of the left seat cushion and the center console;
3. Between 235 and 250 seconds post ignition, flames burned through the left front seat cushion;
4. Between about 250 and 255 seconds post ignition, maximum temperature of the floor panel was 582 ^{o} C. Floor carpet over the drive train tunnel under the center console was burned, charred, and consumed by the fire;
5. Between 250 to 260 seconds post ignition, test was ended and fire suppression was started.

Data measured in the test are summarized in Table 3-6 for the concentrations of products in the passenger compartment and in fire plume and release rates of heat and products just before time to untenable/flashover ($\mathbf{t_{u,fl}}$) conditions. The $\mathbf{t_{u,fl}}$ value is estimated to be 250 seconds (see Chapters IV and V for details of the $\mathbf{t_{u,fl}}$ estimation).

Table 3-6. Concentrations of Products and Release Rates of Heat and Products Just Before Time to Untenable/Flashover Conditions for Test #6

Measurement		Passenger Compartment	Fire Plume
Concentration	CO (ppm)	1,600	50
	CO_2 (ppm)	38,000	513
	CH_4 (ppm)	300	
	C_2H_4(ppm)	470	
	C_2H_2(ppm)	450	
	HCN(ppm)	40	
	NO(ppm)	30	
	HCl(ppm)		
	Smoke (mg/m^3)	1,350	28
Generation Rate	Heat (MW)		0.60
	CO (g/s)		1.55
	CO_2 (g/s)		44
	Smoke (g/s)		0.54

3.2.7 Test #7: Propagation of an Engine Compartment Fire (1998 Honda Accord)

The test information is listed in Appendix B-7 [7]. The test was performed on February 23, 1999. Flames spread into the passenger compartment through the windshield and the pass-through openings in the left side of the dash panel. Flames entering the passenger compartment via pass-through openings in the dash panel ignited components in the left side of the instrument panel. Flame spread through the windshield progressed by: 1) flame spread rearward along the top of the instrument panel and 2) ignition of the interior components by pieces of windshield with the inner layer burning and falling into the passenger compartment.

Following were observed during the penetration of the flame into the passenger compartment:

1. <u>Flame Spread into the Passenger Compartment through the Windshield</u>
   a. About 420 seconds post ignition, left corner of the windshield exposed to heated gases from the fire;
   b. About 1320 seconds post ignition, a section of the windshield in front of the left front seat was exposed to flames from the burning HVAC air intake cowl;
   c. Between about 1320 and 1440 seconds post ignition, a hole developed in the lower left side of the windshield in front of the steering wheel. Flames from the engine

compartment entered the passenger compartment through this hole and spread upward along the interior surface of the windshield, igniting the windshield inner-layer around the hole and in an area where pieces of glass were dislodged from the windshield and the inner-layer was exposed;

d. Between about 1380 and 1410 seconds post ignition: pieces of windshield with the inner layer burning started to fall into the passenger compartment;
e. Between 1470 and 1500 seconds post ignition, a section of windshield sagged onto the left side of the instrument panel.

2. Flame Spread Rearward Along the Top of the Instrument Panel

a. Between about 1380 and 1410 seconds post ignition, forward edge of the left side of the instrument panel ignited. This occurred in the same area where holes developed along the lower edge of the windshield between about 1320 and 1440 seconds post ignition;
b. Between about 1410 and 1500 seconds post ignition, flames spread to the right across the front of the instrument panel;
c. Between about 1410 and 1620 seconds post ignition, flames spread rearward on the center of the instrument panel, coincident with the timing of holes developing in the center of the windshield;
d. Between about 1530 and 1560 seconds post ignition, flames spread to the right on the forward section of the instrument panel and ignited the deployed passenger side air bag.

3. Ignition of the Front Seats, Center Console and Steering Wheel

a. At about 1620 seconds post ignition, pieces of burning windshield inner-layer fell into the passenger compartment and ignited the deployed passenger side air bag, the floor carpet in the front of the right front seat, the front seat cushions, the steering wheel cover, and the center console.

4. Flame Spread into the Passenger Compartment through the Left Inner Hinge Pillar

The upper left corner of the insulation on the interior of the dash panel was burned and charred.

5. Heat and Fire Damage to the Headlining Panel and Front Seats

   a. The pattern of heat and fire damage to the roof trim panel, temperature profiles along the lower surface of the headlining panel and the data recorded by the aspirated thermocouple assembly located in the passenger compartment, indicated that a burning upper layer did not develop in the passenger compartment during the test.

6. At about 1620 post ignition, test was ended and fire suppression was started.

Data measured in the test are summarized in Table 3-7 for the concentrations of products in the passenger compartment and in fire plume and release rates of heat and products just before the time to untenable/flashover ($\mathbf{t_{u,fl}}$) conditions. The $\mathbf{t_{u,fl}}$ value is estimated to be 1620 seconds (see Chapters IV and V for details of the $\mathbf{t_{u,fl}}$ estimation).

Table 3-7. Concentrations of Products and Release Rates of Heat and Products Just Before Time to Untenable/Flashover Conditions for Test #7

Measurement		Passenger Compartment	Fire Plume
Concentration	CO (ppm)	440	
	CO_2 (ppm)	12,500	1,316
	CH_4 (ppm)	30	
	C_2H_4(ppm)	45	
	C_2H_2(ppm)	28	
	HCN(ppm)	NR	
	NO(ppm)	18	
	HCl(ppm)		
	Smoke (mg/m^3)	6,224*	43
Generation Rate	Heat (MW)		1.13
	CO (g/s)		
	CO_2 (g/s)		84
	Smoke (g/s)		1.20

*: smoke concentration appears to be too high.

3.2.8 Test #8: Propagation of an Underbody Gasoline Pool Fire (1998 Honda Accord)

The test information is listed in Appendix B-8 [8]. The test was performed on February 25, 1999. Flame spread into the passenger compartment occurred through the crashed induced seam openings around the left and right wheelhouses simultaneously in the rear of the vehicle. These flames entering the passenger compartment ignited several items in the rear: 1) left side of the seat back, 2) left seat belt, 3) left side of the shelf trim panel, 4) right seat back bolster, and 5) interior trim panel on the right rear pillar.

Following were observed during the penetration of the flame into the passenger compartment:

1) By 10 seconds post ignition, smoke and hot gases started to vent from both wheelhouses and were observed behind the rear seat back;
2) By 15 seconds post ignition, flames were visible in the area between the left side of the floor panel in the trunk and the inboard side of the left rear tire;
3) Between 15 to 20 seconds post ignition, flames were present behind the right side of the rear seat back sporadically;
4) Between 20 and 30 seconds post ignition, flames started to spread into the passenger compartment through crash induced seam opening between the left rear wheelhouse panel and the left inner quarter panel;
5) By 75 to 90 seconds post ignition, flames had begun to vent from the right rear wheelhouse and from the left rear wheelhouse. Flames began to contact the back surface of the left side of the rear seat back;
6) By 120 seconds post ignition, flames were visible on the lower surface of the roof trim panel through the upper left corner of the rear window opening;
7) By 155 seconds post ignition, flames started to vent from the passenger compartment along the rear edge of the roof. The height of the fire plumes venting from the rear wheelhouses increased until the fire was extinguished starting at about 155 seconds post ignition.

Data measured in the test are summarized in Table 3-8 for the concentrations of products in the passenger compartment and in fire plume and release rates of heat and products just before time to untenable/flashover, $\mathbf{t_{u,fl}}$. The $\mathbf{t_{u,fl}}$ value is estimated to be 155 seconds (see Chapters IV and V for details of the $\mathbf{t_{u,fl}}$ estimation).

Table 3-8. Concentrations of Products and Release Rates of Heat and Products Just Before Time to Untenable/Flashover Conditions for Test #8

Measurement		Passenger Compartment	Fire Plume
Concentration	CO (ppm)	1,600	59
	CO_2 (ppm)	10,000	1,377
	CH_4 (ppm)	230	
	C_2H_4(ppm)	350	
	C_2H_2(ppm)	240	
	HCN(ppm)	15	
	NO(ppm)	5	
	HCl(ppm)		
	Smoke (mg/m^3)	428	13
Generation Rate	Heat (MW)		0.91
	CO (g/s)		1.70
	CO_2 (g/s)		67
	Smoke (g/s)		0.34

3.2.9-10 Tests #9 and #10: Propagation of an Engine Compartment Fires in a Control Vehicle and a Vehicle Containing FR HVAC Unit (1999 Chevrolet Camaro)

Information for the tests is listed in Appendix B.9.10 [9]. The tests were performed on February 17 and 21, 2000. Two 1999 Chevrolet Camaro were used in the tests; vehicle with the standard HVAC unit is identified as the standard vehicle and the vehicle with FR HVAC unit as the FR vehicle. In the tests, flames entered the passenger compartment concurrently through: 1) the windshield onto the instrument panel top cover and 2) the HVAC module in the dash panel. During the tests, pieces of windshield fell inward igniting the deployed passenger air bags and the front seat cushions. Sections of A/C evaporator and blower upper cases, exterior to the dash panel, also ignited during the tests.

The following were observed during the penetration of the flame into the passenger compartment:

1. Between about 240 and 300 seconds (control vehicle) and about 180 and 240 seconds (FR vehicle) post ignition: temperatures on the air inlet screen and sections of the windshield just above it exceeded 600 ^{o}C;

2. Between about 420 (control vehicle) and 480 (FR vehicle) seconds post ignition: radiation from the flames heated the windshield and caused its inner layer to soften and stretch and its lower portion to sag onto the instrument panel top cover in both the tests;
3. By about 480 seconds post ignition (both vehicles): pieces of windshield separated and fell onto the instrument panel top cover and deployed passenger air bag in the passenger compartment in both the tests;
4. By about 750 seconds post ignition (both vehicles): flames had spread rearward along the top of the instrument panel to the passenger air bag cover and the bag itself in both the tests. The lower section of the right A-pillar trim panel had ignited and was burning in both the tests;
5. Both the tests were terminated at 780 seconds post ignition.

Data obtained in the test are summarized in Table 3-10 just before untenable/flashover (**$t_{u,fl}$**) conditions. The **$t_{u,fl}$** value is estimated to be 780 seconds (see Chapters IV and V for details of the **$t_{u,fl}$** estimation). Maximum concentrations of products at about 390 seconds post ignition for the FR vehicle are also listed in Table 3-10.

Table 3-9. Concentrations and Release Rates of Heat and Products for Tests #9*and #10* Just Before Time to Untenable/Flashover Conditions

Measurements		390s PI	Close to $t_{u,fl}$			
		Passenger Compartment			Fire Plume	
		FR Vehicle	FR Vehicle	Control	FR Vehicle	Control
Concentration	CO (ppm)	1,000	100	330	31	34
	CO_2 (ppm)	3,200	400	2,400	1,870	2,874
	CH_4 (ppm)	350	100	70		
	C_2H_4(ppm)	550	100	50		
	C_2H_2(ppm)	450	80	50		
	HCN(ppm)	27	8	10		
	NO(ppm)	6	3	14		
	Smoke (mg/m^3)				16	49
Generation Rate	Heat (MW)				1.23	1.05
	CO (g/s)				0.96	1.73
	CO_2 (g/s)				92	131
	Smoke (g/s)				0.46	1.30

3.2.11 Test #11: Propagation of an Underbody Gasoline Pool Fire (1999 Ford Explorer with Intumescent Painted Underbody)

Information for the tests is listed in Appendix B-11 [10]. The test was performed on February 23, 2000 using a 1999 Ford Explorer with an intumescent painted underbody, identified as the experimental vehicle. The results were compared with the results of the test performed previously on June 11, 1998 with a 1998 model of Ford Explorer (test #6) [6], identified as the control vehicle (Appendix B-6). The objective of the test was to evaluate the effectiveness of intumescent coating applied to the floor panel in blocking the flame penetration into the passenger compartment and in reducing the heat transfer through the floor panel by the gasoline pool fire under the vehicle.

In the test for the experimental vehicle, flames entered the passenger compartment through the electrical pass-through openings in the floor panel under the left front seat, very similar to the test for the control vehicle. Times for flame spread into the passenger compartment in the experimental and control vehicles were similar.

Data obtained in the test are summarized in Table 3-10 just before untenable/flashover ($\mathbf{t_{u,fl}}$) conditions are reached in the passenger compartment. The $\mathbf{t_{u,fl}}$ values are estimated to be 300 seconds for the experimental vehicle (test #11) and 250 seconds for the control vehicle)(test #6) (see Chapters IV and V for details of the $\mathbf{t_{u,fl}}$ estimation).

Table 3-10. Concentrations and Release Rates of Heat and Products just before Time to Untenable/Flashover Conditions for Tests #6 and #11

Measurements		Passenger Compartment		Fire Plume	
		Exp (#11)	Control (#6)	Exp (#11)	Control (#6)
Concentration	CO (ppm)	7,500	1,600	83	50
	CO_2 (ppm)	205,000	38,000	544	513
	CH_4 (ppm)	650	300		
	C_2H_4(ppm)	1,550	470		
	C_2H_2(ppm)	2,600	450		
	HCN(ppm)	300	40		
	NO(ppm)	90	30		
	Smoke (mg/m^3)		1,350	26	28
Generation Rate	Heat (MW)			0.36	0.60
	CO (g/s)			2.50	1.55
	CO_2 (g/s)			25	44
	Smoke (g/s)			0.72	0.54

Following were observed during the penetration of the flame into the passenger compartment:

1) Flow of hot gases onto the lower surface of the foam pad: in about 20 seconds post ignition in the test for control vehicle and between 50 and 60 seconds post ignition in the test for experimental vehicle;
2) Flow of smoke out of the passenger compartment: in about 90 seconds post ignition in the test for control vehicle and about 120 seconds post ignition in the test for experimental vehicle;
3) Temperature greater than 600 ^{o}C just below the lower surface of the foam pad in the left front seat cushion: at about 220 seconds post ignition in the test for control vehicle and between about 240 and 360 seconds post ignition in the test for experimental vehicle;
4) Gas temperature between the driver and front passenger seat: comparable for control and experimental vehicle tests at 13 and 89-mm below headliner. For locations farther than 165-mm from the headliner, gas temperatures in the control vehicle test were significantly higher than for the experimental vehicle test;
5) Concentrations of products in the passenger compartment close to the time for the untenable/flashover conditions are higher in the test for experimental vehicle than for the control vehicle;
6) Time to reach untenable/flashover conditions is longer in the test for experimental vehicle (300 s) compared to the control vehicle (250 s);
7) Heat release rate is lower and the ratio of CO to CO_2 concentration higher, indicative of fuel rich condition in the plume in the test for experimental vehicle than for the control vehicle;
8) Although intumescent coating does not prevent flames to penetrate the passenger compartment, it, however, decomposes and contributes towards the concentrations of various products in the passenger compartment maintaining lower temperatures in compartment, reduces heat release rate in the plume by shifting the combustion towards fuel-rich condition. As a result, time to untenable/flashover condition is increased;
9) Further improvement in the intumescent coating and its mode of application could prevent or further delay the flame penetration into the passenger compartment.

3.2.12 Test #12: Full Scale Suppression Tests for Vehicle Fires (1999 Honda Accord)

Information for the tests is listed in Appendix B-12 [11]. The tests were performed on August 10, 1999 at the GM Proving Ground, using a 1999 Ford Honda Accord with fire suppression system installed in the engine compartment. The fire suppression system was based on optical fire detection and solid propellant gas generator (SPGG) technology developed by NIST [16].

The left front crash test resulted in a fire in the engine compartment of the vehicle. Flames were observed in the area of the exhaust manifold starting at about 184 ms after time zero. Flames were also observed in the area between the front of the engine and the upper radiator cross member at 220 ms after time zero. Fire was detected by the optical flame detector on the left at 298 ms, triggering the discharge of the SPGG unit on the left. Detector on the right did not detect fire at this time and thus the unit on the right did not discharge. However, discharge of the SPGG unit on the left failed to extinguish the fire in the tests at the GM Proving Ground, except for a very short time in the beginning, thus, fire had to be extinguished manually. This was contrary to the results from NIST.

Four static fire tests were also performed using the crashed 1999 Honda Accord. The vehicle was stationary and other components in the engine compartment were at ambient temperature. Two new, fully charged SPGG units were installed in the vehicle before each test. The first static test involved manual activation of the SPGG unit without a fire in the engine compartment. In the subsequent three static tests, fires were ignited in the engine compartment using an electrical igniter or by spraying power steering fluid onto an electrically heated metal block. The observations made during the static tests are listed in Table 3-11.

The results from the fire suppression tests performed by GM [11] were different from the results of tests performed by NIST [16]. In the NIST tests, engine compartment mock ups and the engine compartment of a stationary vehicle with no crash damage were used. In the NIST tests, 200 ml/min gasoline fire in the engine compartment of a stationary vehicle in the absence of forced ventilation was suppressed by less than 500 g of the solid propellant generator. The tests performed by GM, however, showed that the solid propellant generator was not effective in the suppression and extinguishment of the engine compartment fire. Several reasons were given for these differences [11].

Table 3-11. Observations for the Static Fire Tests for Suppression Using a 1999 Honda Accord

Test	Action	Observations
#1	Manual SPGG discharge without a fire in the engine compartment	Fragments of hood liner in the engine compartment and on the ground in the front of the vehicle. Ignition of materials in the engine compartment by the heated gas discharge from SPGG. Smoke rising from the hood liner fragments in the engine compartment. Glowing embers in some of the hood liner fragments
#2	Electric ignition of plastic	Flaming ignition of the plastic in 90 seconds and shortly afterwards SPGG units discharged. Power to the igniter was not turned off. Fire was extinguished, but plastic reignited in about 18 seconds. Fire was extinguished manually.
#3	Autoignition of the power steering fluid on a hot metal plate at 400 ^{o}C	The SPGG units discharged shortly after flames were detected. The flames were extinguished, but reignited after about 37 seconds after the first fire. Fire was extinguished manually
#4	Electrical ignition of top of the battery	Flaming ignition of the plastic in 90 seconds. Power to the igniter was turned off. Fire was not detected so SPGG units were discharged manually. Fire was extinguished.

3.3 DATA ANALYSIS

All the data measured in the vehicle burn tests were to assess the penetration of the flame into the passenger compartment with fire started in the engine compartment in the front or under the vehicle in the rear using a gasoline pool fire. Mode of ignition and flame penetration into the passenger compartment in the vehicle burn tests are summarized in Table 3-12. Data measured in various tests close to the time for untenable/flashover conditions in the passenger compartment are summarized in Tables 3-13 and 3-14.

3.3.1 Mode of Ignition and Flame Penetration into the Passenger Compartment

In the tests for front crashed vehicles with ignition in and under the engine compartment, flames entered the passenger compartment through windshield and dash panel openings. In the tests for rear-crashed vehicles with ignition of a gasoline pool under the vehicle in the rear, flames entered the passenger compartment through split weld seams, gaps and holes in the floor pan. In the tests, there were significant differences between the times to reach the passenger compartment in the front and rear crashed vehicles. In the rear-crashed vehicles with ignition of gasoline pools under the vehicles, times for flame penetrations into the passenger compartment varied between 0.5 to 3.0 minutes. For the front crashed vehicles with ignition in and under the engine compartments, times for flame penetrations into the passenger compartment varied between 10 to 24 minutes.

3.3.2 Fire Growth

Examination of the heat release rate profiles for the tests indicate that the major difference between the front and rear ignition is in the time for the flames to enter the passenger compartment. Once the flame spread process starts in the passenger compartment, fire growth in both cases becomes rapid and untenable/flashover conditions are reached rapidly. Values for the heat release rates ($\dot{\mathbf{Q}}_{\mathbf{ch}}$) and fire growth rates ($\mathbf{V_{fire}}$) just before time to untenable/flashover ($\mathbf{t_{u,fl}}$) conditions are listed in Table 3-14. $\mathbf{V_{fire}}$ values in the table are obtained from the heat release rate profiles just before $\mathbf{t_{u,fl}}$.

The $\mathbf{t_{u,fl}}$ values are between 10.5 to 15.5 min for the front crashed vehicle tests and are longer than the values for the rear crashed vehicle tests, which are between 1.6 to 5.0 min. This difference is due to the times taken by the flames to enter the passenger compartment, which are about 4 to 5 times longer for the front crashed vehicle tests than the times for the rear crashed vehicle tests. In the front crashed vehicle tests, flames entered the passenger compartment through the openings in the windshield, HVAC units, and some service units. In the rear crashed vehicle tests, flames entered the passenger compartment from the underbody of the vehicle through service openings and openings created by the vehicle crash.

For the front and rear crashed vehicle burn tests, $\dot{\mathbf{Q}}_{\mathbf{ch}}$ values just before $\mathbf{t_{u,fl}}$ are similar and vary between 0.89 to 1.89 MW, except for test #6 (0.60 MW, test probably terminated prematurely) and test #11 (0.36 MW; in this test the underbody of the vehicle was protected from heat from the gasoline pool fire by intumescent paint). The similarity of the $\dot{\mathbf{Q}}_{\mathbf{ch}}$ values indicates that once the flames reach the passenger compartment, both front and rear crashed vehicle tests become similar. The $\mathbf{V_{fire}}$ values in Table 3-14, just before $\mathbf{t_{u,fl}}$ also indicate similarity between the front and rear crashed vehicle tests after flame enters the passenger compartment. The $\mathbf{V_{fire}}$ values vary between 6 to 11 kW/s, except for test #2 (20 kW/s), #3 (14 kW/s) and #7 (4 kW/s).

Table 3-12. Mode of Ignition and Flame Penetration into the Passenger Compartment in Vehicle Burn Tests

#	Vehicle Model	Crash/Ignition	Flame Penetration into the Passenger Compartment
1	1996 Dodge Caravan	Front crash; electrical ignition around the battery in the engine compartment	Through broken windshield, AC evaporator and condenser-line pass-through and HVAC air intake
2	1996 Plymouth Voyager	Rear crash; ignition of gasoline pool under the vehicle in the rear	Through split weld seams
3	1997 Chevrolet Camaro	Rear crash; ignition of gasoline pool under the vehicle in the rear	Through crashed induced seam openings, gap between the driver's door and door frame, and drain hole in the floor panel
4	1997 Chevrolet Camaro	Front crash; ignition of sprays and pools of mixtures of hot engine compartment fluids by a propane torch in and below the engine compartment	Through windshield and HVAC module in the dash panel, both of which were broken in the crash test.
5	1998 Ford Explorer	Rear crash; ignition of gasoline pool under the vehicle in the rear	Through crashed induced seam opening, ignition of quarter trim panel by fire plume and heat conduction across the floor pan.
6	1998 Ford Explorer	Front crash; ignition of gasoline pool under the vehicle in the rear	Through openings in the floor panel
7	1998 Honda Accord	Front crash; ignition of sprays and pools of mixtures of hot engine compartment fluids by a propane torch in and below the engine compartment	Through windshield and pass-through openings in the dash panel
8	1998 Honda Accord	Rear crash; ignition of gasoline pool under the vehicle in the rear	Through crashed induced seam openings
Effectiveness of Fire Retardant Treatment of HVAC Unit			
9	1999 Chevrolet Camaro, Non-FR HVAC (control)	Front crash; ignition by electrical igniter installed in the air cleaner housing in the engine compartment	Through windshield and HVAC module in the dash panel
10	1999 Chevrolet Camaro, FR HVAC		

Table 3-12 continued on the next page

Table 3-12 continuing from the previous page

#	Vehicle Model	Crash/Ignition	Flame Penetration into the Passenger Compartment
Effectiveness of Intumescent coating of the Underbody of the Vehicle			
11	1999 Ford Explorer, Test #6 is the control	Rear crash; ignition of gasoline pool under the vehicle in the rear	Through electrical pass-through openings in the floor panel similar to test #6 (control)
Effectiveness of Fire Suppression System for Engine Fires			
12	1999 Honda Accord	Front crash, ignition of fluids in the engine compartment in the crash test	Test terminated well before flame penetration into the passenger compartment

Table 3-13. Concentrations of Products and Their Ratios in the Passenger Compartment Just Before Times to Untenable/Flashover ($t_{u,fl}$) Conditions

Test #	$t_{u,fl}$ (min)[a]	Concentration (ppm)							C_{sm} (mg/m^3)	C_{CO}/C_{CO2} (ppm/ppm)	C_{sm}/C_{CO} (g/g)	C_{HCN}/C_{CO} (ppm/ppm)
		CO	CO_2	CH_4	C_2H_4	C_2H_2	HCN	NO				
Front Crashed Vehicles, Fires Started in the Engine Compartment												
1	10.5	1,370	20,770	165	230	145	52	25	-	0.066	-	0.038
4	15.5	1,100	3,500	262	353	281	11	5	67	0.314	0.032	0.010
7	26.5	440	12,500	30	45	28	-	18	6,224**	0.035	12.30**	-
9	11.5	330	2,400	70	50	50	10	14	-	0.138	-	0.030
10	6.5*	1,000	3,200	350	550	450	27	6	-	0.313	-	0.027
10	11.5	100	400	100	100	80	8	3	-	0.250	-	0.080
Rear Crashed Vehicles, Fires Started Under the Vehicle in the Rear												
2	3.3	4,244	122,500	602	784	827	103	66	-	0.035	-	0.024
3	3.3	4,797	123,100	464	2,221	2,198	64	48	-	0.039	-	0.013
5	2.6	2,500	40,000	400	800	500	-	10	1,548	0.063	0.541	-
6	4.0	1,600	38,000	300	470	450	40	30	1,350	0.042	0.269	0.025
8	1.6	1,600	10,000	230	350	240	15	5	428	0.160	0.234	0.009
11	5.0	7,500	205,000	650	1,550	2,600	300	90	-	0.037	-	0.040

a: for estimations of $\mathbf{t_{u,fl}}$ see Chapter IV; *: peak before the untenable/flashover conditions are reached; **: $\mathbf{C_{sm}}$ value appears to be too high; -: not measured. or not available.

Table 3-14. Concentrations and Release Rates of Heat and Products and Their Ratios in the Fire Plume Just Before $t_{u,fl}$

Test #	$t_{u,fl}$ (min)[a]	C_j (ppm)		C_{sm} (mg/m^3)	$\dot{Q}_{ch}$ (MW)	G_j (g/s)			V_{fire} (kW/s)	$\dot{G}_{sm} / \dot{Q}_{ch}$ (g/MW)	C_{CO}/C_{CO2} (ppm/ppm)	C_{sm}/C_{CO} (g/g)
		C_{CO}	C_{CO2}			G_{CO2}	G_{CO}	G_{sm}				
Front Crashed Vehicles, Fires Started in the Engine Compartment												
1	10.5	41	2,831	-	1.25	93	0.99	-	8	-	0.014	-
4	15.5	32	1,512	19	0.89	66	0.85	0.45	10	0.51	0.021	0.529
7	26.5	-	1,316	43	1.13	84	-	1.20	4	1.1	-	-
9	11.5	34	2,874	49	1.05	131	1.73	1.30	9	1.2	0.012	0.751
10	11.5	31	1,870	16	1.23	92	0.96	0.46	9	0.37	0.017	0.465
Rear Crashed Vehicles, Fires Started Under the Vehicle in the Rear												
2	3.3	109	2,927	45	1.89	139	3.23	1.12	20	0.59	0.037	0.347
3	3.3	45	1,776	24	0.98	63	1.20	0.55	14	0.56	0.025	0.458
5	2.6	87	2,407	27	1.19	88	2.31	0.88	8	0.74	0.036	0.381
6	4.0	50	513	28	0.60*	44	1.55	0.54	6	0.90	0.097	0.349
8	1.6	59	1,377	13	0.91	67	1.70	0.34	11	0.37	0.043	0.200
11	5.0	83	544	26	0.36**	25	2.50	0.72	6	2.0	0.153	0.288

a: see Chapter IV for estimations; -: not measured or unavailable; *: test probably terminated prematurely; **: underbody protected from the gasoline pool fire by the FR intumescent paint

The results from the vehicle crash fires indicate that it is possible to enhance the survivability of the passengers in the vehicle crash fires by the modifications of vehicle parts to resist flame penetration into the passenger compartment. One of the tests (#11) did demonstrate that undercoating the vehicle by intumescent paint was somewhat beneficial as it increased the $\mathbf{t_{u,fl}}$ value to 300 seconds, which was the highest amongst the rear crashed vehicle burn tests and shifted the combustion towards fuel-lean condition.

3.3.3 Nature of Plastics in the Vehicle Parts involved in Fires in the Burn Tests

From the ratio of the generation rate of smoke ($\dot{G}_{sm}$) to heat release rate ($\dot{Q}_{ch}$), the nature of the burning plastic and fire ventilation condition can be identified [17]. An example is shown in Fig. 3-2, where the ratio is plotted against the equivalence ratio (**Φ)** using data from Ref. 17.

The ratio is highest for PVC (halogenated fuel), increases with **Φ** and reaches a constant value even for fuel-lean conditions. The ratio for PS (aromatic fuel) is less than the ratio for PVC, but is higher than the ratio for the aliphatic fuels. Amongst the aliphatic fuels, the ratio is higher for nylon compared to polypropylene (PP), polyethylene (PE), polymethylmethacrylate (PMMA) and wood. For both aromatic and aliphatic fuels, the ratio increases slowly with changes to fuel-rich conditions up to **Φ** ≈1.5 and then rapidly beyond that value.

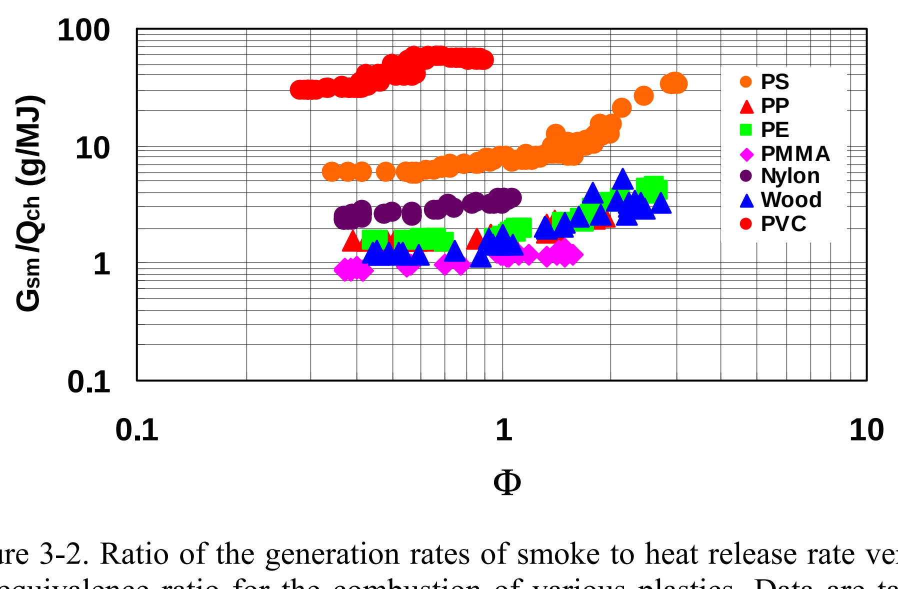

Figure 3-2. Ratio of the generation rates of smoke to heat release rate versus the equivalence ratio for the combustion of various plastics. Data are taken from Ref. 17.

For the vehicle burn tests, data in Table 3-14, just before $\mathbf{t_{u,fl}}$, show that the $\dot{G}_{sm}/\dot{Q}_{ch}$ values ≤ 1.2 (except for #11). Comparisons of these values with those in Fig. 3-2 show that they are similar to the values for aliphatic fuels for stoichiometric condition. Thus, in vehicle burn tests, vehicle parts and fluids burn predominantly like aliphatic fuels and just before $\mathbf{t_{u,fl}}$, conditions are close to stoichiometric combustion.

3.3.4. Concentrations of Products in the Passenger Compartment and in the Fire Plume

The concentrations of products in the passenger compartment were measured at a single location between the driver and passenger seats, slightly over the top of the seats. Figure 3-3 shows an example of the measured data for test #2. There is rapid increase in the concentrations of products paralleling the fire growth as flames enter the passenger compartment (80 to 120 s and ignition of one of the seats). Formation of HCN starts at about 120 s and its concentration increases with time, supporting the observation of ignition and burning of polyurethane based seat. A similar behavior is observed for the CO and CO_2 concentration profiles in the fire plume, as shown in Fig. 3-4 for test #2.

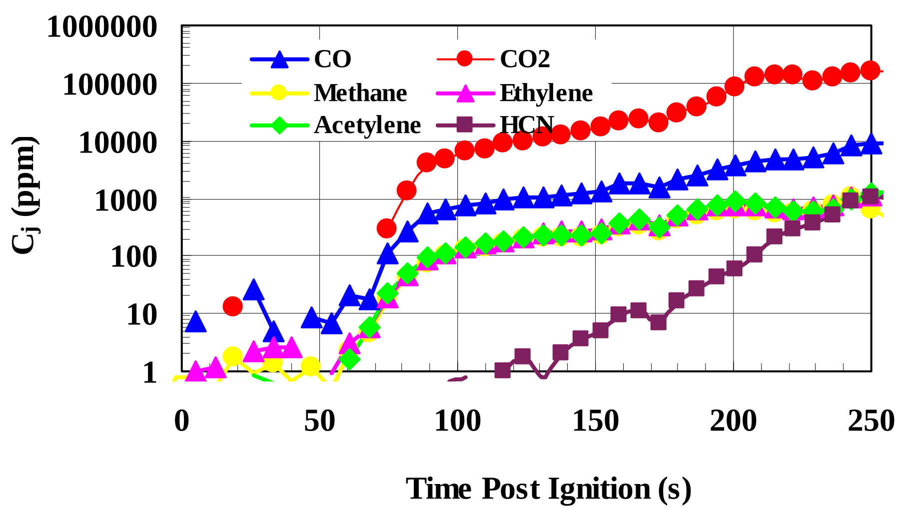

Figure 3-3. Concentrations of products in the passenger compartment versus post ignition time for test #2.

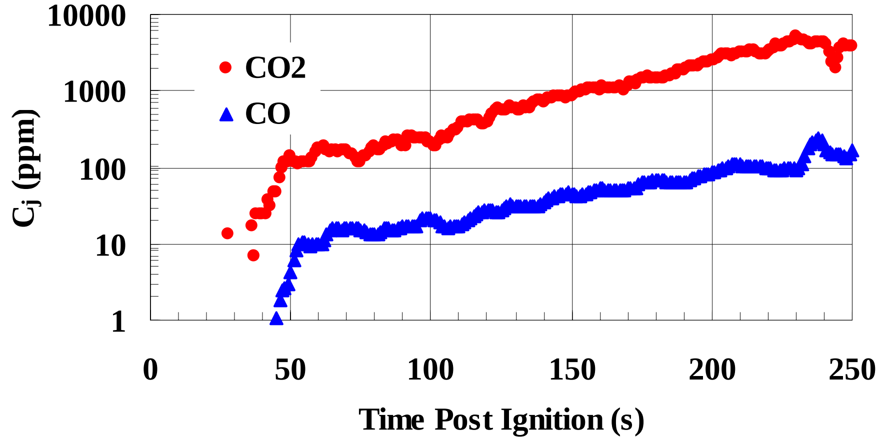

Figure 3-4. Concentrations of CO and CO_2 in the fire plume versus post ignition time for test #2.

The increase in the concentrations of products in the passenger compartment creates untenable conditions leading to flashover and the increase in the concentration of products in the fire plume results in the increase in the fire intensity of the burning vehicle.

The concentration ratios of the products provide information as to the mode of combustion and extent of involvement of the plastic parts based on the conversion of carbon, hydrogen, and nitrogen atoms that are present in the chemical structure of the plastics.

3.3.4.1 Concentration Ratio for CO to CO_2

The ratio is commonly used to examine the combustion behavior of plastics and liquids. An example is shown in Fig. 3-5, where the ratio of CO to CO_2 concentration ($\mathbf{C_{CO}/C_{CO2}}$) is plotted against the equivalence ratio, $\mathbf{\Phi}$. For $\mathbf{\Phi} < 1$ (fuel-lean conditions), the $\mathbf{C_{CO}/C_{CO2}}$ ratio is highest for PVC (halogenated fuel), followed by PS (aromatic fuel) and nylon, PE, and PP (aliphatic fuel) in that order. For fuel-rich conditions, the ratio for aliphatic fuels becomes higher than for the aromatic fuel (highest for nylon comparable to PVC).

For the vehicle burn tests, the $\mathbf{C_{CO}/C_{CO2}}$ ratio in the passenger compartment and in the fire plume are shown in various figures in Appendix B (for example, in Appendix B-1 in Fig. B-1-14 for a front crashed vehicle burn test (#1) and in Appendix B-3 in Fig. B-3-9 for a rear crashed vehicle burn test (#3)). Data in these two figures suggest the following:

- Test #1: fuel-rich conditions in the passenger compartment and fuel-lean conditions in the fire plume;
- Test #3: fuel-rich conditions in both passenger compartment and fire plume;
- Close to stoichiometric combustion conditions in the passenger compartment and in the plume just before untenable/flashover for both the tests.

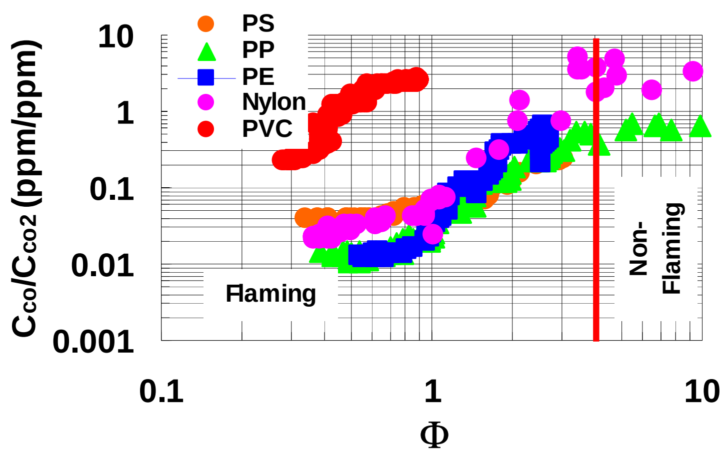

Figure 3-5. CO and CO_2 concentration ratio versus the equivalence ratio in the combustion of various plastics. Data are taken from Ref. 17.

The $\mathbf{C_{CO}/C_{CO2}}$ ratios in Tables 3-13 and 3-14, just before $\mathbf{t_{u,fl}}$, are also similar to the ratios that are closer to the stoichiometric combustion conditions for aliphatic fuels in Fig. 3-5. Under these conditions, gas temperatures are higher and thus there is a higher possibility of burn injuries to passengers relative to the injuries due to toxicity and lethality, a conclusion similar to that derived from the estimations for times to pain, 2^{nd} and 3^{rd} degree burns, flashover, toxicity, and lethality in Chapter V.

3.3.4.2. Concentration Ratios for Smoke to CO and for HCN to CO

CO, smoke, and HCN are some of the major products of incomplete combustion that are responsible for toxic hazards. CO is generated from the partial oxidation of fuel pyrolyzate. Smoke, which is a mixture of soot and organic compounds, is generated from the partial oxidation and further decomposition of the fuel pyrolyzate. Sometimes, smoke is mixed with oxidized inorganic compounds from fuel additives. The ratio of soot to organic compounds depends on the generic nature of the fuel, oxygen concentration, and reaction zone temperature. With increase in the oxygen concentration and reaction zone temperature, ratio of soot to organic compounds increases. In addition, the ratio increases as the nature of chemical bonds in the fuel changes to aromatic and unsaturated aliphatic in nature. HCN, on the other hand is released from fuels with nitrogen atoms in the chemical structure. The ratios of concentrations of smoke to CO (**C_{sm}/C_{CO}**) and of HCN to CO (**C_{HCN}/C_{CO}**) thus provide relative tendencies of plastics and liquids for the release of CO, smoke, and HCN.

Examples of the data for the concentration ratios of smoke to CO are shown in Fig. 3-6, where data are taken from Ref. 16. The concentration ratios of HCN and CO along with the CO to CO_2 ratios are listed in Table 3-15, where data are taken from Ref. 18. A chemical kinetic model for the formation of CO, CO_2, and HCN from a mixture of methylamine and ethylene, following a stationary flamelet concept, was used to calculate their concentrations [18]. The experimental concentration ratios in Table 3-15, were measured in the combustion of nylon-6,6 in the ISO 9705 room with 0.89-m and 0.56-m high openings [18].

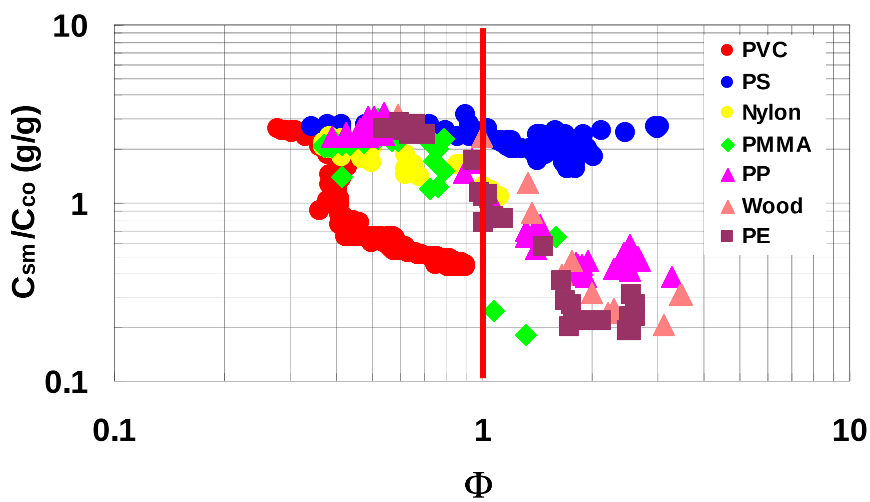

Figure 3-6. Smoke to CO concentration ratio versus the equivalence ratio for the combustion of various plastics. Data are taken from Ref. 17.

An examination of the data in Fig. 3-6 shows that for the fuel-lean conditions, the **C_{sm}/C_{CO}** ratio is about 3 g/g for all the fuels included in the figure. For PS, an aromatic fuel, the ratio remains approximately constant (between about 2 and 3 g/g) in the fuel-lean as well as fuel-rich combustion conditions. For PVC, a halogenated fuel and other aliphatic fuels, the **C_{sm}/C_{CO}** ratio decreases as combustion conditions change from fuel-lean to fuel-rich. These results suggest that since soot in smoke has an aromatic structure, conversion of aromatic fuel pyrolyzate to soot probably involves significantly less reaction steps compared to those for the aliphatic and halogenated fuels.

Table 3-15. Calculated and Measured Concentration Ratios of HCN, CO, and CO_2 in the ISO 9705 Room

Opening Height (m)	Φ	Ventilation	C_{CO}/C_{CO2} (ppm/ppm)		C_{HCN}/C_{CO} (ppm/ppm)	
			Calculated	Measured	Calculated	Measured
0.89	0.43	Fuel-Lean	0.004		0.014	
	0.43		0.004		0.014	
	0.52	Fuel-Rich	0.014		0.037	
	0.55			0.011		0.080
	0.55			0.011		0.076
	0.65		0.014		0.037	
0.56	0.70			0.009		0.279
	0.75			0.009		0.282
	0.94		0.043		0.106	
	0.94		0.043		0.119	

For the vehicle burn tests, the $\mathbf{C_{sm}/C_{CO}}$ ratios in the passenger compartment and in the plume in Tables 3-13 and 3-14 (just before $\mathbf{t_{u,fl}}$) are similar to values in Fig. 3-6 that are closer to the stoichiometric combustion for aliphatic fuels.

An examination of the $\mathbf{C_{HCN}/C_{CO}}$ ratio in Table 3-15 shows that the ratio increases from a value of 0.014 (for the mixture of methylamine, which is a nitrogen containing fuel, and ethylene, which is a non-nitrogen fuel) to a value as high as 0.282 for nylon-6,6 (only nitrogen containing fuel), as the conditions change from fuel-lean to close to stoichiometric combustion. The $\mathbf{C_{HCN}/C_{CO}}$ ratios for the vehicle burn tests, listed in Table 3-13, however, are lower than the ratios in Table 3-15, as nitrogen containing as well as non-nitrogen containing plastics are involved in vehicle burn tests.

The $\mathbf{C_{HCN}/C_{CO}}$ ratio can be used to estimate the relative contribution of nitrogen containing plastics in the vehicle burn tests. For example, in test #1, instrument panel constructed of ABS (a nitrogen containing fuel) was involved in the fire, in test #2, polyurethane seat (a nitrogen containing fuel) was involved, whereas in test #11, nitrogen containing intumescent paint applied to underbody of the vehicle was exposed to flames from gasoline pool fires. For these tests, the $\mathbf{C_{HCN}/C_{CO}}$ ratios are 0.038, 0.024, and 0.040 respectively in Table 3-13. The $\mathbf{C_{HCN}/C_{CO}}$ ratio is 0.080 in test #10 with FR-HVAC, which is the highest ratio in the table.

3.3.5 General Information Derived from the Vehicle Burn Test Data

1. Untenable/flashover conditions are reached earlier in the rear crashed vehicle fires than the front crashed vehicle fires, primarily due to delay in the flame penetration into the passenger compartment;
2. Conditions in the passenger compartment and in the fire plume are closer to the stoichiometric combustion conditions just before untenable/flashover, suggesting higher probability of burn injuries to passengers relative to the injuries due to toxicity and lethality in agreement with the times calculated from the burn and toxic hazard models and flashover times discussed in Chapter V;
3. Under fuel-lean conditions, the mass of smoke is three times the mass of CO. In the vehicle burn tests, where predominantly aliphatic fuels are involved, the smoke to CO mass ratio is about 0.4 for conditions that are closer to stoichiometric combustion conditions;
4. In vehicle fires, the HCN concentration is about 3 % of the CO concentration in the passenger compartment;
5. The analysis of the data measured in the vehicle fires suggests that it is possible to model vehicle fires to assess survivability of passengers through modifications to the vehicles and their plastic parts. It is possible to successfully model the survivability of passengers from vehicle crash fires as extensive information is now available for the fire behaviors of vehicle parts (Chapter II) and crashed vehicles (this Chapter), for the ignition and flame spread behaviors of plastics, and survivability in vehicle fires (Chapters IV and V) and theories behind these behaviors (Volume II) and data for the thermophysical and fire properties of plastics in vehicle parts and engine compartment fluids (Volume III).

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CHAPTER IV

IGNITION AND FLAME SPREAD ASSOCIATED WITH POST COLLISION VEHICLE FIRES

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4.1 INTRODUCTION

A review was conducted of 9 reports involving 10 vehicle burn tests that were performed after the vehicles were crashed in the GM sponsored studies. These reports were prepared by J. Santrock of General Motors Corporation and are published in the National Highway Traffic Safety Administration (NHTSA) series as listed below:

1. 1996 Dodge Caravan (13-Nov-1996)-front crash and ignition (NHTSA-1998-3588-119);
2. 1996 Plymouth Voyager (15-Nov-1996)-rear crash and ignition (NHTSA-1998-3588-143);
3. 1997 Chevrolet Camaro (30-Sept-1997)-rear crash and ignition (NHTSA-1998-3588-158);
4. 1997 Chevrolet Camaro (01-Oct-1997)-front crash and ignition (NHTSA-1998-3588-178);
5. 1998 Ford Explorer (09-June-1998)-rear crash and ignition (NHTSA-1998-3588-188);
6. 1998 Ford Explorer (11-June-1998)- front crash and rear ignition (NHTSA-1998-3588-189);
7. 1998 Honda Accord (23-Feb-1999)-front crash and ignition (NHTSA-1998-3588-203);
8. 1998 Honda Accord (25-Feb-1999)-rear crash and ignition (NHTSA-1998-3588-201);
9. 1999 Chevrolet Camaro-Control (17-Feb-2000)-front crash and ignition (NHTSA-1998-3588-190);
10. 1999 Chevrolet Camaro-FR HVAC (21-Feb-2000)-front crash and ignition (NHTSA-1998-3588-190);

The GM sponsored studies were carried out by GM with collaboration of the National Institute for Standards and Technology (NIST) and FM Global. Two scenarios were examined for upright passenger vehicles: (1) engine compartment fires, and (2) gasoline spill fires from punctured fuel tanks. (See Figure 4-1). In both cases, the fire eventually spread into the passenger compartment. In all cases, the doors were closed and the windshield (although shattered) was intact due to the plastic inter-liner of the two safety glass screens. In all cases, at least one side window was open or broken. The tests were heavily instrumented and monitored by visual recording systems. Energy release rate (or firepower) was measured in the Fire Products Collector. Analyses were conducted in the report to assess toxic conditions in the passenger compartment and burn injury potential. No overview analysis was conducted in the series, and that is the purpose of the present review. The data from these reports are summarized in Chapter III and Appendix B.

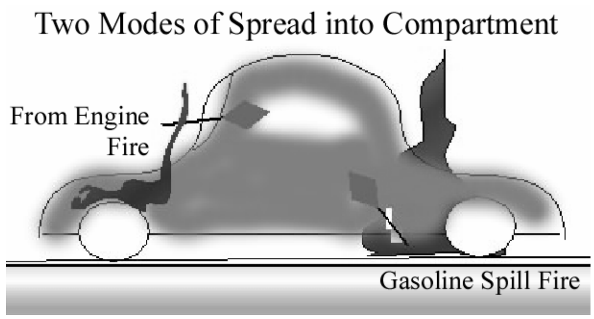

Figure 4-1 GM-NHTSA vehicle test fire scenarios.

The reports of the ten vehicle fires were examined with the intention of identifying the characteristics of the fire growth from the igniting fire in the engine or the gasoline spill to the onset of flashover in the passenger compartment of the vehicle. Although various criteria were used to stop and extinguish a test (see Chapter III), it is clear from the reports that they were stopped near the onset of flashover in the compartment. The onset of flashover was identified in the vehicle passenger compartment by the temperature recorded of bare thermocouples below the headliner centered in the vehicle, or by the array of aspirated thermocouples located below the headliner. In most cases, this was based on a sudden increase in temperature or temperatures exceeding 400 to 500 ^{o}C. Here, *flashover* is defined as the start of the transition between a growing fire and a fully developed fire in the compartment that would consume all of the fuel or all of the entering air. This flashover time was clearly bounded and similar to the time for extinguishment imposed in the tests as the time for extinguishment was prompted by the desire to preserve the pathways of fire into the passenger compartment.

The extinguishment criteria was based, in practice, on exceeding 200 ^{o}C below the headliner, flame spread on the headliner, ignition of the front seat, or a perception that flashover was about to occur. In addition, the observations recorded in the tests to indicate the time for flames to penetrate the passenger compartment were used in establishing the data in Table 4-1.

Table 4-1. Onset of Flashover in the Test Vehicles

Test #	Vehicle	Flashover Time (min)	Firepower at Penetration (kW)	Firepower at Flashover (kW)
Rear Crashed Vehicles, Fires Started Under the Vehicle in the Rear				
8	98 Honda Accord #201 400 mL/min	1.6	150.	250.
5	97 Ford Explorer #188 750 mL/min	2.6	800.	1100.
3	97 Chevy Camaro #158 515 mL/min	3.3	600.	1000.
2	96 Plymouth Voyager #143 250 mL/min	3.3	100.	700.
6[a]	97 Ford Explorer #189 350 mL/min	4.0	250.	500.
Front Crashed Vehicles, Fires Started in the Engine Compartment				
1	96 Dodge Caravan #119 Battery fire	10.5	100.	1100.
9	99 Chevy Camaro #190 Std HVAC	11.5	600.	1000.
10	99 Chevy Camaro #190 FR HVAC	11.5	600.	1000.
4	97 Chevy Camaro #178 HVAC	15.5	250.	750.
7	98 Honda Accord #203 washer fluid	26.5	500.	1000.

a: front crashed vehicle

The firepower (energy or heat release rate, **HRR**) data recorded over time were used in an attempt to characterize the rate of growth of the fire, and identify the role of the ignition fire and the passenger compartment fire. The hazard of toxic gases relative to the onset of flashover was also examined. The carbon monoxide levels generally ranged between 0.05 and 0.5 % at the onset of flashover, and the computed lethal effective dose time in the reports occurred after flashover, and in nearly half the tests never exceeded the lethal condition. Of course, the lethal condition would have been exceeded had suppression not intervened. *In most cases, flashover of the passenger compartment appears to be the principal hazard and not the toxicity of the fire gases***.** This implies that victims trapped in burning vehicles following accidents are likely to be simultaneously subjected to lethal heat and toxic gas conditions. The level of COHb obtained from the autopsy reports of victims who died in auto accidents should be an indicator of whether the death was due to heat or smoke. Low values of COHB would indicate heat effects. The COHb issues are examined in greater detail in Chapter V.

4.2 Times to Flame Penetration and Flashover in the Passenger Compartment

Table 4-1 gives an abbreviated overview of the nature of these vehicle test fires. The vehicles are correlated to the report numbers in the NHTSA series, i.e., NHTSA-1998-3588-#. In the gasoline spill cases, the leak rate imposed is shown; and for the engine fires, the nature of the starting fire is given. Due to the variety of the damage characteristics, location of the start of the engine fires, seam breaches in the under carriage for the gasoline fires (details are described in Chapter III). In this chapter, only general characteristics of the flame penetration into the passenger compartment are described.

For the gasoline fires, all started in the rear, the critical condition appears to be the nature of the breach in the under carriage. This was typically a seam that opened as a result of the crash scenario; in no case did the fire enter through an open window. In the case of the engine fires, the critical event for passenger compartment flashover was the failure of the windshield with its falling into, or allowing flames to enter the passenger compartment. The time to flashover, the passenger compartment was always faster in the gasoline undercarriage fires than the engine fires. The contrast was 1.6 to 4 minutes for the gasoline fire, and 10.5 to 26.5 minutes for the engine fires. The gasoline undercarriage fires are clearly more hazardous to the passenger compartment. For the gasoline leak rates tested, the diameter of the fires ranged from about 30 to 90 cm. The time to cause flashover appears to depend more on the nature of the opening exposed to the fire. These details were not sufficiently documented in the reports.

In all cases, the fires continuously propagated. The engine compartment fires primarily grew due the components present and in at least one case (Test #1, NHTSA-1998-3588 #119) were assisted by intentionally spilled engine fluids. The gasoline fires, on some occasions, involved ignition of a tire, or the plastic empty gasoline tank. In no case was the involvement of the undercoating indicated. The combustible components of the vehicles, both interior and exterior, appeared to easily carry the fire propagation in these tests.

Figure 4-2 indicates the time for the fire to penetrate either the windshield or the undercarriage and the corresponding time to flashover. These times are well correlated as directly shown in Fig. 4-2. Indeed, there is nearly a linear relationship between the times with a coefficient of proportionality of about 1.5. The difference in the times is 2.3 minutes with a

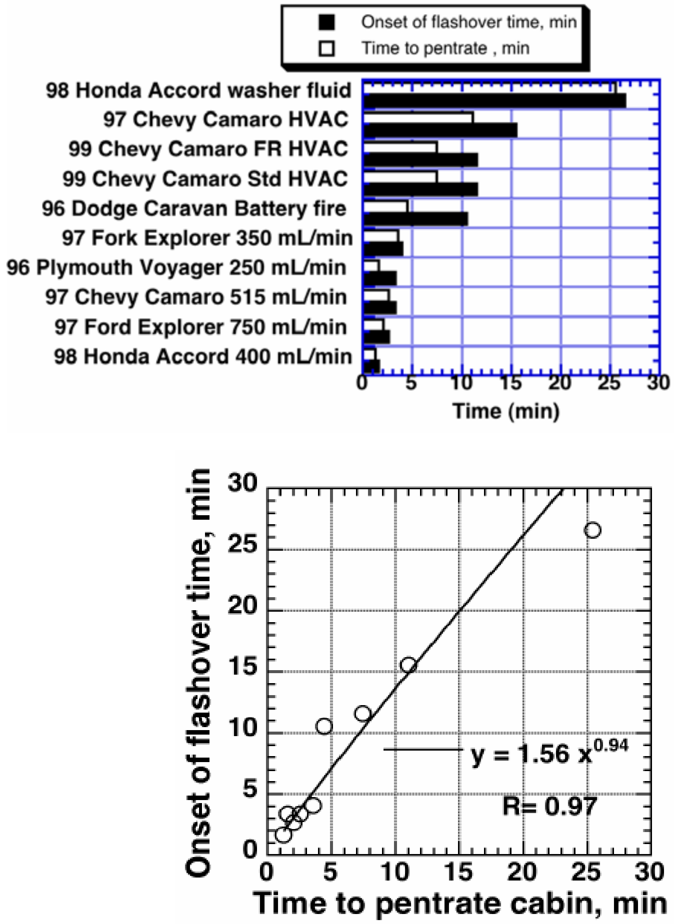

Figure 4-2. Penetration and flashover times

standard deviation of 2.1. *Hence, flashover is likely to occur within several minutes following fire penetration into the passenger compartment.* The nature of the fire penetration can be pieces of flaming windshield screen falling on the seats and dash panel, flames impinging on the headliner, or flames entering in the seat cushions. Flames and hot gases entering through the HVAC vents is also important. Thus, for flame penetration into the passenger compartment, HVAC system and extent of the breaking of the windshield are important.

The state of the art does not allow for accurate predictions of the extent of breakage in normal window glass, and prediction for a laminated safety-glass windshield is beyond the state of the art. While the windshield glass laminate is clearly a factor in fire penetration, the "fire wall" barrier system between the engine and the passenger compartment should always bear consideration, and not be forgotten as a potential way fire can be transferred.

Figure 4-3 shows the firepower at the time of flame penetration and the time for flame penetration following gasoline or engine ignition scenarios. The time for flame to penetrate the passenger compartment is not a function of the gasoline firepower or leak rate, as this depends on the under carriage openings exposed. The time for flame to penetrate the windshield is somewhat dependent on the firepower of that fire, but depends mostly on when the engine fire significantly affects the windshield.

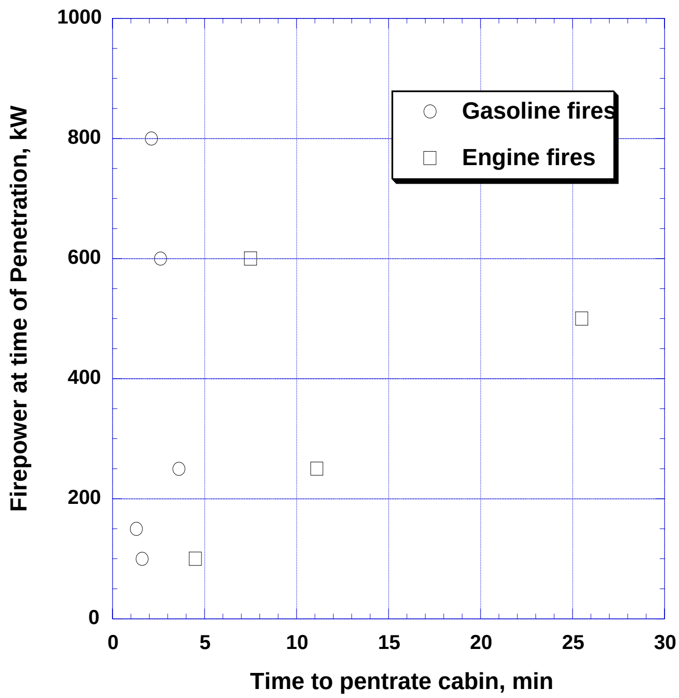

Figure 4-3. Firepower and time at flame penetration into the passenger compartment

4.3 Firepower at Flame Penetration and Flashover

Figure 4-4 indicates the firepower at the time of flame penetration into the passenger compartment and at the onset of flashover. The components of this fire can include the gasoline leak, the engine components and exterior components ignited. In the case of the gasoline-initiated fires, it can be seen that the firepower of the gasoline was nearly the same as the

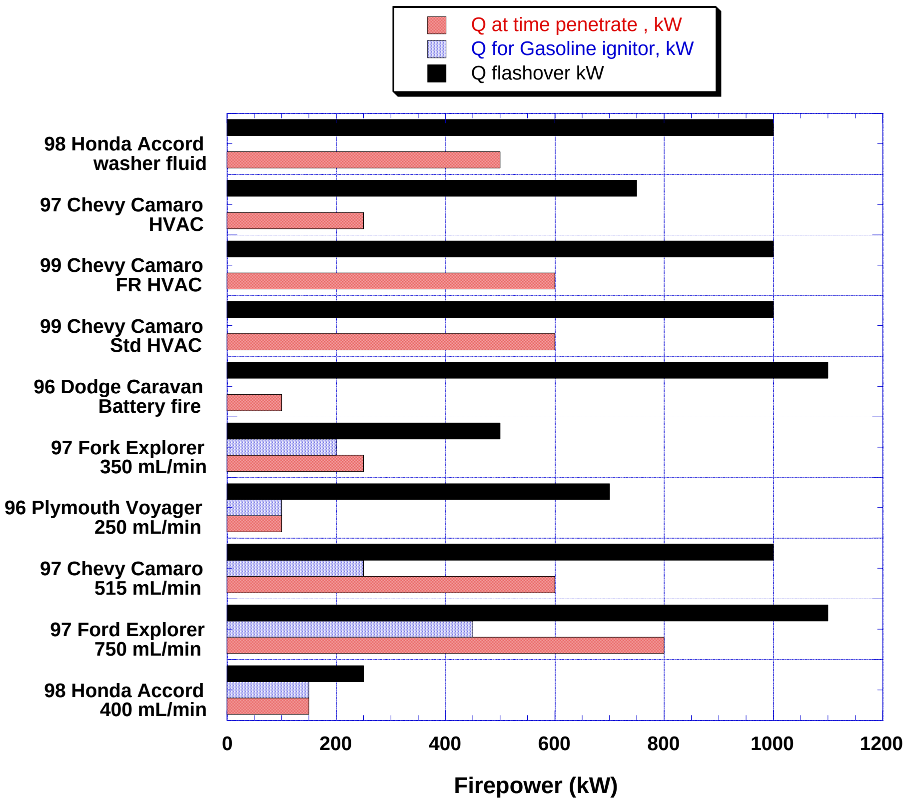

Figure 4-4. Firepower at flame penetration and flashover

firepower at the time of flame penetration noted into the passenger compartment, except in one test. That test was the 1997 Ford Explorer (test #5, NHTSA 3588-188) that had the highest leak rate and gasoline firepower, and the rear tire ignited and burned after 30 seconds following ignition. *Thus, the gasoline induced passenger compartment fires appear to occur solely due to gasoline fuel products entering through seams in the undercarriage to cause ignition of the interior components.* An example of modeling is illustrated for the case of a gasoline spill rate of 243 cm^3/min (test #2, NHTSA 3588-143).

From the flow rate and the diameter of the steady spill, 40 cm, it can be determined that the burning rate is about 22 g/m^2s. This is reasonable for a spill on the ground. It might be assumed that this is the mass flux entering a seam at the bottom of the floor, because of the small distance from the ground to the underbody of the vehicle.

It is important to know the dimensions of the seam opening (not given in the report). If we know that dimension as the width of the seam slit, we can estimate the flame height into the vehicle passenger compartment. From a correlation for line fire plumes, if the width of the seam is 1 cm, the flame height into the passenger compartment is estimated to be about 20 cm, which is the indicated threat to the interior.

These types of examinations of flame penetration should be done systematically to access this hazard potential. The estimate of a significant gasoline flame through a very small seam in the underbody appears consistent with rapid-fire growth in the passenger compartment from this ignition scenario. *In general, the flame from gasoline fuels through a small seam can be extensive in height, 10 cm or more.*

The firepower needed to cause flashover in the passenger compartment of an automobile will depend on the size of the space and its ventilation openings. The vehicles in this study ranged from small compact size to minivans. The window openings consisted of at least one side window and the possible breakage of the windshield in part. Figure 4-5 shows the difference in the firepower at flashover and that at penetration to the passenger compartment.

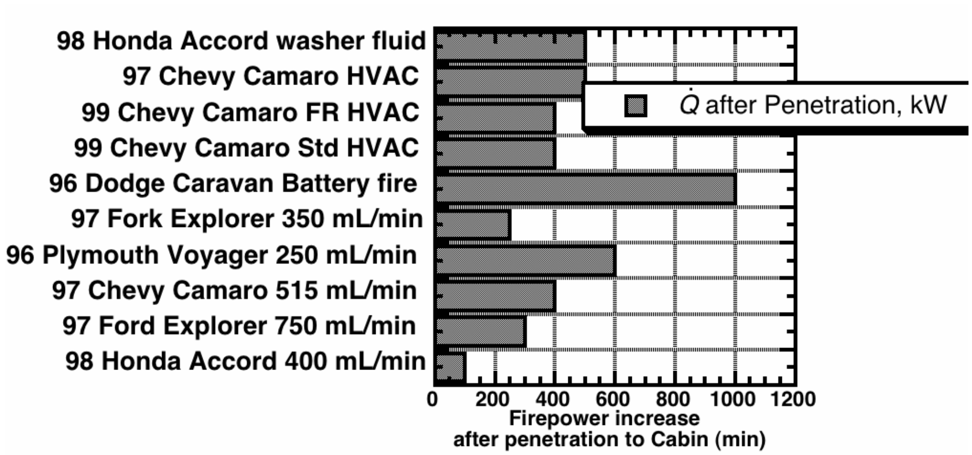

Figure 4-5. Estimation of interior firepower needed to cause passenger compartment flashover

The 96 Dodge Caravan had the longest time of 6 minutes between flame penetration and flashover. During that time, the contribution to the firepower would be from both the engine and the passenger compartment. Where the time difference is small, the increase in the firepower measured is more an accurate measure of the passenger compartment contribution. *With that premise, it would appear that flashover of the passenger compartment requires about 425 kW with a standard deviation of about 250 kW.*

Analytical approximate formulas to predict the firepower needed for flashover in compartments with open windows have been proven reliable for the room fire case [1]. One such formula gives the needed firepower as

$$\dot{\mathbf{Q}} = \mathbf{610(0.030\,kW/m^2K)A_w A_o \sqrt{H_o})^{1/2}\,kW} \tag{1}$$

where $\mathbf{A_w}$ is the surface area of the compartment (m^2), $\mathbf{A_o}$ is the area of the opening (m^2), $\mathbf{H_o}$ is the height of the opening (m), and the heat loss factor is taken here as $0.030\ \mathrm{kW/m^2K}$, which depends on the nature of the surface materials.

Estimations for the typical vehicles tested suggested rough values for the geometric parameters as $\mathbf{A_w}$= 20 m^2, $\mathbf{A_o \sqrt{H_o}}$ =0.065 to 0.26 m$^{1.5}$. The formula then suggests flashover firepower of roughly 150 to 250 kW. This is consistent with the test results, especially for the gasoline fires. The automobile is a complex compartment with most of it filled with seats (and people) that is very different from the basis of this empirical formula. However, the results suggest that is reasonably accurate.

Figure 4-6 shows the increase in firepower after penetration and the incremental time to flashover. This figure attempts to represent the behavior of the fire within the passenger compartment itself.

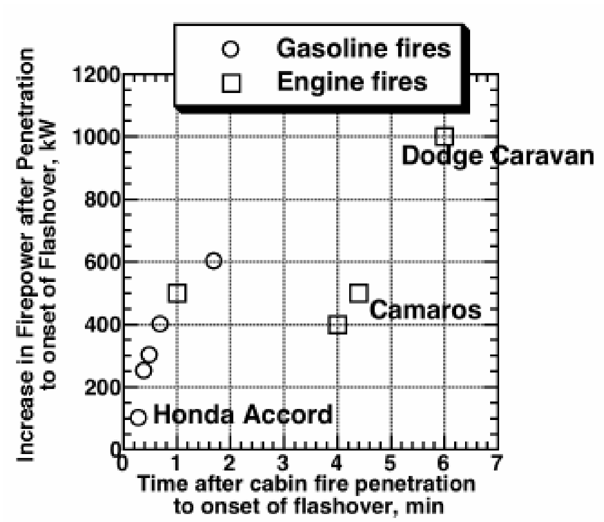

Figure 4-6. Passenger Compartment firepower and flashover time

Data for the Dodge Caravan in the figure is not as accurate due to long time difference and the contribution of the engine fire to the passenger compartment fire. If we adopt 425 kW as the value needed to flashover the passenger compartment, the figure would then suggest that we are calling the time to flashover either too short or too long. Excluding the Dodge Caravan, using 425 kW as a criterion for flashover would lead to an estimate of the flashover time after penetration to within less than 1 minute of the observed time. Hence, the 425 kW value appears to be a good representative firepower to cause flashover in the passenger compartment[1]. Of course, the volume of the space and the window openings will affect this rough value. A very rough estimate of the increase in the firepower after the fire began to develop in the auto passenger compartment after gasoline penetration has been made here.

An attempt was made to exclude the effect of the external gasoline pool and additional burning from the vehicle exterior from this fire growth. The latter was difficult and done by noting the time for flame penetration and forcing the firepower to zero at that time. This gave a very rough t-squared growth that characterized the passenger compartment fire with a coefficient of 0.18 kW/s^2. This is shown in Figure 4-7. Although it is a crude estimate, it is reasonably indicative of the rapid fire growth in the passenger compartment once flames enter from the bottom.

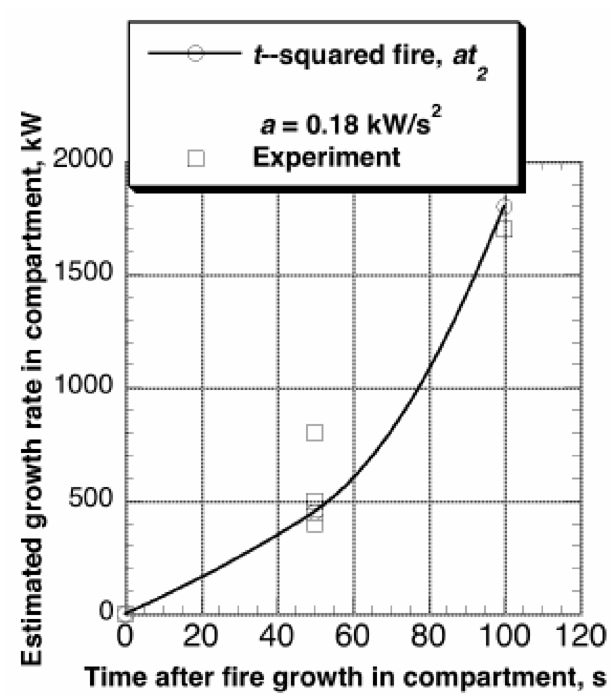

Figure 4-7. Estimated growth rate of the passenger compartment fire.

[1] See Section 4.5 for the criterion used by SwRI [4] for the critical fire power.

The literature [2] has classified t-squared fire growth rates in a relative manner reflecting the range of standard free-burning commodities. That classification is based on the time to reach 1 MW for the t-squared growth rate:

1	Slow	600 s
2	Medium	300 s
3	Fast	150
4	Ultra-fast	75 s

The passenger compartment growth rate indicated here has a classification of 80 s. *The passenger compartment fire growth is very fast in the spectrum of fire growth rates.*

4. 4 Ignition Fires

4.4.1 Gasoline Pool Fires

The growth and firepower of the gasoline spill fires and the engine fires can be characterized by the experimental results in the GM-NHTSA reports. The gasoline fires were initiated about 30 seconds following the constant leak flow rate commenced under the rear of the vehicle. The flame spread over the gasoline pool is nearly immediate, given an ignition source in the flammable limits, as the flame propagation would follow the laminar burning speed of 50 cm/s or more. The firepower computed from a gasoline heat of combustion of 41 kJ/g and the leak rate is compared favorably to the measured calorimeter value during the steady period before other fuels contributed. This is shown in Figure 4-8, indicating consistency of the data in these tests. It also indicates that the firepower can be computed from a specified leakage rate, and the corresponding diameter of the pool fire can theoretically be computed. This follows since the diameter is related to the mass flow rate of the gasoline by

$$\dot{m} = \dot{m}'' \pi D^2 / 4 \qquad (2)$$

where $\dot{m}''$ is the burning rate per unit area (mass flux). Estimated pool diameters are indicated in Figure 4-9. They appear to have not exceeded 1 m in the GM tests. The mass flux depends on the heat transfer available to evaporate the gasoline. In these fires under the vehicle, the heat radiated from the heated undercarriage will affect the flux. This was obvious in the Honda test #8(NHTSA 3588-#201), where the pool area decreased as the burning rate increased. This increase was suggested due to radiation feedback. The burning flux appeared to increase from about 18 to 65 g/m^2-s. Generally, the data suggested a burning flux of roughly 20 g/m^2-s.

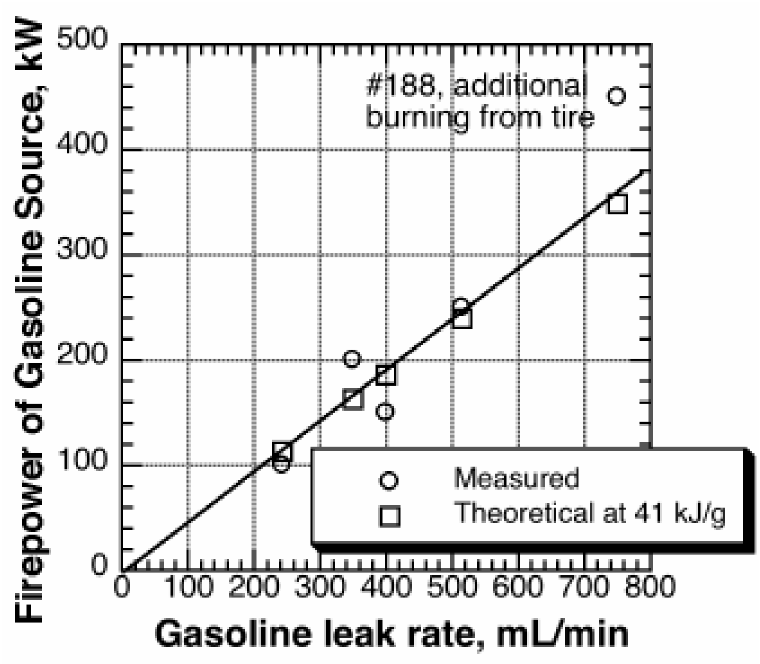

Figure 4-8. Gasoline firepower based on leak flow rate and calorimeter

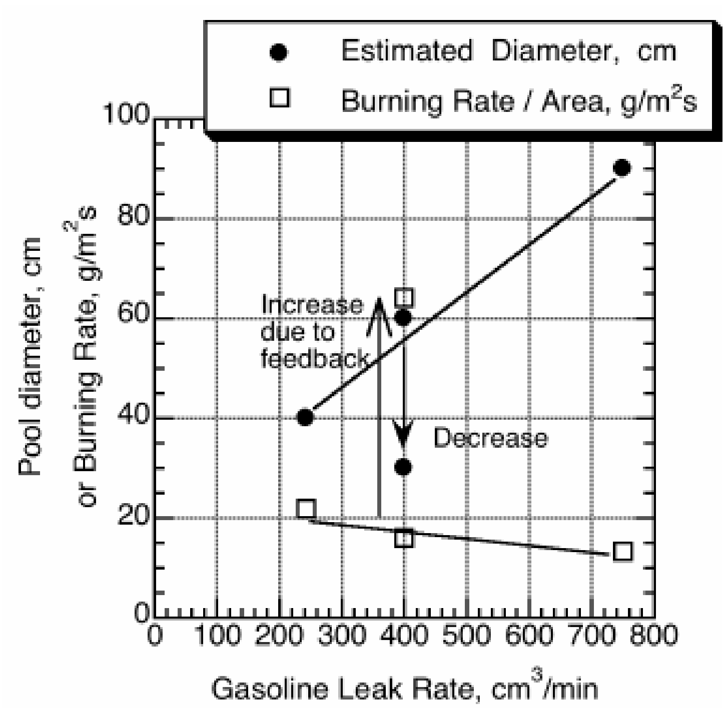

Figure 4-9. Burning flux and diameter of gasoline fires

A classical study by Blinov and Khudiakov [3] gives the mass flux free burning gasoline pools, which is shown in Figure 4-10. It can be seen that the asymptotic flux is about 45 g/m^2-s, but has been reported as high as 55 g/m^2-s in the literature. These results along with the equation for mass leak rate can yield the fire diameter. The diameter of the fire is important in auto fires since it will indicate the range of exposure. *Moreover, the breach of a tank in a crash and the subsequent leak rate is an important parameter missing from the current study.*

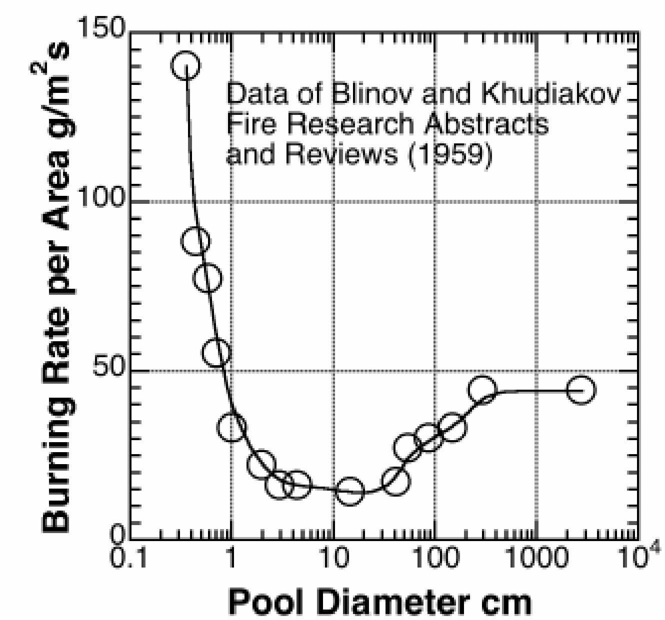

Figure 4-10. Burning rate for free burning gasoline pools [3]

Figure 4-11 gives a theoretical estimate for the pool diameter assuming a burning flux of 20 g/m^2-s as suggested by these fires. It would appear that diameters of about 150 cm, at most, might be expected for about 4000 cm^3/min—a much larger leak rate than was used in these studies. However, in a crash scenario larger leakage rates might occur from massive tank ruptures, and information on these rates are not considered. Moreover, the effects of acceleration of the air born liquid and its dispersal into droplets from a ruptured tank in a crash, can produce other fire effects than have been observed in the tests reviewed here.

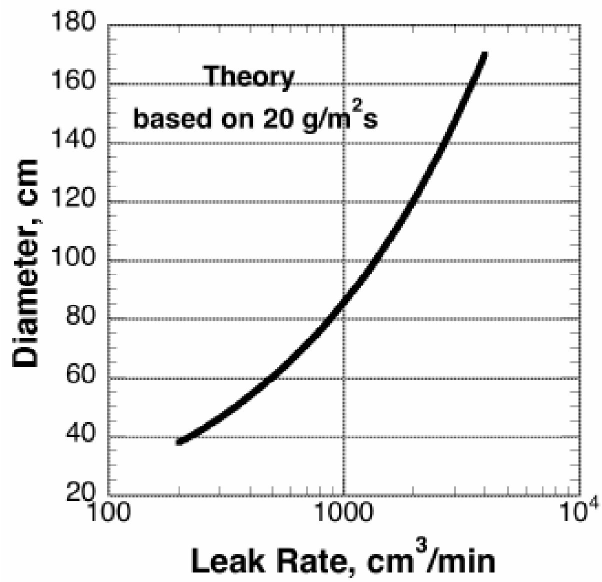

Figure 4-11. Theoretical estimates of gasoline pool diameter.

4.4.2 Engine Fires

The rate of growth of the engine fires is shown in Figure 4-12.

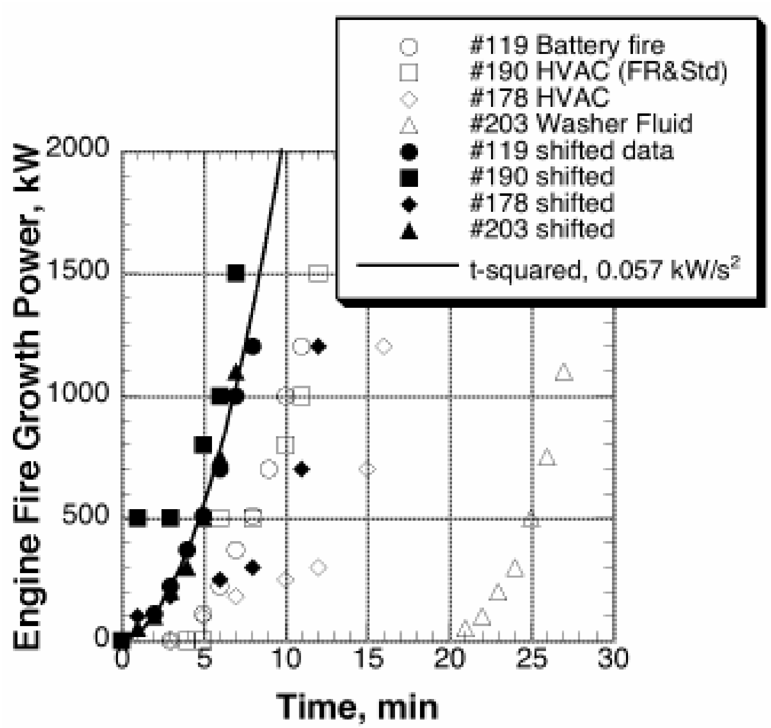

Figure 4-12. Engine fire growth rate

As shown by the data in Fig. 4-12, significant growth was usually preceded by an "incubation period" that is typical and represents the small ignition fire involving other fuels. The incubation period depends on the vagaries of spread and is part of the randomness at reproducing fire growth. If the incubation period is adjusted out of the data, indicated by the filled symbols in Fig. 4-12, the actual growth rate can be assessed. To a large extent, the engine fire growth can be represented by a t-squared fire growth with a coefficient of 0.0057 kW/s^2. This corresponds to 420 s to reach 1 MW and can be classified as a "medium to slow" fire growth.

4.5. South West Research Institute (SwRI) Criterion for the Performance of Materials for Engine

SwRI [4] conducted a review of two of the GM vehicle fires in the 10 tests reviewed here. They examined the 1996 Dodge Caravan (test #1, NHTSA 3588-#119) and the 1997 Chevrolet Camaro (test #4, NHTSA 3588-#178). In addition, SWRI made fire measurements of the individual engine components, and formulated a criterion for evaluating the fire hazard of a particular engine material. This compares to firepower penetration values in Table 4-1, based on the time when the windshield was breached, of 100 kW (96 Caravan) and 250 kW (97 Camaro). One sees that the firepower at penetration is not necessarily a constant since this depends on the ignition scenario for the engine, the spread rate to the windshield or firewall separating the engine and passenger compartments, and on the particular materials.

SwRI suggests a criterion for evaluation of engine material flammability based on the time for that material to produce a critical firepower; namely 400 kW in their assessment. The model uses the peak firepower intensity measured in the Cone Calorimeter ($\dot{\mathbf{Q}}''$ in kW/m^2) at an external heat flux ($\dot{\mathbf{q}}''_{\mathbf{e}}$) of 35 kW/m^2. The model assumes a horizontal slab of material spreading from an initial circular area ($\mathbf{A_o}$) of 0.0079 m^2 at a radial spread rate such that its radius increases by 50 per cent in the time it takes ignition to occur in the Cone Calorimeter ($\mathbf{t_{ig}}$). This spread rate is totally arbitrary, and thus the model includes no realistic element of flame spread. The formula for their model is given without derivation as

$$\dot{\mathbf{Q}}_{\mathbf{crit}} = \mathbf{A_o}\dot{\mathbf{Q}}''(\mathbf{1.5})^{\mathbf{2(t-t_{ig})/t_{ig}}} \tag{3}$$

It might be of interest to see how this formula can be determined from the specified spread rate. The spread is given that the radial increase in time $\mathbf{t_{ig}}$ is

$$\mathbf{\Delta R = 0.5R} \tag{4}$$

where $\mathbf{R}$ is the previous radius. This can be presented in a continuous speed as

$$\frac{dR}{dt} = \frac{0.5R}{t_{ig}}. \tag{5}$$

Integration where $\mathbf{R_o}$ associated with $\mathbf{A_o = \pi R_o}$ is specified to have occurred at $\mathbf{t = t_{ig}}$ gives

$$R = R_0 e^{(t - t_{ig})/2t_{ig}} \tag{6}$$

Then

$$\dot{Q} = \dot{Q}''\pi R^2 = \dot{Q}'' A_0 e^{(t - t_{ig})/t_{ig}} \tag{7}$$

Since $\mathbf{e^{\tau} = b^{2\tau} = (b^2)^{\tau}}$ or $\mathbf{b = \sqrt{e} = 1.65}$, the 1.5 given appears to be in error.

The SwRI proposal appears a bit arbitrary and simple to be accepted as a true quantitative relationship of the fire hazard to passengers from engine materials. However, its premise to use $\dot{\mathbf{Q}}''$ and $\mathbf{t_{ig}}$ measurements are proper. In the analysis used for this report, it was found that the flammability of materials involves the firepower of engine compartment materials, and is essential to reduce it to reduce the fire hazard to passengers. Keeping the firepower of a given engine component so that it is small compared to a critical firepower needed for passenger compartment penetration is a consideration. Also, the ignition time of the material determines how fast it will get involved in burning. The location and quantities of the materials are also significant factors. A standard for approving engine materials might consider all of these factors.

4.6 Conclusions

A review of the ten GM vehicle fire tests has attempted to examine the dynamics of fire growth into the passenger compartment. These tests considered two scenarios (1) engine fires and (2) rear underside gasoline spill fires. There were five tests of each scenario. The following general conclusions can be drawn from the analysis:

1. Flashover times are much shorter for the vehicle fires initiated by gasoline pool fires than those initiated by engine fires. Flashover time (gasoline) = 1.6 to 4.0 minutes. Flashover time (engine) = 10.5 to 26.5 minutes. The gasoline scenario is much more hazardous;

2. Flashover time correlates with the time for flames to penetrate the passenger compartment,

$$\mathbf{t_{FO} = 1.56\ t_{pen}^{0.94}},$$

which is nearly linear. But more significantly for these tests,

$$\mathbf{t_{FO} \approx t_{pen} = 2.3 \pm 2.1\ minutes}.$$

Hence, flashover occurs quickly after passenger compartment penetration, suggesting passenger compartment materials that readily burn under these scenarios.

3. Passenger compartment appears to require the materials in the compartment to contribute at most about 425 kW ± 250 kW to cause flashover. A theoretical estimate suggested as little as 150 kW to 250 kW.

4. The growth rate of the passenger compartment fire was represented as t^2 fire growth due to the gasoline fires as

$$\mathbf{\dot{Q} = (0.18 \frac{kW}{s^2}) t^2}$$

which is very fast in the spectrum of commodity fires.

5. The growth rate of the engine fire could also be represented as a t^2 fire, but with an extensive incubation period before this growth begins. An approximate representation of engine fire growth rate was

$$\mathbf{\dot{Q} = (0.0057 \frac{kW}{s^2}) t^2},$$

which is relatively slow. The incubation time could vary from 3 to 20 minutes, the longest for a window washer fluid ignition source.

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CHAPTER V
SURVIVABILITY IN VEHICLE FIRES

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5.1 INTRODUCTION

In this chapter, a review has been made of: 1) fatal and incapacitating injuries sustained by drivers of passenger vehicles involving post-crash fires [1,2] and 2) combustion product data from the large-scale vehicle burn tests numbers 1 to 11 [3-12] along with the data and analysis included in Chapters II, III, and IV, with an emphasis on aspects affecting survivability. Advantage has been taken of the survivability assessment engineering tools that the author of this chapter has developed (as published in the SFPE Handbook 3rd Edition) [13]. Apparatuses [14-18] that may be suitable for the measurement of properties for toxic hazard assessment have also been reviewed.

The review of the fatal incident reports has been used to establish the main features of fatal crashes involving post-crash fires, in terms of the basic crash and fire scenarios and the effects on vehicle occupants in terms of toxicology and pathology. The engineering tools used have been tested for their applicability to the assessment of survivability in vehicle fires and in providing pertinent information on countermeasures to enhance survivability in vehicle crash fires via fire hardening of materials and/or fire suppression.

The large-scale vehicle fire tests have been reviewed as follows:

- The crash and post-crash fire scenarios used for the large-scale tests have been examined for their applicability to the incident crash scenarios and outcomes;
- The methods used for the large-scale fire tests, in particular the methods used for measurement of temperature and heat flux and methods for sampling and analysis of toxic fire effluent, have been examined in terms of their applicability to hazard analysis for occupants of the passenger compartment;
- The engineering methods used for the evaluation of the effects of heat on passenger survivability (the BURNSIM model) [19] have been reviewed;

- The engineering methods used for the evaluation of the effects of toxic gases on passenger survivability (FAA combined hazard survival model [20] and Purser toxic hazard model) [21] have been reviewed;
- A detailed independent hazard/survivability analysis has been made for two large-scale vehicle fire tests (one involving a gasoline pool fire [Part 10 Ford Explorer] [8] and one involving an engine fire [Part 7 Chevrolet Camaro]) [6] to validate the methods used in these reports. The analysis applies a heat and burn survivability model developed by Purser [13] and compares the findings with those from the BURNSIM model. For toxic gases, the latest form of the Purser SFPE toxic hazard model [13] has been applied, and the results compared with the findings in the large-scale vehicle test reports. The application of these methods to the assessment of time to incapacitation and death in vehicle fires is discussed. The results have been related to the toxicology and pathology findings from occupants of crashes involving fatal post-crash fires [2].
- The review has then been extended to a hazard analysis for all 11 large-scale fire tests in which toxic gases were measured in the passenger compartments. For each test, the key features affecting fire and fire hazard development have been examined and summarized. Based upon the findings, key aspects affecting survivability have been identified and proposals have been made for remedial measures to improve survivability, with predictions of likely affects on fire risk outcomes.

Consideration has then been given to appropriate toxicity testing and toxic hazard analysis approaches for the evaluation of vehicle fire protection strategies and for toxic hazard performance specification of products and materials used in vehicles. Test methods for the evaluation of fire growth rate and toxic product yields have been discussed. The small and intermediate scale test methods used in the NHTSA/MVFRI sponsored study [22] have been reviewed for their applicability to toxic hazard analysis. The toxic product yield data obtained from these tests have been reviewed and validated against other data obtained from standard tests and full-scale fires. The application of toxicity indices has been examined in the context of full-scale fire hazards, and relevance to Fractional Effective Dose (FED) toxic hazard assessment methods in the SFPE Handbook [13] and in current ISO standards (ISO 13344 and ISO TS 13571) [23,24]. For the evaluation of these toxicity tests and also the FMVSS 302 test [25] (a current NHTSA standard test under consideration for inclusion of survivability considerations), advantage will be taken of the approach the author of this chapter has used in the past for the evaluation of the applicability of various ASTM/ISO standard tests to describe the creation of hazardous environments in fires of burning materials and products via simple engineering tools.

5.2 POST-CRASH FIRE SCENARIOS, ACCIDENT STATISTICS AND CAUSES OF DEATH

Although a major subject of this review is the large-scale vehicle burn test data, vehicle accident reports and statistics, and in particular post-mortem reports on fatalities, provide an important potential source of information on vehicle fire survivability. Two reports have been reviewed:

1. A clinical evaluation of the death investigations for 206 decedents who died in passenger vehicles that experiences post-crash fires (NHTSA-98-3588-170) [1];
2. An evaluation of fatal and incapacitating injuries to drivers of passenger vehicles experienced post-crash fire in North Carolina (NHTSA-98-3588-145) [2].

The reports have been reviewed with regard to two major topics:

1. What are the major accidents scenarios involving post-crash fires and how do they compare with the fire scenarios used in the large-scale tests?
2. What can be learned about the causes of death and events leading to death or serious injury of accident victims involved in post-crash fires and how do these compare with the results and hazard modeling predictions from the large-scale vehicle burn tests?

5.2.1 Post-Crash Fire Hazard Scenarios

One issue in relation to this study is that it addresses only post-crash vehicle fires. At some point it may be important to consider vehicle fires other than those involving crashes. How do such scenarios develop and what is the time-course and extent of damage sustained? How many injuries or even deaths occur from such cases?

With regard to crash incidents of passenger vehicles in North Carolina [2], the basic findings are:

1. <u>For single vehicle crashes</u>:

a) 243,109 incidents analyzed of which 1840 (0.76%) had fires;

b) 14,518 drivers sustained serious injuries (category A) or were killed (category K) of which 322 (2.22%) had fires;

c) 1,776 drivers were killed of which 85 (4.79%) had fires;

d) 1840 incidents with fires: 1840-322 = 1518 had no serious injury (82.5%), 85/1840 = 4.6% were killed.

2. <u>For multiple vehicle crash incidents of all passenger vehicles in North Carolina</u>:

a) 1,505,566 analyzed of which 5,411 (0.36%) had fires;

b) 27,333 drivers sustained serious injury or death of which 248 (0.91%) had fires, 2204 drivers were killed of which 87 (3.95%) had fires;

c) 5411 of incidents with fires: 5,411-248 = 5163 had no serious injury (95.4%) , 87/5411 = 1.6% were killed.

Vehicles experiencing post-crash fires generally involved more serious crashes than vehicles that did not experience post-crash fires. In order to establish the effect of fires on survivability it was necessary to correct for this difference in crash severity. After controlling for impact location and severity, drivers of passenger vehicles involved in single vehicle crashes experiencing post-crash fires were associated with 1.87 times as many A+K injuries and 3.44 times as many K injuries. For multi-vehicle crashes the figures were 1.93 (A+K) and 5.66 (K).

*This means that on average, drivers of vehicles involved in post-crash fires were approximately twice as likely to suffer serious injury or death and approximately four times likely to die as drivers involved in crashes of similar severity that did not involve post-crash fires***.** It is therefore likely that the fires were the cause of these excess injuries and deaths.

Another important point is that many people survive post-crash fires. From the statistics presented above, when post-crash vehicle fires occur, 82.5% of occupants (single vehicle) and 95.4% (multi-vehicle) survived without serious injury while 4.6% and 1.6% died. These suggests that for the majority of post-crash fires, either the occupants escape or are rescued before the fire becomes serious, or the fires do not become sufficiently serious to affect trapped occupants. It is also relevant to consider the fate of occupants who are seriously injured, since this is likely to involve more serious incidents, with occupants trapped in vehicles for some time. The statistics indicate that many occupants survive although they are seriously injured (73.6% [single vehicle] and 64% [multi-vehicle] of seriously injured survive). This suggests that even in serious incidents, injured occupants often escape or are rescued before the fire becomes life threatening.

These are encouraging findings from the perspective of this study. It is likely that even small improvements in decreasing the rate of fire hazard development in post-crash vehicle fires could lead to a reduction in injuries and deaths. Some other findings from this study are:

The probability of being injured or killed in a post-crash vehicle fire is low at 0.13% of single vehicle crashes and 0.016% of multi-vehicle crashes. The probability of suffering serious injury or death from physical trauma because of the impact is much higher at 6% for single vehicle crashes and 1.8% for multi-vehicle crashes. There are obvious differences between single and multi-vehicle crash scenarios. In particular, single vehicle crashes are much less likely to involve damage to the rear of a vehicle, which may have implications for the incidence and effects of fuel tank rupture. However, it may be significant that the percentage of fires in single vehicle crashes involving serious injury or death is eight times greater than for multi-vehicle crashes.

The clinical evaluation study [2] is particularly useful because it provides brief descriptions of 207 fatal accidents involving post-crash fires occurring in Texas between (1990–1992) and in North Carolina between (1995-1996). A review has been made of all the Texas cases in which fire was considered likely to have contributed to the death of the driver or passengers. The results of the toxicology, the pathology and the opinion of the medical examiner on cause of death are summarized in Table 5-1.

Although a detailed analysis of the incident crash scenarios has not been made, a general impression from these incidents is that a large proportion involves young adult drivers with blood alcohol levels (BAC) in excess of legal limits. Many consist of single vehicle crashes in which the driver had left the road and hit an obstruction such as a sign or tree. Multi-vehicle crashes commonly involve vehicles stationary at the road side that are hit from behind, vehicles running stop lights, failing to yield precedence at junctions, head on collisions or collisions resulting from failures of lane discipline. Many of these incidents involve impacts at several points on the vehicles, and rear impact damage is more common in multi-vehicle crashes. For both single and multi-vehicle incidents, it appears to be quite common for vehicles to roll during the incident, quite often coming to rest inverted.

Table 5-1. Toxicology and Pathology Database of Post Crash Fire Fatalities in Texas (where fire was a cause of death)

Case	BAC[a]	COHb%	1st cause	2nd cause	3rd cause	Age, medical examiner opinion on cause of death and further comments[b]
TX1	0.2	18	Asphyxia			23, Asphyxia soot and CO
TX2	0.107	18	Asphyxia			24, Asphyxia soot and CO
TX3	0.196	6	Broken Neck	burns	char	34, Soot, broken neck, 2nd and 3rd degree burns 40%, char
TX6		25	Asphyxia			74, asphyxia soot and CO
TX7		22	Asphyxia	char	cancer	76, asphyxia CO and soot
TX9	0.244	7	Char	alcohol		28, charred body
TX10	0.273	55	Asphyxia	char		34, asphyxia soot and CO
TX13	0.157	5	Burns			32, 3rd degree burns 90%, soot and charred body
TX14	0.048	10	Asphyxia	char		41, asphyxia soot and CO and charred body
TX17	0.208	20	Asphyxia	char		24, asphyxia soot and CO, charred body
TX20	0.218	30	Asphyxia	char		24, asphyxia soot and CO charred body
TX21	0.238	5	Char			40, charred body
TX22	0.336	5	Crush	char	Jaw	63, crushed chest and charred body
TX24	0.204	9	Crush	neck	back	29, crushed head, chest, abdomen, broken neck, back
TX25	0.320	10	Fire flash	char		33, fire flash injury
TX27	0.114	0	Lung	asphyxia		16, lacerated lung and asphyxia due to soot
TX31	0.025	38	Neck, soot, CO	char		22, broken neck, soot and CO
TX34	0.245	5	Crush	char		24, crushed chest and charred body
TX35		5	Char	seizure		52, charred body, seizure (epileptic)
TX40	0.260	20	Asphyxia	pelvis and ribs	char	42, asphyxia soot and CO. Fractured pelvis and right ribs 1-10
TX42	0.121	10	Asphyxia	char		34, asphyxia soot and charred body
TX43		11	Asphyxia	ribs	char	42, asphyxia soot and CO, multiple rib fractures and charred body
TX44	0.151	60	Char			20, charred body
TX48	0.155	5	Burns	liver, ribs, pelvis		38, 3rd degree burns 100% lacerations of liver with hemoperitoneum, multiple rib fractures and pelvis
TX49		14	Smoke, burns, CO			19, smoke and burns consistent with flash fire
TX50	0.24	1	Smoke, burns char,soot	head	Alch	34, smoke and burns. Char, soot, subarachoid, atlanto-occipital hemorrhage, acute ethanol intoxication
TX51		29	Smoke, burns,	head		23, smoke and burns. Also blunt force injuries to head with hemorrhages over brain surface
TX54		6	Char,CO	heart		52, smoke and burns. Hypertrophic cardiomyopathy
TX55	0.13	11	Impact, burns	alcohol		33, multiple impact injuries with total body burns, subdural hemotoma, burns and partial incineration, alcohol
TX59		11	Burns, smoke			38, burns and smoke. No blunt force injuries, 100% burns, soot in airways, burns in pharynx
TX62	0.02	27	Smoke, burns	Neck		24, smoke, burns and broken neck
TX63	0.19	16	Fractures	Char	Heart	36, blunt force and thermal injuries. 95% char
TX64	0.13	12	Impact and thermal			41, blunt force ad thermal injuries
TX66	0.20	29	burns, CO			39, 3rd and 4th degree burns 60%, CO, soot upper and lower airways, obesity, post hysterectomy, alcohol
TX68	0	8	smoke, burns			45, smoke and burns. Charring and 3rd degree burns, extensive soot in airway, CO, no lethal blunt force injury
TX69	0	<1	burns			7, months. Multiple full thickness burns, no blunt force in.
TX70	0	2	burns		heart	60, thermal injuries. 4th degree burns 100%. Mild atherosclerosis, cardiomegaly

Table 5-1 continued on the next page

Table 5-1 continuing from the previous page

Case	BAC	COHb%	Ist cause	2nd cause	3rd cause	Age, medical examiner opinion on cause of death and further comments[b]
TX71	0.19	17	Impact	Smoke, burns		23, combined effects of blunt injuries and near total body surface thermal injuries. Fractured sternum, brain injuries. Burns 100% from superficial to full thickness
TX73	0	<1	Burns			burns. Charring, minimal soot larynx
TX75	0.22	31	Impact	Smoke, burns, alch		29, multiple blunt force injuries, smoke, extensive burns and toxic effects of alcohol.
TX76	0.22	22	Burns	CO	fracture	43, blunt force injury to head, burns almost 100%
TX79	0.05	11	Impact	Soot, burns		33, inhalation of heat and blunt force injuries. Fracture clavicle, blood in pleural cavity, right femur, moderate soot in airways with superficial burns of epiglottis
TX80	0.15	10	Impact	Flash		32, burns, intoxication by fire products, blunt force. Fractured sternum, flash fire exposure: partially charred body, small amount of soot in airways
TX81	0	1	Fire			54, fire injury (but next case in same vehicle)
TX82	0	39	Burns	Soot CO		18, inhalation of combustion products and thermal injury. 4th degree burns 100%, soot upper and lower airways heat fracture to skull subdural haemorrhage
TX83	0.17	17		Smoke		cause unknown
TX85*	0	26	Impact			44, blunt force injuries and smoke. Multiple fractures of rib cage with contusions of both lungs. Liver and spleen lacerations. Moderate soot
				Burns		in airways.
TX86*	0	10	Smoke			18, inhalation of toxic smoke products and extensive burning. Smoke with soot and coloured mucus in upper and lower airways, 4th degree burns 85%. No traumatic injuries, 12-14 weeks pregnant
				Smoke		10, burns and smoke. "Open area". Extensive burns with partial
TX87*	0	9	Burns			charring. Small soot in airways.
				Burns		25, combination of blunt force and burns – flash fire?
TX97	0.21	3	Impact			18, multiple injuries and thermal burns No CO data
TX98				CO		18, thermal injuries. Extensive 4th degree burns
TX99	0.10	27	Burns			Three persons in one vehicle – little information
TX100 -02				alcohol		17, smoke inhalation and thermal burns. 80% burns, extensive soot in
TX103	0.27	73	Burns, smoke			airways. 16, acute fire injuries from an accelerant fire, also trauma. Extensive
TX105	0	<1%	fire			4th degree burns, laceration of liver and spleen, hemoperitoneum, brain injuries,

a: BAC: blood alcohol level; b: first number represents age

5.2.2 Examination of Toxicology and Pathology Data from Fatal Post-Crash Vehicle Fires in Texas

An important aspect of this project is to establish the causes of death in post-crash fires, and in particular the relative importance of toxic smoke inhalation and that of heat and burns. Also important is to estimate the time from first exposure to death. In this context the percentage blood carboxyhemoglobin concentrations (%COHb) provide a valuable source of information, especially when considered in conjunction with the pathology reports. In general, all fires produce some carbon monoxide [13]. The longer a vehicle occupant survives during a post-crash incident the higher the %COHb. Carbon monoxide is also the major toxic fire gas and a major cause of incapacitation and death from exposure to toxic fire effluent [13,26]. An examination of the %COHb in a decedent therefore enables estimates to be made of how long the exposure continued before death, the extent to which death can be attributed to inhalation of toxic fire effluent, and the extent to which death resulted from physical trauma, or heat and burns.

Figure 5-1 shows the percentage frequency distribution of deaths at different post-mortem %COHb levels in a large sample of fire and non-fire deaths in the United States studied by Nelson [27]. The non-fire deaths consist mainly of accidental CO exposures resulting from faulty space heaters or suicides (mostly in young men and often by inhalation of vehicle exhaust fumes). The fire deaths are for decedents dying from exposure to fire effluent in the absence of significant burn injuries.

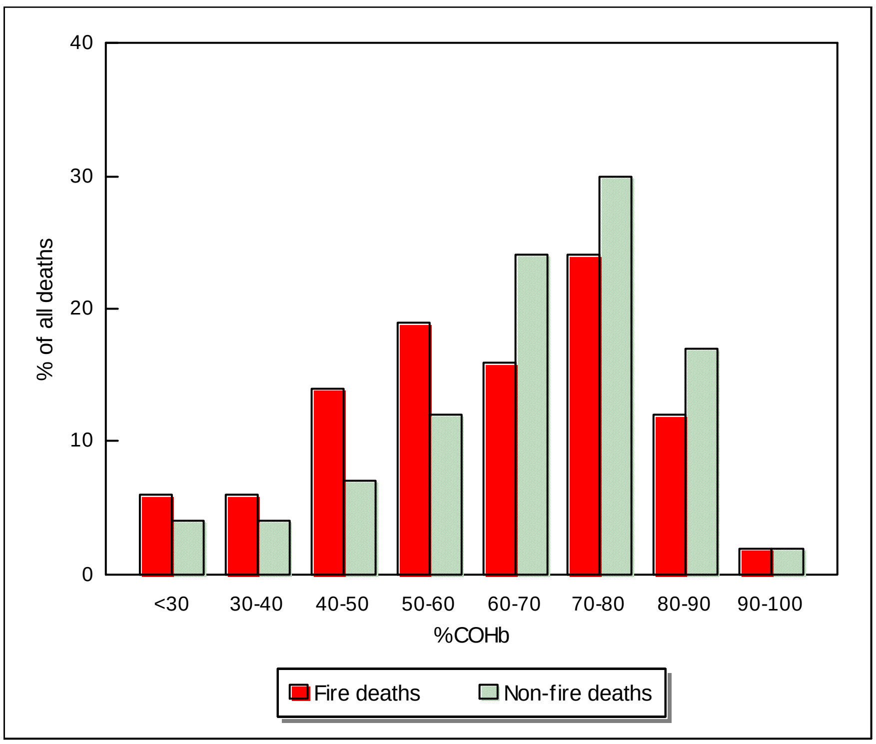

Figure 5-1. Frequency distribution of fire and non-fire deaths at different %COHb concentrations from Purser [13] (data from Nelson [27])

The basic findings from this and from other data, including experimental data on humans and other primates [13,27] are that incapacitation resulting from acute CO poisoning typically occurs between 30 to 40%COHb as intoxication followed by loss of consciousness [28]. It is rare for people dying from CO poisoning to have less than 30% COHb in their blood, although this can occur occasionally, particularly if there is some pre-existing medical conditions such as heart disease. As Figure 5-1 shows, the mode for %COHb in fatal CO poisoning is 70-80% COHb and levels of up to 90% are quite common. It is considered that a typical fatal blood concentration is around 50% COHb, in that subjects rescued alive at this level may not survive even if given prompt treatment. The data for fire fatalities shows similar but somewhat lower blood concentrations in fatalities. The higher incidence of fatalities with 30 to 60%COHb may reflect the added effects to CO poisoning of other toxic products in fire effluent (hydrogen cyanide, smoke particulates and irritants). It is considered that for death to be attributable solely to the inhalation of toxic fire effluent in an otherwise healthy subject the %COHB would be expected to be in excess of 30%COHb and most likely in excess of 50%COHb.

Figure 5-2 shows a similar plot of the %COHb in fatalities from the Texas post-crash vehicle fire data. The data consist of 53 fatalities for which fire is identified as a contributing to the causes of death and a small number for which the effects of fire are less certain. Cases where death was obviously a result of physical impact trauma have been excluded.

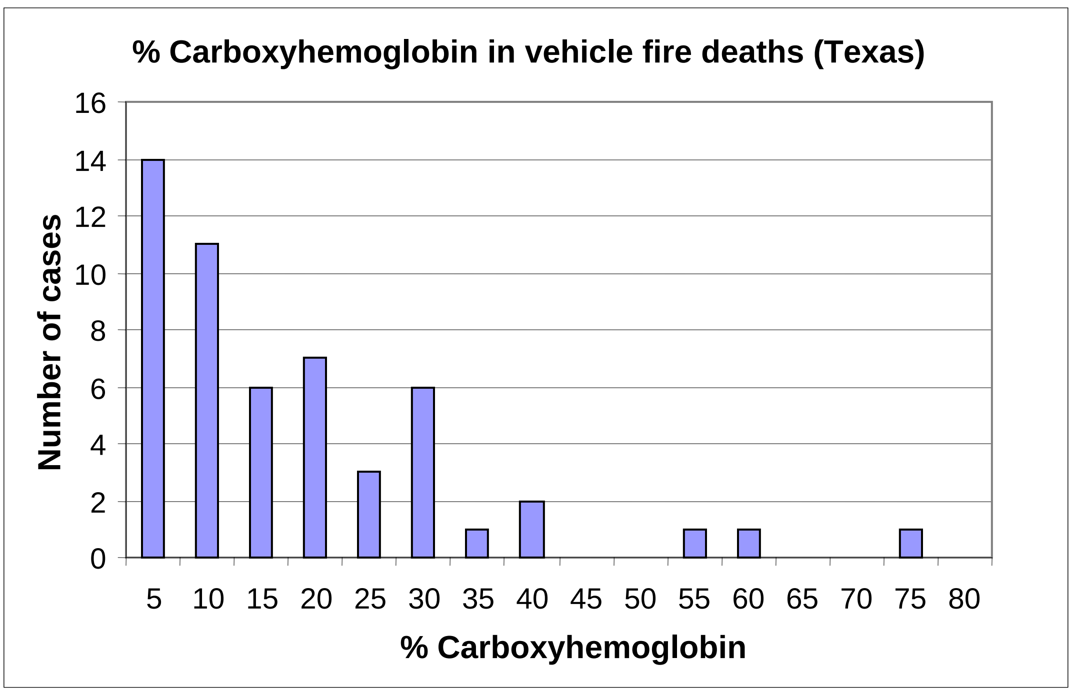

Figure 5-2. Percent carboxyhemoglobin in 53 vehicle fire fatalities from the Texas data for which fire could be idenified as contributing to the causes of death (first set 0-5%, second 6-10% etc).

The results show three cases with %COHb concentrations sufficient to have caused death from CO poisoning alone, plus another three where CO might be considered a possible major factor. For nine cases showing levels between 20 and 30%COHb it is possible that asphyxia from the combined effects of toxic combustion products may have been a major cause of death, but other factors may have contributed. For the majority of cases with %COHb concentrations of less than 20%, it is likely that either physical trauma or heat and burns, or a combination of both were major contributory causes to death, possibly with some influence from inhaled toxic fire effluent.

In general, a low but measurable %COHb in a fatality is evidence that vehicle occupants were alive after the crash, but survived for only a relatively short period during which they were exposed to fire effluent. The exposure time required to achieve a given %COHb depends upon the average CO concentration in the vehicle. In practice, the CO concentration increases over a period of a few minutes as the fire grows and the effluent penetrates the cabin. Figures 5-3 and 5-4 show two examples taken from the full-scale post crash fire tests (Test # 6, Part 10 1998 Ford Explorer mid-underbody gasoline pool fire [8] and Part 7 1997 Test #4, Chevrolet Camaro engine compartment fire [6]).

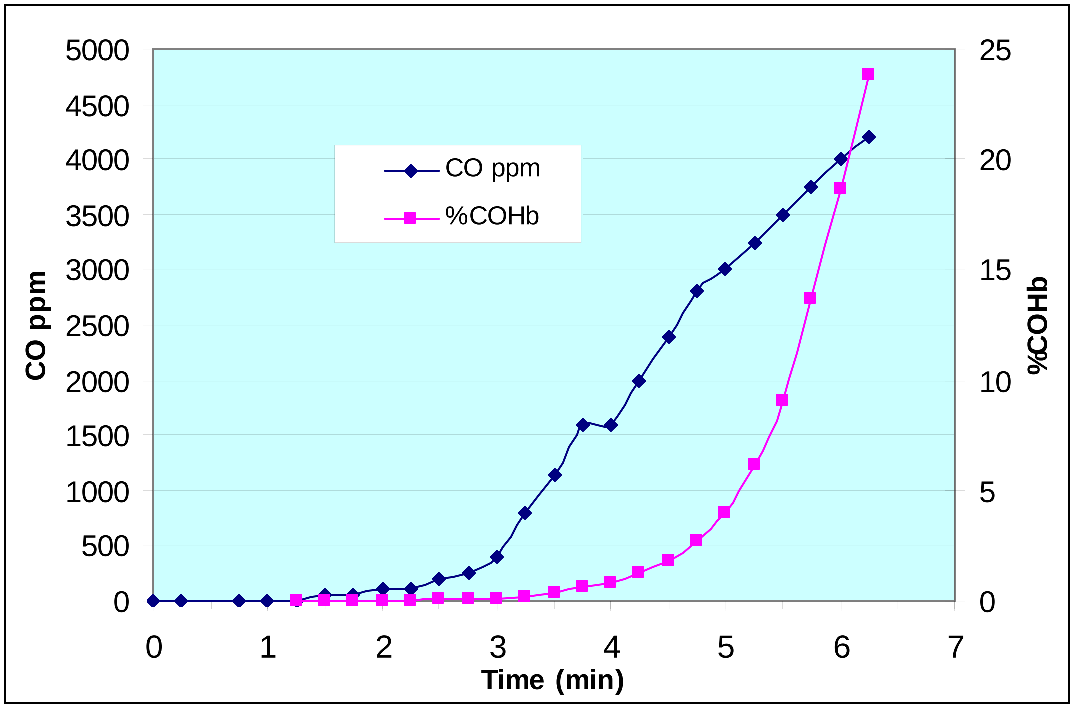

Figure 5-3: Measured passenger compartment CO concentrations and predicted %COHb for an exposed subject. Full-scale fire test report 6-189 Part 10 for Test #6. Mid-underbody gasoline pool fire 1998 Ford Explorer [8]

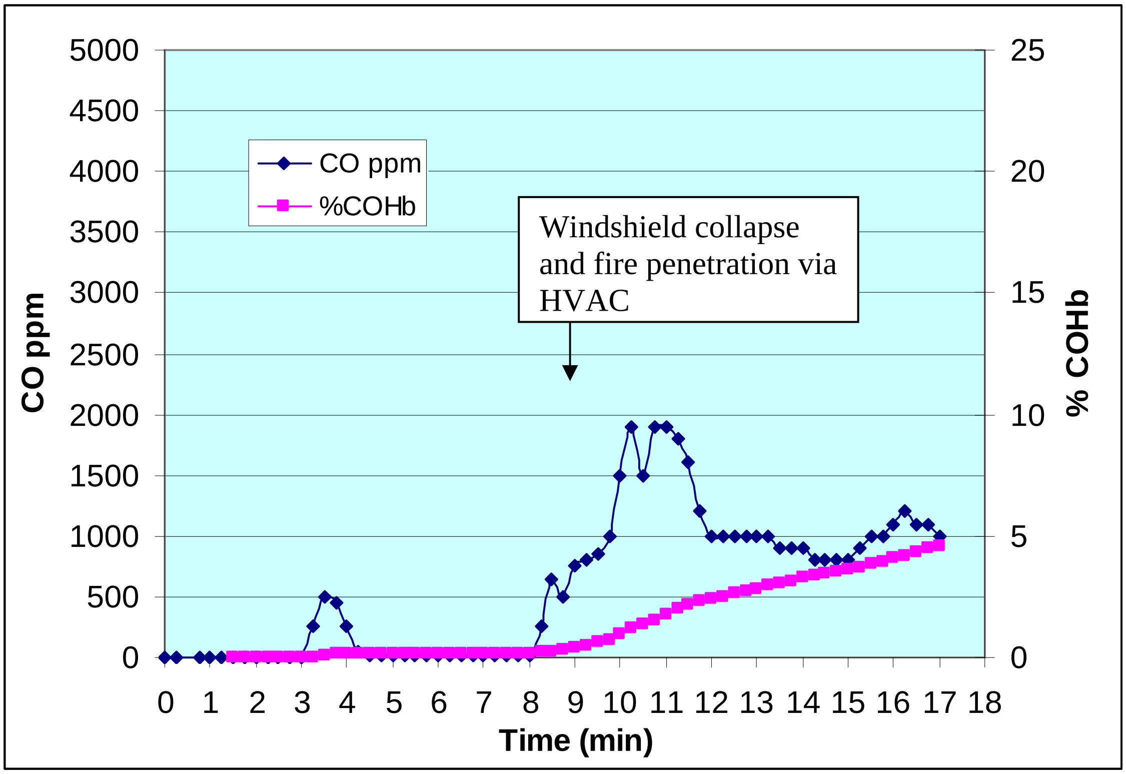

Figure 5-4: Measured passenger compartment CO concentrations and predicted %COHb for an exposed subject. Full-scale fire test #4 report 4-178 Part 7. Engine compartment fire 1997 Chevrolet Camaro [6].

The predicted %COHb with time in the figures has been calculated based upon the CO and CO_2 concentrations measured in the cabin during these tests (using the method of Purser) [13]. The results show that once there is significant penetration of fire effluent into the cabin approximately 1-2 minutes are required for the predicted %COHb to increase by 1%. The subsequent increase depends upon the fire. For the more rapidly increasing CO level in the pool fire case 10% COHb is predicted after approximately 3.5 minutes exposure, while for the slower growing engine fire case the blood concentration is predicted to take approximately 7 minutes to reach around 5%COHb. For these examples the subject was assumed to be a 70 kg adult male with a resting respiration of 10 liters/minute (varied according to the CO_2 concentration during the test).

The background %COHb (before an accident) depends upon the level of environmental exposure and whether or not the subject is a cigarette smoker. Typical background levels in non-smokers in vehicles would be expected to be approximately 0.5-1.5% and for smokers approximately 3-5%, with a maximum in a heavy smoker of 8-10%COHb [13]. Exposure levels in the fire would then be added to these baseline figures. Based upon these examples it is considered likely that decedents with < 2% COHb are likely to have been exposed to fire effluent for a short period of a few minutes depending upon the fire, and may have died from the effects of impact before severe fire exposure occurred. The cases summarized in Table 5-1 show 4 cases with %COHb of less than 10% associated with severe crush or impact injuries. It seems likely that these deaths are mainly attributable to physical trauma. Another 6 cases show <10% COHb with significant physical trauma and severe burns. It is likely that for these cases death resulted mainly from either physical trauma or burns, or a combination of both. For another 15 cases severe burns or charring of the body are associated with an absence of severe physical trauma and <10% COHb. It is likely that these deaths results mainly from the exposure to heat and burns.

There are some cases where a moderate level of CO intoxication is associated with physical trauma affecting the chest and lungs. It may be that for some of the cases the combination of toxic smoke exposure and physical breathing difficulties may have contributed to death. For other cases in this mid-COHb range, it is likely that heat and burns were the main causes of death, with some contribution from toxic smoke inhalation. It is also likely that a significant period elapsed between the first penetration of fire effluent into the vehicle and the time of death. Based upon the two test examples shown this could be anything between 2-3 minutes after fire effluent penetration to more than 10 minutes. For a few cases, exposures may have been longer and inhalation of toxic fire effluent may have been the primary cause of death.

In a number of cases, the medical examiner has given the opinion that asphyxia, soot and CO inhalation were the cause of death when the %COHb was less than 30%. One factor that may add somewhat to the toxic effects of CO is alcohol intoxication. In general, exposure to carbon monoxide is unlikely to be fatal at these levels, but involvement of other factors such as heat and burns or, physical trauma may influence the fatality.

In general, the evidence from these cases points to heat and burns as a major cause of death in the majority of cases where physical trauma is unlikely to be fatal. Many of the deaths are likely to have occurred after a relatively short period (a few minutes), either due to physical trauma or heat exposure. For some cases, the vehicle occupants may have survived for a longer period, enabling asphyxiant fire gases to reach incapacitating or fatal levels in the blood. In almost all cases (including those where death occurred immediately due to impact), the post-crash fires became sufficiently severe to cause major burns and charring of the bodies, much of which may have occurred after death.

In general, it is considered that a more in-depth analysis of post-crash fire incidents would be valuable. It would be useful to examine the type and extent of crash-scenarios in different classes of vehicles and the extent of subsequent post-crash fires. It would be useful to determine the history of a sample of incidents in terms of the time the fire started, how long it burned, the time of arrival of the emergency services and the status of the vehicle occupants. A more detailed examination of the post-mortem data to establish exposure history and effects of heat and toxic gases would also be useful. Information on survivors of post-crash fire incidents and their experiences could also be valuable.

5.2.3 Implications of Fire Incident Data for Choice of Fire Scenarios in Full-Scale Fire Tests

Based on the analysis of the fire incident data it would seem that choice of crash scenarios and post-crash fire scenarios used for the full-scale fire tests can be considered representative of many typical real incident scenarios. Front or side impact followed by a fire is typical of many singe vehicle crashes and a proportion of multi-vehicle crashes. Rear impact damage is a common feature of multi-vehicle crashes. *It would be useful to consider full-scale post-crash fires in overturned vehicles in any future work.*

5.3 TOXIC EFFLUENT INCAPACITATION AND LETHALITY MODELS

In order to estimate the fractional effective doses, and times to incapacitation and death, use has been made of the FAA combined hazard survival model [20] and Purser's model from the SFPE Handbook 1995 edition [21]. Both these models aim to predict dose and time to incapacitation resulting from asphyxia. The FAA model computes FEDs (fractional effective doses) for the incapacitating effects of CO_2, CO, HCN, HCl and low oxygen hypoxia. The expressions for CO, HCN and HCl are corrected for the hyperventilatory effect on uptake rates of elevated CO_2 concentrations (VCO_2). The individual terms are summed to provide an overall FED for incapacitation. The individual expressions for each component of the model are derived from a review of experimental data obtainable from a number of animal species including some human data for some terms. The Purser SFPE Handbook model is also derived from a comprehensive review of available animal and human data for the effects of each component and their combined effects based upon physiological principles. The version used for these reports considers the asphyxiant effects of CO, HCN and low oxygen hypoxia. As with the FAA model, the uptake of CO and HCN are considered to be increased by the hyperventilatory effect of CO_2. The Purser model as used differs from the FAA model in that HCl is not considered as an asphyxiant and the direct incapacitating effects of CO_2 are considered to act separately from the asphyxiant effects of the other gases. The expressions used for each term have been obtained mainly from human and primate data and differ somewhat from those derived for the FAA model.

The FAA model also has a set of equations designed to predict time and dose to lethality. For the Purser model, it is stated that the lethal dose should be considered as approximately 2 to 3 times the incapacitating dose [13, 21].

There is some degree of uncertainty with respect to predictions of dose and time to incapacitation by these models. This results partly from the problem that it is not possible to carry out detailed experiments in humans to obtain accurate data for incapacitation or lethality, so in developing these models reliance has to be placed on human experimental data for sub-incapacitating exposures and incapacitating or lethal data obtained from animals, combined with modeling of predicted effects of gas mixtures. Another source of uncertainty is the inherent range or susceptibilities within the human population. This is illustrated to some extent by the range of susceptibilities to CO poisoning shown in Figure 5-1. Sensitive subjects may have died with as little as 20% COHb while subjects that are more resistant are found dead with up to 90% COHb in their blood. Despite these difficulties, it is possible to predict time to incapacitation in most fires with some confidence. This arises from the t^2 rate of increase in the concentrations of toxic products in most fires. As the analyses in the large-scale fire tests reports show, the predicted FEDs tend to increase very rapidly when fire conditions become serious. The time interval between a predicted FED = 1 and FED = 2 or more is often only a matter of tens of seconds. Thus, in the Part 10 report [8], the predicted times to incapacitation from the different models using different input assumptions differ by only about 20 seconds.

The predicted times to incapacitation by the FAA model are somewhat shorter than those predicted by the Purser model. One reason for this may be the treatment of HCN intoxication. The FAA model multiplies the inhaled concentration of HCN by VCO_2 in order to calculate the fractional dose at each time interval. The Purser model calculates the dose and then multiplies this by VCO_2. Since the FED expression is exponential, the FAA method provides a larger estimate of dose received for a particular exposed concentration than does the Purser model. More recent versions of the Purser model (See SFPE Handbook 3rd edition [13]) allow for this alternative approach for dealing with HCN and also include a term for the overall asphyxiant contribution from inhaled irritants. This provides a closer agreement to the FAA model.

In general, it is considered that both models provide a reasonably good estimate of time to incapacitation and lethality for the average young adult. It is possible in more detailed analyses to allow for children of different ages and adults, taking into consideration the effects of gender and body weight adults as well as different levels of activity. An independent analysis of the data and predicted doses and times of incapacitation has been made for large-scale fire, report parts 7 and 10 [6,8] as a check on the analyses performed in the report. These are presented and discussed in a later section, but in general a good agreement is obtained with the analysis in the reports. *It is therefore considered that the FAA and Purser models have been correctly applied and interpreted, and that they are suitable for this purpose.*

5.4 BURNSIM MODEL AND PREDICTIONS FOR TIME TO BURNS AND INCAPACITATION AND DEATH FROM EXPOSURE TO HEAT

The prediction of time to pain, burns, incapacitation, and death because of heat exposure is an important aspect of survivability in fires. Reasonably good human experimental models exist for predicting "dose" and time to pain and burns from exposure to radiant heat [13]. There are also reasonable data and models for prediction of the extent of first, second and third degree burns resulting from radiant heat exposure [13]. Long-term survivability following burns depends upon the depth of burn, body surface area burned and age of the subject, as well as the treatment received. This has also been well documented.

In contrast, the time to pain and burns from convected heat (contact with hot air) has been less well studied. Empirical correlations between temperature and time to pain for exposed skin have been derived by Purser from the experimental work of Blockley as reviewed by Purser [13]. An expression for time to pain, second and third degree burns has also been developed by Purser for exposure to radiant heat [13,24]. Total "dose" and time to pain for exposure to both convected and radiant components is obtained for this model by summation of the convective and radiant terms. Since this additive model was published in the SFPE handbook 3rd edition

[13] and ISO TS13571 [24], an attempt has been made to develop a total heat flux model by calculating and summing the convective and radiant terms in terms of flux (kW/m^2). Time to pain and burns is then given by reference to the radiative flux data.

The “BURNSIM” model as applied to the large-scale vehicle fire study by Strom et al. [19] and originally developed by Knox et al. (see reference 19), has been reviewed and is considered to be an advance model for the prediction of burns. The direct measurement of total heat flux in the large-scale fires enables a combined convective and radiant flux term to be used as input to the BURNSIM calculation.

It is therefore considered that the BURNSIM model provides a good method for application to the vehicle fire study. For review and comparison, the Purser combined flux model (developed for this review) and the published Purser SFPE models have been applied to two example fires included in parts 7 and 10 reports [6,8]. In general, a good agreement is obtained, in that both models predict burns or lack of burns from the same data. The results of these example calculations are presented in a later section. A possible difficulty with the data in part 10 report [8] is that the measured total heat flux seen by the total heat flux meters appears to be somewhat lower than that predicted from the temperature of the effluent as measured by the aspirating thermocouples. Since the smoke density was high, a significant radiant flux would be predicted from the hot smoke. This is discussed in detail in a later section.

Although the relationships between heat flux, pain and burns are reasonably well understood, it is more difficult to predict time to death from a short exposure to extreme heat. This subject is reviewed in Purser [13]. There are two main mechanisms whereby exposure to heat may cause death within a few minutes. One mechanism is inhalation of very hot gases. This may cause burns to the throat followed by laryngeal spasm and asphyxiation. Although the spasm may relax as the subject becomes unconscious, inhalation of very hot gases appears to cause respiratory arrest followed by death, possibly due to subsequent cardiac arrest. At least one report of burns to the epiglottis was included in a Texas pathology report. Another reported mechanism (based upon experimental work using pigs) is death due to cardiac arrest caused by heated blood entering the heart. In these experiments [29], when pigs were exposed to high temperatures above 120°C for periods of up to 15 minutes, they suffered from skin burns and hyperthermia. In this situation the exposure duration was considered insufficient to raise the body core temperature greatly, so hyperthermia was insufficient to cause death, but if the temperature of the heated blood returning to the heart reached 42.5°C the animal died within a few minutes from circulatory collapse. Human volunteers have been exposed to hot dry air at temperatures of up to 205°C for up to 4 minutes (clothed but bare-headed) without injury, tolerance time being limited by skin pain. However, it is considered that the total heat flux to a subject enveloped in smoke at this temperature would be higher than for air, due to the radiative component from smoke particles that would be absent from heated air. In general, it is considered that exposure to hot smoke at temperatures in excess of 200°C or to total heat flux of more than approximately 12 kW is likely to be fatal within a few minutes, as is direct contact with flames.

Also from a modeling perspective it is considered that once 3rd degree or full thickness burns are predicted, time to death from a continued exposure may be within a minute of so. Post-exposure survival is threatened once full thickness burns are predicted over more than approximately 50% of body surface area.

Another variable referred to in the reports regarding respiratory tract burns (which is also likely to apply to skin burns) is the water content of the fire effluent atmosphere. As stated in the reports, inhalation of steam at 100°C causes massive and rapidly fatal lung burns. In experiments, the highest temperature at which fully saturated air can be breathed is reported to be 60°C [13]. Based upon calculations of latent heat delivery to the lung and the water content of fire atmospheres, it is considered that the additional heat delivery to the lungs from the water in combustion product atmospheres should not be a significantly more serious cause of lung burns than hot dry air [30]. The water vapor content of combustion atmospheres such as those involved in the vehicle fires should be approximately the same as the CO_2 concentration. At this concentration the heat delivery by the water vapor should not be extreme. A serious problem from water vapor could occur when a spray mist or sprinkler is released onto a fire and fails to provide rapid extinction. If the air temperature is maintained above 60°C fully saturated for a minute or so, then heat delivery to the lung from this source could be a problem. In practice, it has been found that sprinkler and water sprays have generally provided a rapid temperature decrease to below this level.

In general, it is considered that the BURNSIM model using a total heat flux (convective + radiant heat) input provides a useful advance on previous methods for predicting the extent of *burns in hot environments. This does not predict time to death from heat exposure. Suggestions have been made on how this may be addressed.*

5.5 RESULTS OF LARGE-SCALE VEHICLE BURN TESTS FOR OCCUPANT SURVIVABILITY

For the review of occupant survivability in the large-scale burn tests a detailed examination has been made of the results of the 11 large-scale burn tests in which toxic gas concentrations were measured in the passenger compartment (See details in Chapters III and IV).

In order to assess survivability and the effects of different system components and performance it is first necessary to consider both general and specific aspects of the fire scenarios. The general fire incident scenario chosen for this work is a post-crash scenario in which the vehicle occupants are incapacitated or trapped in the vehicle so that at least several minutes are needed for rescue to be carried out. The incident scenario is important because it is necessary to consider what is an appropriate target time for occupants to be protected from fire during a post-crash fire.

If occupants are uninjured and not trapped then protection should be required for only a few minutes. For such a scenario a reasonable target time might be two minutes (to enable a short recovery time from the immediate incident, evacuate the vehicle and remove young children). A more conservative post-crash protection target for such a scenario might be five minutes.

If the scenario is designed for the protection of trapped or injured vehicle occupants, then much longer target protection times may be required. For example, protection may be required until the average or the maximum time of attendance and rescue by the emergency services. This depends upon time to reporting of the incident and attendance times, which may be quite short (5-10 minutes) in a city up to hours in a rural area. If the target time is related to a city scenario then it might be set at 15 or 30 minutes. If more comprehensive protection is required then target times become very long and the only realistic solution would be total protection of the occupants (i.e. that all vehicle fires should be prevented or fires should remain small and self-extinguish before penetrating the passenger compartment).

Leaving aside the question of target protection times, this review has been conducted on the basis that vehicle occupants are trapped or injured. Survival time therefore depends upon how long tenability is maintained in the passenger compartment. There are several potential mechanisms whereby tenability in the passenger compartment may be lost:

1. Passenger compartment remains intact and there is no internal fire or penetration of fire effluent, but an external fuel or engine compartment fire raises the temperature inside the passenger compartment and occupants are overcome by heat;
2. Passenger compartment remains intact and there is no internal fire but toxic gases from fuel or engine compartment fire penetrate passenger compartment and overcome occupants;
3. Passenger compartment remains intact and there is no internal flaming fire but heating of vehicle shell causes off-gassing of toxic fumes which overcome occupants;
4. Fire penetrates the passenger compartment and occupants are overcome by heat or toxic products from the primary fire;
5. Fire penetrates the passenger compartment, igniting secondary fires inside the passenger compartment. Occupants are overcome by heat and/or toxic gases mainly from the secondary fire.

There is no doubt that the key aspect of protection is to maintain the integrity of the vehicle passenger compartment. If loss of tenability depends upon simple external heating then important aspects are simply the size of the fire and the thermal insulation of the passenger compartment. Remedial measures should address flammability and insulation.

If the second mechanism (toxic gas penetration) is important, then attention may need to be given to both flammability and the toxic potency of combustion products from burning fuels and engine components, and the flame pathway into the passenger compartment. Toxic hazard is dependent on the mass burning rate multiplied by the toxic potencies of the burning fuels. There can potentially be a trade-off between improved fire performance and toxicity. In some cases, fire-retarded materials burn more slowly but produce more toxic fumes, so that attention may need to be given to the nature of the products, if this mechanism of tenability loss proves to be important. To some extent increased toxicity results from reduced combustion efficiency leading to increased yields of "normal" toxic combustion products such as carbon monoxide. It also results from an additional range of toxic products derived from the "heteroelements" used in fire retardants (such as nitrogen, fluorine, chlorine, bromine and phosphorus).

The third possibility is that heating of the passenger compartment exterior results in non-flaming thermal decomposition of the passenger compartment lining materials, producing toxic fumes, which overcome the occupants. An example of this process could be heating of the steel under body by a pool fire under the vehicle causing decomposition of the carpeting.

The fourth possibility is an extreme version of mechanisms 1 and 2. For this case the fire and/or fire effluents from the external primary fire enter the passenger compartment so that occupants are overcome by the heat and/or products of combustion. For this case, survival time depends upon the fire size, the extent of penetration of heat and/or effluent into the passenger compartment and the yields of toxic effluent species from the primary fire.

The fifth possibility is that the fire penetrates the passenger compartment and ignites the compartment interior. Occupants are overcome mainly by heat and/or toxic gases generated by this secondary fire. For this case, survivability depends to some extent on the fire performance and toxic hazards from fires involving the passenger compartment contents (carpets, linings, seats etc.).

In practice, it is likely that all these mechanisms are involved to a greater or lesser extent and of course they are not all independent of each other. Despite this, it is considered that identification of the key processes affecting tenability may indicate improvement strategies most likely to provide improved survivability.

In the next section, the results of the individual large-scale vehicle burn tests are reviewed and the extent to which different mechanisms affect survivability is identified. A very detailed analysis has been made of two large-scale fires, one consisting of a rapidly growing gasoline pool fire (Test 6: Part 10 Propagation of a mid-underbody gasoline pool fire in a 1998 sports utility vehicle [Ford Explorer – NHTSA-98-3588-189]) [8] and the other consisting of an engine fire (Test 4: Part 7: Propagation of an engine compartment fire in a 1997 rear wheel drive passenger car [1977 Chevrolet Camaro – NHTSA-98-3588-178]) [6]. Following this, a detailed analysis and review of the results of the other 9 large-scale vehicle fire tests has been made and the overall results and their implications have been examined.

5.5.1 Hazard from Heat in Crashed Vehicle Burn Test #6

In Test #6, crashed 1998 Ford Explorer was used and fire was started mid-underbody by a gasoline pool fire [8]. Details of this test are described in Appendix B-6 and in Chapter III. In the test, measurements were made for the temperatures, radiant flux and concentrations of products in the cabin. The temperature and radiant flux measured in the cabin in the cabin are shown in Figure 5-5. The data are averaged over 0.25 minute periods (using data read from the charts in the report). The convective heat flux has been calculated from the temperature and the sum represents the total heat flux to an occupant at approximately head height. The summed maximum value of 2.2 kW/m^2 between 4 and 4.25 minutes agrees well with the maximum total heat flux measured over this period by heat flux transducer.

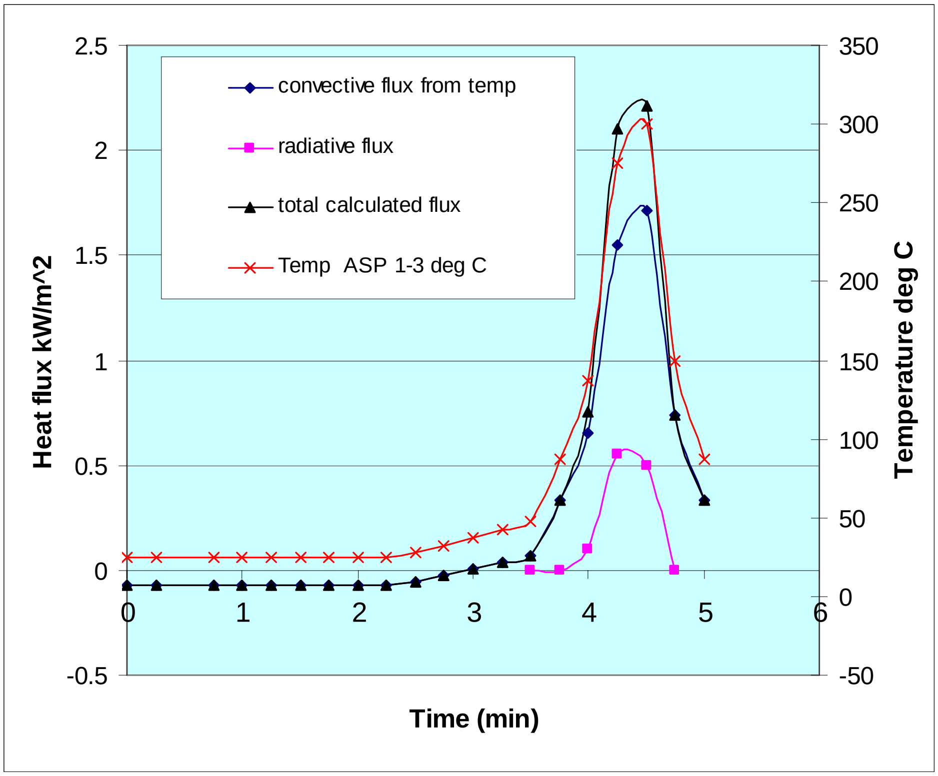

Figure 5-5 Test 6-189 Part 10 [8]: Ford Explorer – gasoline pool fire: temperature, radiant and total heat flux in the passenger compartment

There is, however, a concern that at an average temperature of around 300°C, with high smoke particulate concentrations of 1354 mg/m^3, the radiation from the hot smoke would be expected to be considerably more than the measured value of 0.6 kW/m^2. It is estimated that a flux close to 5 kW/m^2 may be more appropriate. It is possible that the effluent temperature at the radiometers may have been somewhat lower than that sampled by the aspirating thermocouple.

Assuming the heat conditions in the cabin were as shown in Figure 5-5, it is possible to estimate the effects these would have on a cabin occupant. The results of the application of several modeling approaches are shown in Figure 5-6. In the figure, heat exposure is treated as an accumulating "dose" of heat in the same way that toxic gas effects are treated.

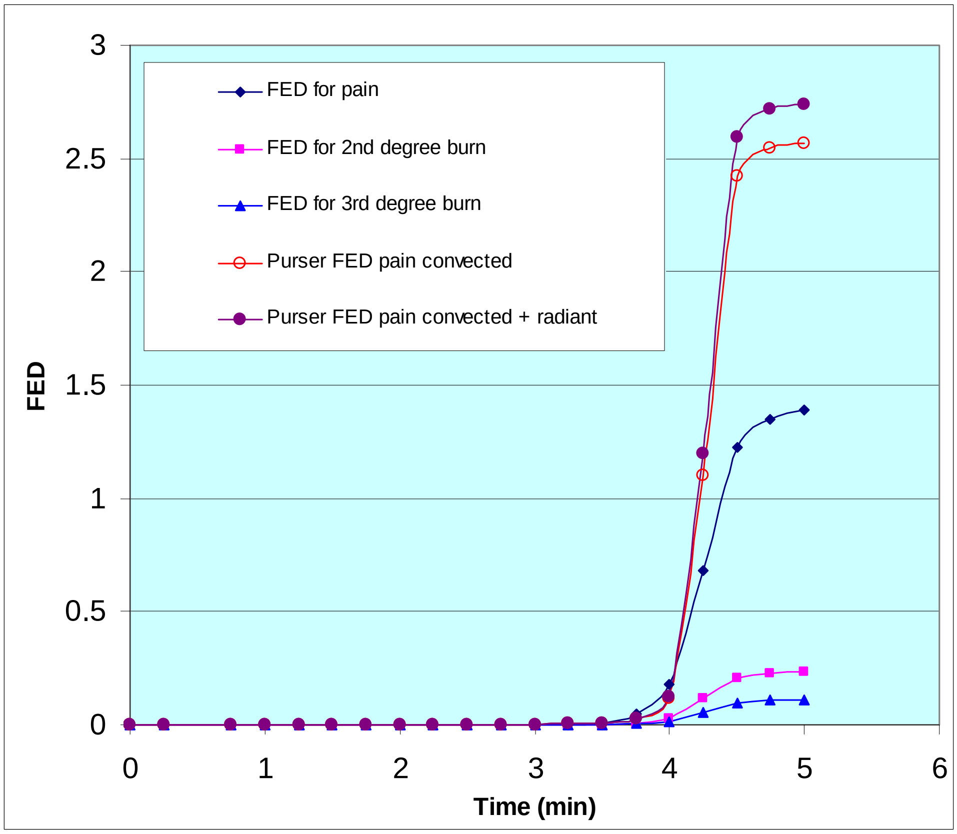

Figure 5-6. Test 6-189 Part 10 [8]: Ford Explorer – gasoline pool fire: Fractional effective doses for heat parameters in the passenger compartment

Different heat exposure endpoints are predicted when the FED for that endpoint reaches 1.0 For the main method of analysis shown in the figure, the total heat flux to an occupant (radiant and convected) was calculated from the data shown in Figure 5-5. The heat dose required for different endpoints (pain, 2nd and 3rd degree burns) was as stated in Purser (SFPE Handbook 3rd edition) [13]. The threshold for pain is predicted at approximately 1.33-1.67 $(kW.m^{-2})^{4/3}$, second degree burns at 3-12.17 $(kW.m^{-2})^{4/3}$ and third degree burns at 16.67 $(kW.m^{-2})^{4/3}$. Based upon this analysis it is predicted that a cabin occupant would experience pain to exposed skin from around 4.25 minutes, but that burns would not occur, since the fire is extinguished and the temperature and flux decreases rapidly when the fire is extinguished. (For this analysis, the water content of the atmosphere has been ignored.) In practice, the temperature seen by thermocouple was maintained above or around 100° for approximately four minutes. The application of the water mist would have provided high water content for this atmosphere. It is therefore possible that a cabin occupant exposed to these conditions would have suffered skin and respiratory tract burns due to the latent heat released from condensing water vapor/steam.)

The other two curves in Figure 5-6 are for the FED equations published in the SFPE Handbook [13]. One is based upon empirical measurements of tolerance time for exposure to convected heat for human volunteers (after Blockley) [37]. This predicts pain at the same time as the other method, but the higher FED of 2.5 suggests that the pain may be somewhat more severe than that predicted by the method used for the first curve. The fifth curve represents the FED for pain due to radiation alone added to the FED calculated for convective heat. The first and fifth curves therefore represent two different approaches to estimating time to pain from exposure to convected and radiant heat. The differences illustrate the uncertainty inherent in assessing this endpoint, but in practice the predicted time to pain is very similar in both cases.

The overall analysis therefore predicts that an occupant of the cabin would experience pain to exposed skin but not serious burns (under the conditions of test ignoring the effects of the water mist). This prediction can be compared with the BURNSIM predictions in the Part 10 fire test report [8]. The BURNSIM model predicts skin heating to a maximum of around 40°C. This represents a level of some possible discomfort but below the pain threshold and no burns would be predicted. There is therefore a good general agreement between the both methods used for this report and that in the Part 10 fire test report [8], that heating of the skin but no burns are predicted. The analysis in this report suggests that pain might be experienced but this result may be partly due to the coarser time steps used for the review (0.25 minutes) than for the finer time steps that would have been available from the electronically captured data used in the Part 10 test report [8].

5.5.2 Toxic Hazard and Comparison with Heat Hazard in Crashed Vehicle Burn Test #6

Figure 5-7 shows the results of the hazard analysis for the effects of asphyxiant toxic gases, compared to those for heat. The results are all expressed in terms of the fractional effective doses for predicted incapacitation (FED = 1) for each parameter. As with most fires, the first

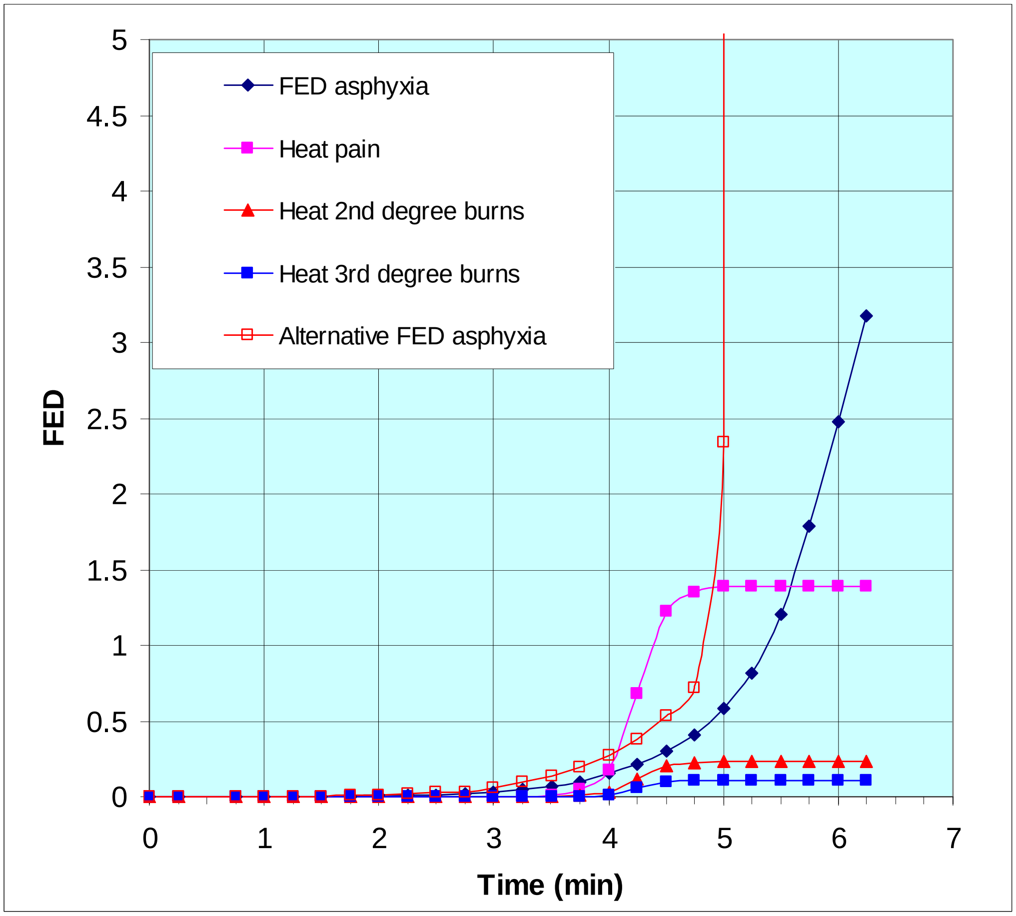

Figure 5-7 Test 6-189 Part 10 [8]: Ford Explorer – gasoline pool fire: Fractional effective doses for toxic gases and heat parameters in the passenger compartment

toxic hazard predicted to affect a vehicle occupant is exposure to irritant smoke. The smoke in the cabin is dense from two minutes after ignition, and based upon the analysis of the particulate phase, it contains significant concentrations of irritant acid gases (particularly HCl, as well as NO, HBr, phosphate) and a range of organic substances some of which are likely to be irritants (see Chapter III and Appendix B-6). Exposure to this smoke is likely to be distressing, cause breathing difficulties and impair any escape attempts. In itself this irritant smoke is unlikely to cause incapacitation or death, but in combination with physical injury the effects on respiration could be serious.

Predictions of serious incapacitation (collapse and loss of consciousness) and death from toxic fumes have been based upon the prediction of asphyxia, mainly from the combined effects of CO, HCN and CO_2, but also including a contribution from total irritants and low oxygen hypoxia. The main model used is an updated version of the Purser model as published in the SFPE Handbook 3rd edition [13], which has minor differences from the older version used by the Part 10 test report author [21]. The alternative FED asphyxia model uses a different treatment of the interaction between HCN and VCO_2 similar to that in the FAA model.

The predicted time to FED = 1 for asphyxia is 5.8 minutes or 4.8 minutes for the alternative model. This compares with a predicted time in the GM Part 10 test report [8] of 5.5 minutes using earlier Purser model and 5.3 minutes using the FAA model. The minor difference between the Part 10 test report predictions [8] and the prediction in this chapter for the Purser model (5.5 and 5.8 minutes) may arise from the cruder time-step averaging used for the review (whereby data have been taken from the printed graphs in the GM Part 10 test report). The shorter predicted time from this report using the alternative method is somewhat speculative. Overall, it is considered that FED modeling in the GM Part 10 test report using the FAA and Purser models has been competently carried out. The range of predictions between 4.8 and 5.8 minutes is considered a reasonable reflection of the range of times likely to occur in practice, with the proviso that loss of consciousness could occur somewhat earlier in injured or otherwise susceptible individuals.

Using the FAA model [20], death is predicted at approximately six minutes in the GM Test 6-189 test report [8]. Purser [13, 21] predicts a lethal exposure to be approximately 2-3 times the incapacitating FED. This would be between 5.75 and 6.25 minutes, which is in good agreement with the FAA method predictions. It is considered that prediction of exact time to death (cessation of circulation and irreversible cessation of brain function) is difficult and likely to be variable. This should be contrasted with prediction of the time at which a lethal exposure has occurred (i.e., an exposure that will result in death). As Figure 5-8 (and figures in the GM Test 6-189 Part 10 test report [8]) show, the FED expressions are exponential, with very rapid increases in predicted FED soon after an FED of one has been achieved. This means that errors in the prediction of an exact lethal dose should produce only small differences in predicted time to acquire a lethal dose.

A comparison of the predicted FEDs for asphyxia and for pain and burns from heat exposure is also shown in Figure 5-7. Based upon the analysis it is predicted that a cabin occupant would experience some pain to exposed skin approximately 0.5-1 minutes before losing consciousness due to asphyxia. However, burns are not predicted to occur.

Based upon the growth rate of the cabin fire and the rapidly deteriorating conditions at the time the fire was extinguished, it is considered that had the fire not been extinguished, conditions would have resulted in death after approximately 5-5.5 minutes due to the combined effects of heat and toxic fume inhalation.

5.5.3 Hazard from Heat in Crashed Vehicle Burn Test #4

In Test #4, crashed 1997 Chevrolet Camaro was used and fire was started in he engine compartment [6]. Details of the test are described in Appendix B-4 and in Chapter III. In the test, measurements were made for the temperatures, radiant flux and concentrations of products in the cabin. Figure 5-8 shows the temperature, radiation and total heat flux estimated at the location of the drivers head. The convective component of the heat flux is very small, so that by far the major hazard is the radiation. This may be partly derived directly from the engine fire and partly from the growing fire inside the cabin in the dashboard area. This is in contrast to the Test # 6 for which radiation was a relatively minor component of the hazard up to the time the fire was extinguished.

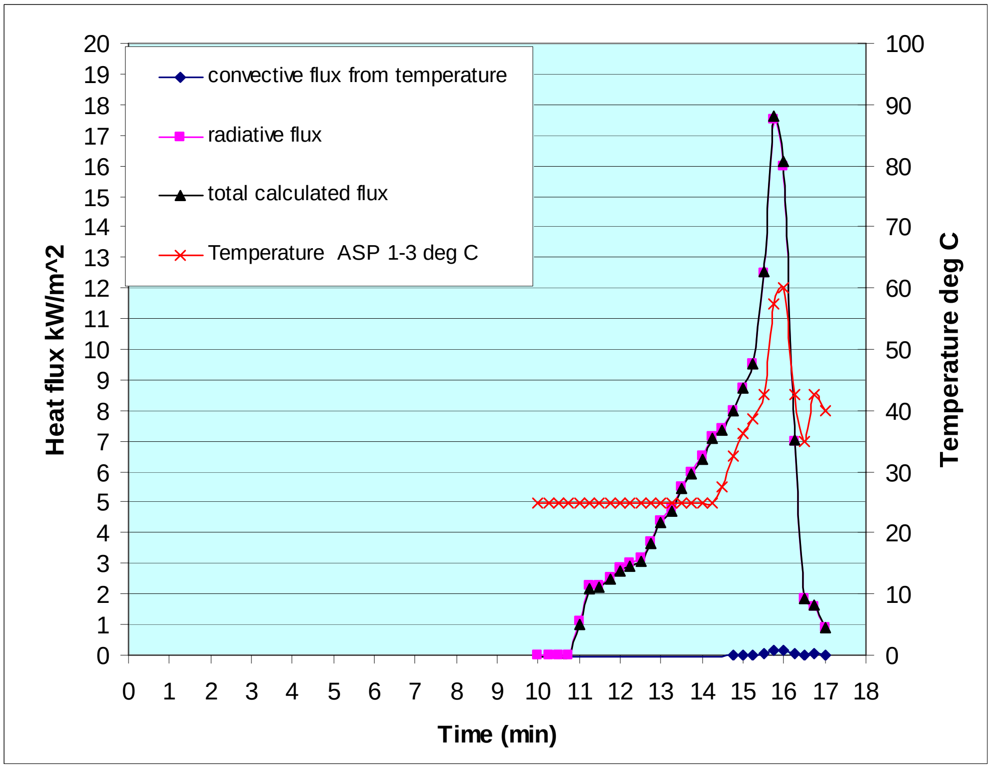

Figure 5-8 Test 4-178 Part 7 [6]: Chevrolet Camaro engine fire: temperature, radiant and total heat flux in the passenger compartment

The FED analysis for the different heat hazard parameters is shown in Figure 5-9.

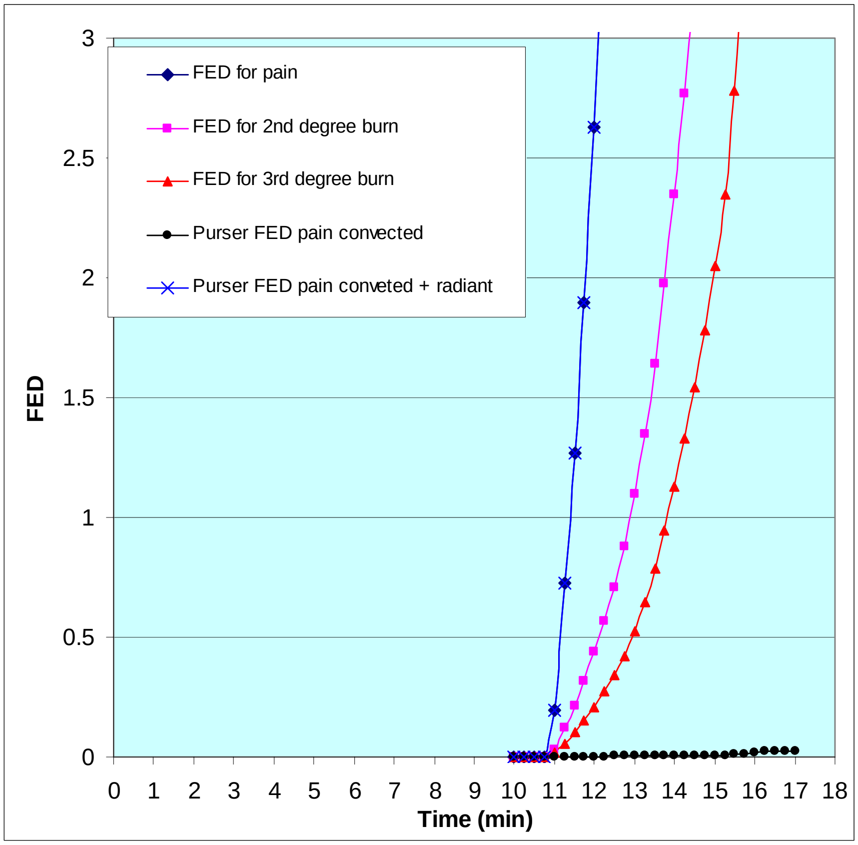

Figure 5-9 Test 4-178 Part 7 [6]: Chevrolet Camaro engine fire: Fractional effective doses for heat parameters in the passenger compartment

There is no serious hazard to an occupant until 11 minutes, at which point the level of radiation is sufficient to cause pain within a few seconds, second degree burns within 1.8 minutes (at just before 13 minutes) and 3rd degree burns after 14 minutes. Death from heat and burns is likely to occur approximately one minute after this, at around 15 minutes, before the fire was extinguished.

The BURNSIM analysis for the drivers side location predicts skin temperatures elevated above 45°C (capable of causing burns) from 13 minutes, with deeper layers affected at 16 minutes when the outer layers are at 80°C. This would therefore result in full thickness burns. The prediction of serious burns is therefore similar to that predicted from the model used for this report, but effects are predicted a minute later than those predicted in this report. The reason for this may be that BURNSIM assumes an absorptivity for exposed skin of 0.6, while the method in this report used a figure of 1 (i.e., in this report effects are related to total received radiation while the BURNSIM model computes skin temperature at different depths). When a factor of 0.6 was applied to the radiant heat component of the model in this report the predicted times to effect are increased to 12 minutes for pain, 14 minutes for 2nd degree burns and 15 minutes for 3rd degree burns. This shows a better agreement with the BURNSIM model. It is difficult to say which is the more correct approach but the differences are likely to be within the uncertainties in the methodologies.

5.5.4 Toxic Hazard and Comparison with Heat Hazard in Crashed Vehicle Burn Test #4

Figure 5-10 shows the FED analysis for asphyxiant gases for the crashed 1997 Chevrolet Camaro fire compared with the FEDs for heat and burns. From approximately eight minutes, an occupant would be exposed to a dense smoke containing significant concentrations of acid gas and organic irritants, but less so than for the 1998 Ford Explorer fire [8].

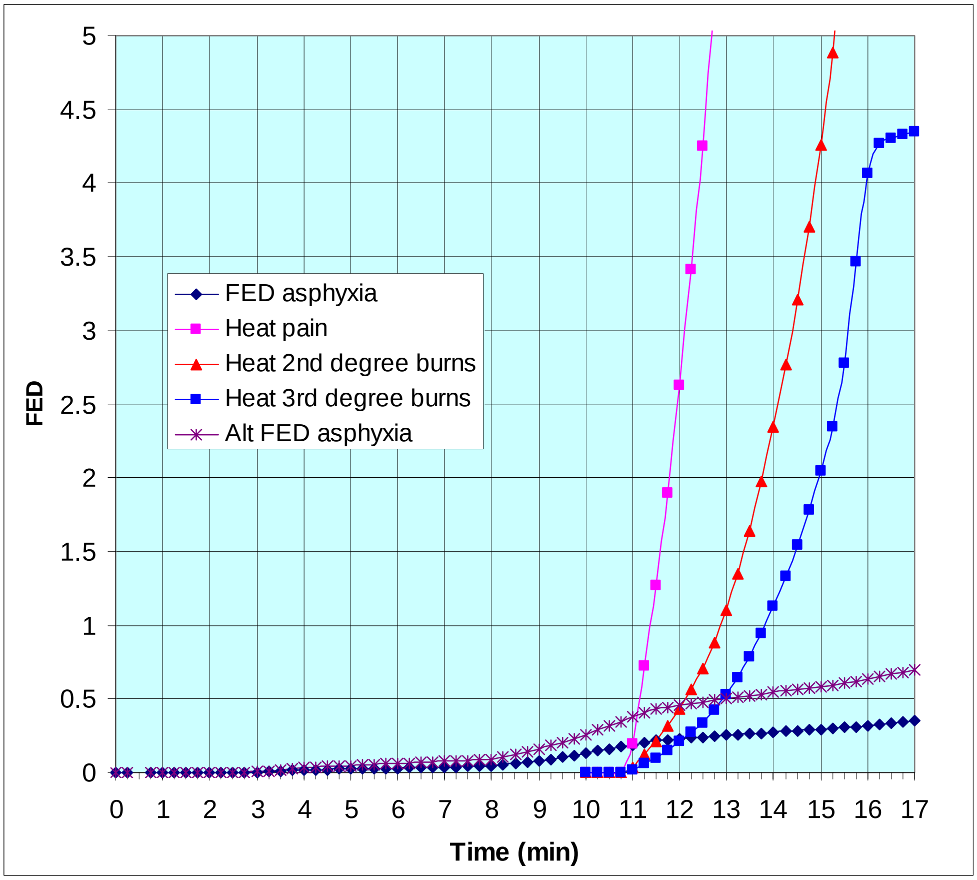

Figure 5-10 Test 4-178 Part 7 [6]: Chevrolet Camaro engine fire: Fractional effective doses for toxic gases and heat parameters in the passenger compartment

The levels are not considered to be seriously incapacitating, but would be expected to contribute to the breathing difficulties of an injured subject. Incapacitation in the form of loss of consciousness due to asphyxia is not predicted for this fire. At the time the fire was extinguished the predicted FED is less than half that required for incapacitation using the latest version of the Purser method and just over half using the most conservative alternative method. This is very similar to the results of the FAA combined hazard survival model and the older version of the Purser model used in the Test 4-178 GM Part 7 test report [6]. The review method gives a slightly higher FED value than that in the report because all gases were included whereas the Test 4-178 GM Part 7 test report [7], only CO was used. The other gases were considered to be below the thresholds for computation in Part 7 test report [7].

5.5.5 Overall Conclusions from In-Depth Review of Two Crashed Vehicle Fire Tests

The two example fires examined were chosen as two very different cases. The post-crash gasoline pool fire case provided a rapid penetration of fire into the passenger compartment within a few minutes leading to predicted incapacitation and death within a few minutes due to the combined effects of exposure to dense irritant smoke, a hot environment and asphyxiant gases. During the early stages of the fire, there was a slow progressive heating of the passenger compartment interior. This was followed by thermal decomposition of the carpet and other materials heated near the floor level and releasing toxic fumes. Continuation of these processes without fire penetration into the passenger compartment was predicted to cause untenable conditions within 20 minutes or so. Fire penetration through splits and holes then led to a rapidly growing fire inside the passenger compartment, which was predicted to cause untenable conditions by approximately 5.5 minutes.

The post-crash engine fire case produced a growing “t^2” fire in the engine compartment, with some flame radiation into the cabin from an early stage. There was little penetration of fire effluent into the passenger compartment for the first 10 minutes or so and little thermal decomposition or combustion inside the passenger compartment. Important events appear to have been the collapse of the broken windscreen and fire penetration into the passenger compartment at low level via the HVAC system. In terms of hazards to passenger compartment occupants, these are considered to have been relatively minor until very high heat radiative fluxes occurred at 15 minutes. These were associated with the large size of the fire in the engine compartment and fire penetration into the passenger compartment. Rapid onset of incapacitation and death is predicted within 1-2 minutes due to heat-induced burns, shock and circulatory failure.

Features these two fires have in common are that in both cases death is predicted within a few minutes once the fire penetrates the passenger compartments of the vehicles. Differences from the hazard perspective are that for the engine fire case there was no serious hazard until fire penetration into the passenger compartment occurred. For the pool fire case, slower penetration and evolution of heat and toxic gases before fire penetration occurred is predicted to have resulted in death from a combination of heat and toxic fumes after approximately 20 minutes or so, if these processes had continued without fire penetration into the passenger compartment.

5.5.6 Toxic and Heat Hazards in the All the Ten Vehicle Burn Tests

All the ten vehicle burn tests are described in detail in Chapter III and Appendix B. Times to key events affecting survivability are listed in Table 5-2 and the results are illustrated in Figures 5-11 to 5-14. for all the ten tests.

5.5.6.1 Mechanisms of Hazard Development and Times to Key Endpoints

The key endpoint in terms of survivability for all large-scale vehicle fires was fire penetration into the passenger compartment. As the data in Table 5-2 and Figures 5-11 to 5-14 show, once the fire actually penetrated the passenger compartment, incapacitation is predicted within 1-3 minutes due to either heat or toxic fumes or both, and death is predicted within a further 1-2 minutes. In practice the fires were extinguished before or at around the predicted times for incapacitation. However, since conditions were becoming rapidly worse at these times, it is certain that they would have been lethal within a very short time (approximately one minute) if the fires had not been extinguished. The precise timing, nature and order of hazards differed somewhat for the different tests, and in particular, the results of the underbody gasoline pool fires differed from those of the engine fires.

Table 5-2. Times to Key Events in Minutes Affecting Survivability in Vehicle Burn Tests

Test #	Fire Penetration	T_g >100°C	$\dot{q}''_{rad}$ >2.5 kW/m^2	C_{CO} > 0.1%	C_{CO}> 0.2%	FED (Heat) Pain, 2nd,3rd	FED[c] (Asphyxia) I L	Fire Extinguishment
Rear Crashed Vehicles, Fires Started Under the Vehicle in the Rear								
3	0.5	3.6	3.0	0.01	0.5	3.1, 3.4, 3.6	3.0 3.5	3.3
6[a]	2.1	3.5	no	3.0	4.0	4.3, no, no	5.3 6.0	4.3
5	2.1	2.0	no	1.7	2.5	no, no, no	3.3 3.7	2.8
2	2.0	2.7	3.0	2.0	3.0	3.5, 3.7, 3.9	3.5 3.8	2.8
8	0.5	1.4	2.0	2.7	2.8	2.6, no, no	no	2.6
Front Crashed Vehicles, Fires Started in the Engine Compartment								
1	10	10	10.5	10.2	10.8	10.8,11.0,11.0	10.8, 11.0	11
4	10	16	11	9.8	11	11.5,13.0,14.0	no	16
9	9	13	9	no	no	8.5, 9.5,10.0	no	16
10[b]	12	no	8	5	no	8.5,10.0, 10.5	no	16
7	24	26	25	no	no	25.5,26.0,27.0	no	27

a: front crashed vehicle; **b**: FR HVAC; **c**: **I**= incapacitation; **L**= lethality; $\mathbf{T_g}$: gas temperature; $\dot{q}''_{rad}$ **:** radiant heat flux

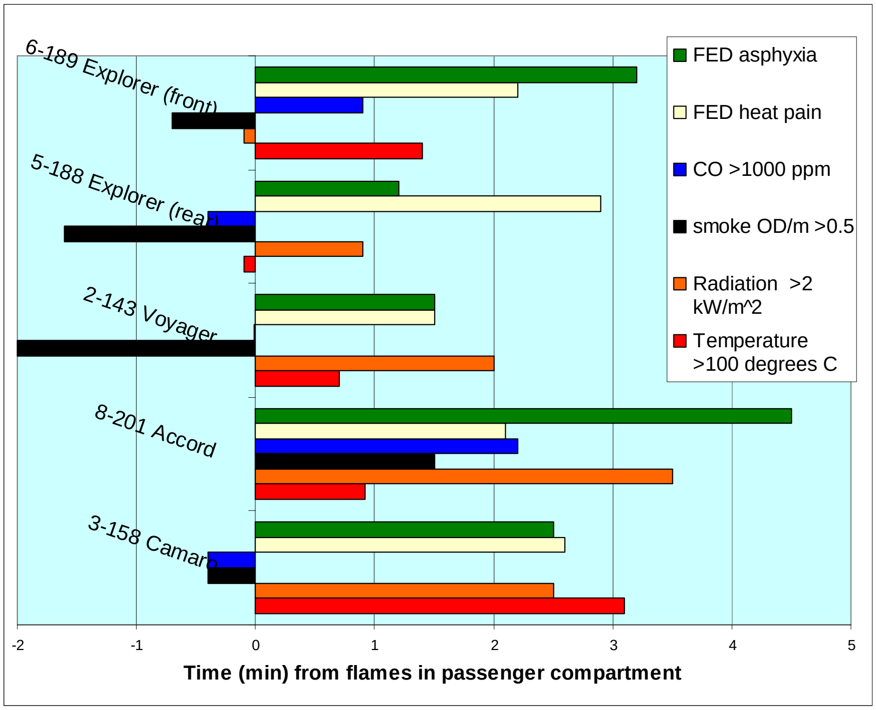

Figure 5-11: Large-scale vehicle fire tests: time from ignition to key survival-related endpoints in the passenger compartment for gasoline pool fires

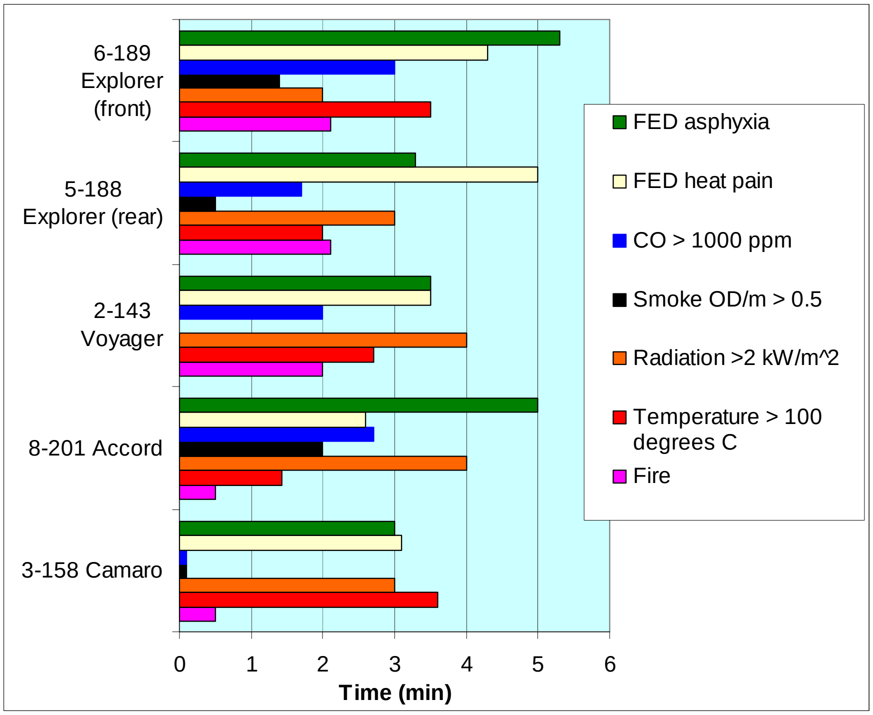

Figure 5-12: Large-scale vehicle fire tests: time from fire penetration into the passenger compartment to key survival-related endpoints for gasoline pool fires

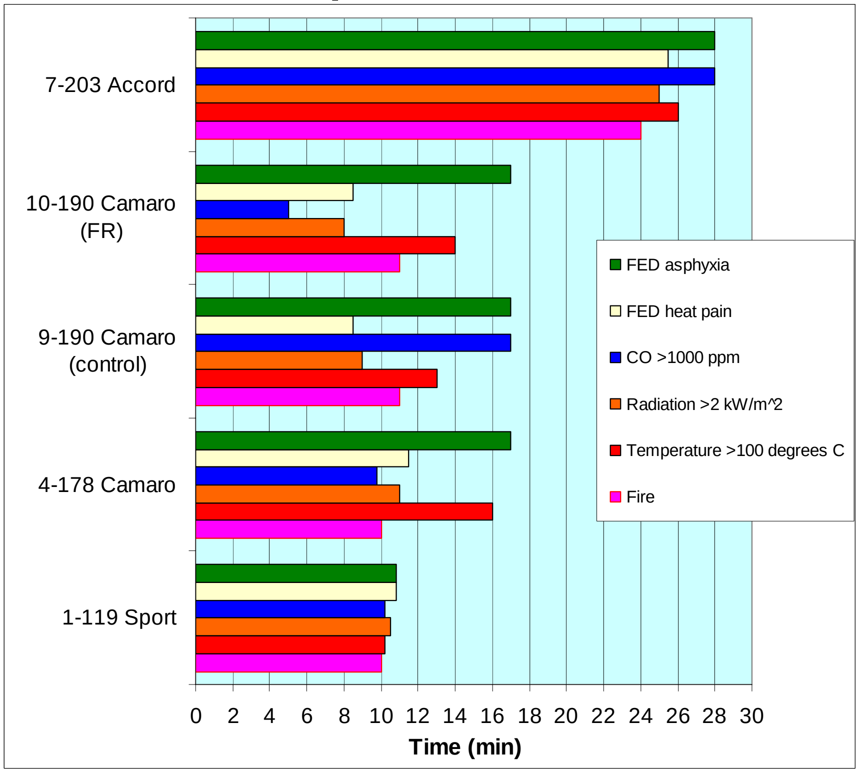

Figure 5-13: Large-scale vehicle fire tests: time to key survival-related endpoints in the passenger compartment for engine fires

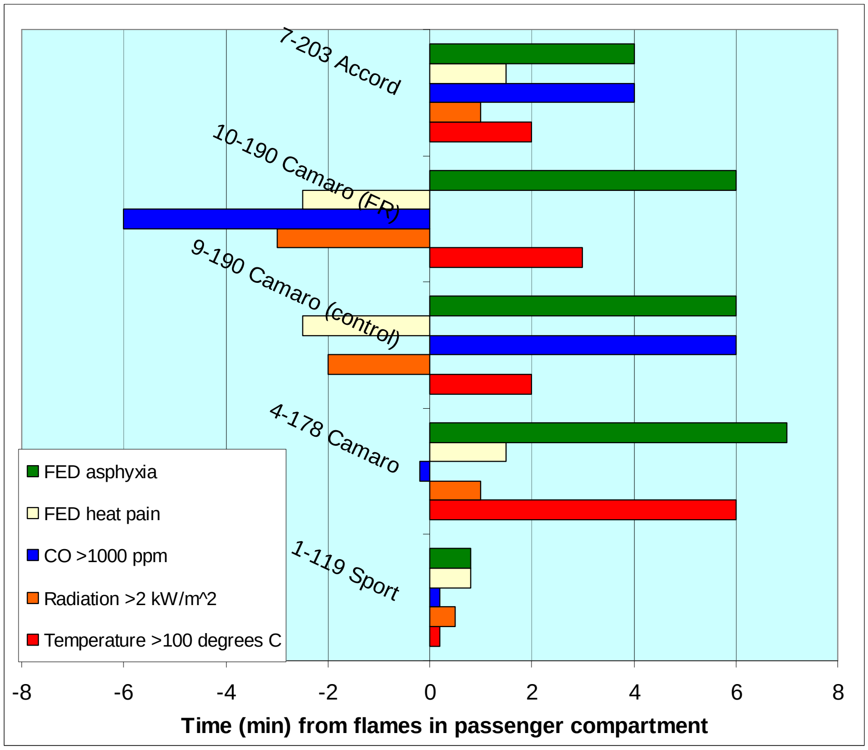

Figure 5-14: Large-scale vehicle fire tests: time from fire penetration into the passenger compartment to key survival-related endpoints for engine fires

5.5.6.2 Gasoline Pool Fire Tests

For the pool fires, fire penetration into the passenger compartment was rapid (within approximately 0.5-2 minutes of ignition). The main mechanism of penetration was through holes and seam openings in the underside of the vehicles. This led to rapidly growing, spreading, fires in the carpets, trim and seating, with incapacitation predicted within 1-3 minutes of fire penetration. Predicted times to incapacitation by heat and asphyxiant toxic gases were generally similar (Table 5-2).

Predicted times to when conditions are considered lethal are slightly longer than those to incapacitation. A complication is that the fires were extinguished at around the time lethal conditions developed. Conditions can be considered lethal for heat at around the time predicted for third degree burns in Table 5-2. The times to predicted lethal condition for asphyxiant gases are also shown in Table 5-2 (FED asphyxia – L). At the times when conditions are predicted to be lethal, the conditions in the passenger compartment were about to become extreme generally with the development of flashover.

It is somewhat academic to consider whether death would be caused by heat or asphyxia, since in most cases both reach lethal levels at around the time flashover occurs. There are some differences between the pool fire and engine fire tests. For the pool fires tests shown in the upper half of Table 5-2, the development of extreme fire conditions can be characterized in terms of the temperature at the headliner and the effects on the occupants by reference to Table 5-2. For two tests (#3-158 Camaro [5]and #2-143 Voyager[4]) the time to a 600°C flashover temperature at the headliner near the driver position (3.7 minutes for Test 3-158 and 3.2 min for Test 2-143), predicted times to 3rd degree burns and death from asphyxia all occurred more or less simultaneously. For the two tests on the Ford Explorer (6-189 [8] and 5-188 [7]) incapacitation is predicted due to asphyxia at 5.3 and 3.3 minutes, and death from asphyxia at 6.0 and 3.7 minutes. Incapacitation and burns from heat are not predicted to occur during either test. An examination of the headliner thermocouple traces shows maximum temperatures of around 400°C at the driver position at the time the fires were extinguished (4.4 minutes for Test 6-189 and 2.9 minutes for Test 5-188 [7]). Higher temperatures of around 600°C were recorded at these times in the rear of the vehicles above the interior fires, so it can be estimated that flashover was imminent. For these two tests it can be said that incapacitation and lethal conditions are predicted due mainly to the effects of asphyxiant gases, but that occupants would have been exposed to lethal heat conditions within a short time afterwards had the fires not been extinguished.

For the Honda Accord (Test 8-201 [11]), fire penetration occurred very rapidly, and the temperature above the driver's position reached 400°C after 2 minutes, but not 600°C. Temperatures around 600°C and above were achieved towards the rear left side of the vehicle, where the crash damage was greater. For the drivers position, neither incapacitation or death from either heat or toxic gases are predicted during the test. It is possible that this is due to the pattern of crash damage, enabling hot effluent to vent somewhat from the rear of the vehicle instead of collecting above the driver location. Based upon the extreme conditions developing in the rear left side of the vehicle, it is likely that lethal heat and toxicity conditions would have developed within a minute or so at the driver location had the test been continued.

For the two "van-shaped" vehicles with rear impacts (Test 2-143 Part 4 Voyager passenger van [4] and Test 5-188 Part 9 Explorer Sports Utility Vehicle [7]) the fire penetrated seams and grew in the rear of the vehicle involving the rear seats. High concentrations of CO and very high concentrations of HCN were evolved at this stage, capable of causing asphyxia one minute after fire penetration. The fire increased the temperature in the vehicles to untenable levels and in the case of the Voyager there was considerable heat radiation from the fire at this time. Incapacitation due to heat (mainly from radiation) is predicted at around the same time as that from asphyxia for the Voyager fire and asphyxiation one minute after fire penetration for the Explorer. Figure 5-11 illustrates the timing of key events from ignition, while Figure 5-12 shows them relative to the time of fire penetration.

In the front crashed Ford Explorer with mid-underbody gasoline pool fire Test #6 [8], fire penetration occurred after the same period as for the rear-crashed vehicle in Test #5 (via drain holes), the fire, which started in the carpet, was somewhat slower growing. This may be because the engine compartment absorbed most of the impact such that seams in the underbody area above the pool fire remained intact. The result was a somewhat longer period before loss of tenability, predicted first due to the hot passenger compartment environment and then to asphyxiant gases. The concentrations of CO and HCN were considerably lower than for the rear-impact case, probably because the fire was extinguished before heavy involvement of the seats.

The front crashed Ford Explorer with mid-underbody pool fire scenario was repeated in test #11. The underside of the floor panel of the Ford Explorer was coated with an intumescent paint. The results from Test #11 were almost identical to those of the Test #6. The heat release rate curve from the fire plume data is very similar in terms of time course and heat release rate, the fire being extinguished after approximately five minutes at 500 kW. As with the original test, the fire penetrated through electrical pass-though openings (which had not been treated with the intumescent paint or fire-blocked). The concentrations of asphyxiant gases reached somewhat higher concentrations than in the original tests (CO peak 0.65% HCN 320 ppm compared with CO 0.44% and HCN 150 ppm in the original test), so that incapacitation due to asphyxia would be predicted somewhat earlier (perhaps one minute earlier) than in the original test. Otherwise, the results were very similar. It is somewhat disappointing that the intumescent paint had no effect on fire development or survivability. Since the mechanism of fire penetration was the same as in the original test and since this was unmodified, this is perhaps not surprising. It would perhaps have been more interesting to have examined the effect on a rear impact crash scenario. This could depend upon the extent to which the intumescent swelling of the heated floor pan would have blocked opened seams and prevented fire penetration into the passenger compartment. It is considered that a more flexible blocking layer, such as a fiberglass or mineral wool interliner, would be more effective, providing cable penetrations and other holes were also fire-stopped.

For the Chevrolet Camaro (Test 3-158 [5]) there was early fire penetration through opened seams (after 0.5 minutes), but the fire then subsided somewhat before serious involvement of the interior occurred after three minutes. Rapid fire growth then led to high passenger compartment temperatures and heat fluxes, as well as moderately high concentrations of asphyxiant gases, so that incapacitation from both heat and asphyxia is predicted simultaneously at around 3 minutes after ignition (2.5 minutes after fire penetration. For the other passenger car (Test 8-201 Part 12 - Honda Accord [11]), initial fire penetration also occurred after 0.5 minutes. The rapidly growing fire resulted in predicted incapacitation from heat (mainly radiation) 2.5 minutes after ignition. Concentrations of CO and HCN were relatively low, so that asphyxia is not predicted to occur until after the fire was extinguished.

The overall situation with respect to the pool fires is therefore of rapid fire penetration though holes and seams (irrespective of the pool fire size) followed by incapacitation within 1-3 minutes of fire penetration by either heat, or asphyxiant gases, or both. Another aspect of these fires is that there is often some heating and penetration (or interior non-flaming generation) of toxic fumes before fire penetration. It is considered that if some method was found to prevent the fire penetration tenability may still be lost over a longer time-scale (approximately 20-30 minutes) due to hyperthermia (incapacitation and death caused by a slow increase in body core temperature, without burns [13]), which could occur from slow heating of the vehicle interior. Alternatively incapacitation or death may occur over a longer time scale due to penetration or interior generation of toxic fumes. As Figure 5-12 shows, there were significant concentrations of smoke and CO in several of these vehicles before fire penetration occurred. It is possible that the use of a fire resisting interliner on the vehicle interior surface between the metal skin and the interior trim (particularly the floor coverings) might offer some protection and increase survival times for pool fires. However, it is possible that occupants may still succumb to hyperthermia if the interior temperature rises to temperatures approaching or exceeding 100°C over time scales of 20 minutes or so. Another problem is that side and/or rear window glazing was lost in these rear impact crashes, which provided another route of fire entry over a similar or somewhat longer time-scale than fire entry through open seams.

5.5.6.3 Engine Fire Tests

In terms of hazard development, by far the most significant event in all the engine fires was heat-induced collapse of the windshield. The outer surface of the windshields of all vehicles was broken during the crashes, but the inner surfaces and plastic laminate layers remained reasonably intact. During the early stages of all engine fires, the windshields of all vehicles provided some protection against heat radiation from the fire and the entry of fire effluent into the passenger compartment. When the fires reached a critical size, so that flames played on the windshields, they fell apart. This had two important effects; it exposed the passenger compartment occupants and the passenger compartment materials to the high radiant heat fluxes from the engine fire and caused hot pieces of windshield to fall into the vehicle, in some cases igniting the seats and interior trim. Figure 5-13 shows the timing of key events in the hazard development for each test, while Figure 5-14 shows the timing relative to the time of fire penetration into the passenger compartment. Figure 5-13 shows that in all cases loss of tenability occurred just before or just after fire penetration (immediately following windshield failure). Figure 5-14 shows that for three fires, loss of tenability due to heat (almost entirely due to heat radiation) occurred within less than two minutes of fire penetration. In Test #9 and #10, loss of tenability due to radiation is predicted approximately two minutes before fire penetration. For these fires, the intense radiation following windshield failure was sufficient to affect the passenger compartment occupants before significant combustion of cabin materials occurred. Asphyxia from exposure to toxic gases is predicted for only Test #1, before the fires were extinguished due to the high concentrations of CO and very high HCN concentrations. For this test, incapacitation is predicted simultaneously due to pain from heat and toxic gases at 10.8 minutes, when a brief intense fire occurred in the cabin. For the two fires in the Camaro and that in the Accord there were no significant toxic gas exposures during the tests, although a rapid conflagration of the cabin is predicted with high yields of toxic gases if the fires had not been extinguished at this time.

The general, picture with the engine fire test is that the primary cause of incapacitation and death is likely to be the effect of heat and burns, primarily from radiation as the windshields failed an as the fire breaks into the passenger compartment. In none of the tests, the temperature at the headliner or roof level above the driver location did not exceed 250°C, but higher temperatures and high radiant fluxes were measured at lower levels near the driver's head and upper body locations. There had thus been no opportunity for a significant build-up of heat and toxic gases within the vehicles at the time conditions became lethal due to the effects of heat directly from the engine fire. Test #1 was slightly different, in that incapacitation, quickly followed by lethal conditions is predicted more or less simultaneously for effects of both heat and toxic gases as the fire breaks into the cabin.

The fire in the Camaro with the FR-treated HVAC system [Test #10] is of interest in that there was a brief but minor period of evolution of toxic gases (including CO and HCN) into the passenger compartment over the period between 5 and 9 minutes. This did not happen in the non-fire retarded control fire. This may have occurred due to minor differences between the course of fire development in the two tests, rather than due to differences in combustion efficiency (there was no CO_2 evolution into the cabin in the control fire at this time), or it may reflect to some extent an effect of the fire retardant treatment of the HVAC components. Either way an important fact emerges. The CO peak was brief and not enough to cause significant toxicity. For all these engine fires (including this one) there was no significant penetration of fire effluent from the engine fires into the passenger compartments up to the time occupants would have been killed by heat radiation. This means that any potential increase in toxic potency of effluent from fire-retarded engine components would not present a significant hazard.

Even if the toxic potency of the products is somewhat increased by fire retardant treatment, the total mass of toxic products, and hence the overall toxic hazard, may well be less anyway due to the reduction in fire growth (since toxic hazard = potency x mass burning rate).

Another question is what would happen if the windshield was protected in some way. The bulkhead between the cabin and engine compartment provides some degree of passive protection to fire penetration, but there are many holes for components passing through this bulkhead that are not fire-stopped. In addition, some holes result from components being forced back though the bulkhead because of the crash. There was evidence from some of the tests that at the time conditions became extreme due to fire penetration through the windshield; fire was also beginning to break through into the passenger compartment at lower levels. It is, therefore, likely that an engine fire would eventually result in a lethal passenger compartment fire, even if the windshield remained intact. However, this would buy more time for rescue or escape.

The overall situation with regard to engine fires is therefore of a fire that grows slowly but eventually become large. When flames passing onto the windshield between the crumpled hood and dashboard cause windshield failure, intense radiation from the engine fire causes loss of tenability for passenger compartment occupants due to heat exposure and ignition of the passenger compartment contents.

5.5.7 SUMMARY

Fatal vehicle accident reports involving post-crash fires have been reviewed for cases where fire was considered to have been a major contributory cause to the deaths. Typical incidents involved front or rear crashes with subsequent engine or gasoline pool fires, as used for the large-scale vehicle fire tests [1, 2]. In the incidents, vehicles were also inverted in a number of cases. Almost all fatalities had serious burns, but for most cases, the carboxyhemoglobin (%COHb) concentrations were low. This indicates that the primary causes of death were physical trauma or burns in at least 50% of cases, and a combination of physical trauma, burns and toxic smoke exposure in others. In approximately 10-17% (i.e. 10% of cases > 40 %COHb, 17% > 30%COHb) of cases, exposure to toxic smoke effluent was sufficient to have been the main cause of death. The carboxyhemoglobin data show that most of these decedents must have survived for several minutes after fire or fire effluent broke though into the passenger compartment (approximately 3-10 minutes depending upon fire growth rate in the passenger compartment).

For all the large-scale vehicle burns tests [3-12], the key event in terms of loss of survivability was penetration of the fire into the passenger compartment resulting in a rapidly growing fire involving the interior materials (carpets, trim, instrument panel, seats). Once this happened, predicted survival times were limited to a few minutes. Predicted times to incapacitation and then to death are similar for the either the effects of toxic gases or of heat. In practice, it is predicted that death would result from a combination of burns, with heat shock, and asphyxia. Before fire started in the passenger compartment there was no significant penetration of heat or toxic gases, although smoke was present in some cases. There were some differences in the patterns of hazard development between the gasoline pool fires and the engine fires.

For the gasoline pool fires, penetration of flames into the passenger compartment through open seams and holes in the floor occurred within a few minutes, igniting carpets, trim and seating. High concentrations of asphyxiant gases were achieved within approximately a minute, leading to predicted incapacitation within approximately 1-4 minutes. The temperature in the passenger compartment increased to high levels and this together with heat radiation is predicted to cause incapacitation due to pain within 1-3 minutes. For these fires, the air temperature and the concentrations of smoke and asphyxiant gases in the passenger compartment started to develop before fire penetration. It is predicted that if fire penetration had been prevented (for example by use of blocking layers), survivability would have been extended over a longer time scale of approximately 20-30 minutes before death would have occurred due to hyperthermia, burns, and asphyxiation.

For the engine fires, the key event was collapse of the windshield. This occurred when the engine fire reached a size such that flames were directed onto the windshield. Collapse of the windshield led to occupants and passenger compartment materials being exposed to high radiant heat fluxes. The radiant heat fluxes are sufficient to have caused pain and severe burns in occupants, followed by death from heat shock within approximately two minutes. Ignition of passenger compartment materials occurred following windshield collapse, due to direct radiation or flame impingement in the dashboard and headliner area, or due to ignition of seats and carpets by falling pieces of hot windshield. In two cases, incapacitation due to heat is predicted before ignition of the passenger compartment interior. For only one engine fire case (Dodge Caravan

Sport) [3] was incapacitation predicted due to asphyxiant gases as well as heat, before the fires were extinguished.

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CHAPTER VI

CONCLUSIONS: FIRE SAFETY ISSUES FOR MOTOR VEHICLE POST COLLISION FIRES AND POSSIBLE SOLUTIONS

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6.1 INTRODUCTION

In this study, results from the GM, MVFRI, and NHTSA sponsored studies as well as from the literature have been reviewed and attempts have been made to provide answers to the following questions:

1. Engine Compartment Fluids: What was learned about the fire behavior of engine compartment fluids? How do fluids ignite in a vehicle crash? Do thermo-physical properties, such as flash point, autoignition temperature, hot surface ignition temperature, boiling point, and others adequately define the ignition resistance of fluids? Do engine compartment fluids participate in flame spread from the engine compartment to the passenger compartment? Do engine compartment fluids need to be fire retarded to enhance survivability of passengers in vehicle crash fires? Is there a need for a standard test for ignition resistance of fluids?

2. Motor Vehicle Parts: What was learned about the fire behavior of plastics in motor vehicle parts? How do plastics ignite and participate in flame spread in a vehicle crash? How effective is fire retardancy of plastics and intumescent painting of the under carriage in enhancing survivability of passengers in vehicle crash fires? How important is dripping, flaming melt and pool fires of molten plastics in the penetration of flames into the passenger compartment? How effective is the underhood insulation blanket in preventing spread of flames into the passenger compartment? Is there a need to fire retard the blanket to enhance the passenger survivability? Is there a need for simple engineering tools to assess the resistance of plastics for ignition and flame spread?

3. Flame Penetration into the Passenger Compartment: How do flames spread in a motor vehicle crash fire? Is there a significant difference in times for flames to penetrate the

passenger compartment for the front and rear crashes? Are these times long enough for fire fighting and extrication by a nearby fire department? Do flames spread rapidly on the "exterior" (outside the passenger compartment, such as the underhood and underbody) or on the "interior" in a crash? Should standards be different for "exterior" and "interior" plastics? How effective is fire suppression in enhancing the survivability of the passengers in the motor vehicle crash fires?

4. Passenger Compartment Environment Created by Motor Vehicle Crash Fires: What was learned about the safety and escape of passengers from fires resulting from the front and rear crashes of motor vehicles? How early do smoke and toxic compounds generate in a vehicle crash? Does the passenger compartment environment become hazardous before flames enter the compartment? Do more people die from toxic gases or burns, which problem is of higher priority? How is the passenger survivability affected by the closed or open windows? Should emissions of smoke and toxic compounds from plastics in vehicles be limited to enhance the passenger survivability? Is there a need for regulatory standard for the release of smoke and toxic compounds? How would the replacement of ordinary glass by safety glass in the side and rear windows affect the survivability of the passengers in motor vehicle crash fires?

5. Regulatory Standards: What are the deficiencies of FMVSS 571.302 standard? Should the standard be upgraded, replaced, and/or supplemented by a new standard? Is there a need for regulatory standards for engine compartment fluids and passenger injuries by release of smoke and toxic compounds and burn injuries?

The answers to the above questions depend on the assessment of passenger survivability, which was the main objective of the studies. The passenger survivability in vehicle crash fires depends on:

- Type and strength of the ignition source;
- Time to ignition of the initial item and its location relative to the passenger compartment;
- Heat transfer from the burning initial item and times for the involvement of the neighboring plastic parts and engine compartment fluids in the ignition and flame spread processes;

- Times for the involvement of other plastic parts and engine compartment fluids in the ignition and flame spread processes, heat transfer to the passenger compartment, and times for the involvement of plastics closer to fire paths into the passenger compartment;
- Times for the entrance of the flames into the passenger compartment via various fire paths;
- Times for the involvement of various plastic parts in the passenger compartment in the ignition and flame spread processes;
- Times for the creation of untenable conditions in the passenger compartment in terms of reduced visibility to escape, burn injuries and impairment due to smoke and toxic compounds generated during the ignition and flame spread processes.

Plastic parts and engine compartment fluids are inherently flammable and have been involved in vehicle fires, with or without vehicle crashes. Currently, the plastics used in the assembly of vehicle parts in the passenger compartment are regulated by NHTSA through the FMVSS 302 Standard Test Specification [1]. The specification deals with only the extent and rate of flame spread on a small scale under low heat flux conditions (simulating burning of a cigarette or a match) and thus the test conditions do not represent the crash fire conditions, where heat fluxes can be significantly higher than used in the 302 Standard. There are no regulations for the engine compartment plastics and fluids.

The survivability of passengers in vehicle crash fires depends on the time to untenable conditions and the severity of the conditions. There are several processes preceding the creation of untenable conditions in the passenger compartment in vehicle crashes. Furthermore, for defining the severity of the untenable conditions, it is necessary to understand how the untenable conditions are created in the passenger compartment and how the conditions can be defined Information on preventive measures that could be taken is also important to enhance the passenger survivability in vehicle crash fires.

6.2 ENGINE COMPARTMENT FLUIDS

The engine compartment fluids are complex mixtures of hydrocarbon-based fluids (motor oils, synthetic motor oils, power steering fluids, transmission fluids, and gear lubrication fluids), glycol-based fluids (antifreeze with water and brake fluids), and alcohol-based fluids with water (windshield washing fluids). The majority of the engine compartment fluids are based on hydrocarbons. Because of the complex compositions of the engine compartment fluids, fluid properties have to be defined in a specialized fashion, as discussed in Volume III.

In front vehicle crashes, fluids can start engine compartment fires if there is an encounter of the fluid sprays and hot metal surfaces and fluids are ignited. In addition, fluids can drip down to the ground and form pools under the engine compartment; mix with molten plastic parts of the vehicle and burn as pool fires. Observations made in the crash and burn tests, discussed in Chapters III and IV and Appendix B, showed that the pool fires of the engine compartment fluids released significant amounts of heat, CO, smoke and other products and assisted in the flame penetration into the passenger compartment.

Ignition data for the fluids (Volume III), temperatures measured in the vehicle burn tests (Chapters III, IV and V and Appendix B) and underhood temperatures during vehicle operations [2,3] show that the engine compartment fluids are capable of starting the engine compartment fire. In the crash tests, it was observed that fire in the engine compartment was started because of the contact between the engine compartment fluid sprays and the hot metal parts of the engine. In the vehicle burn tests, fluids were observed to burn as pool fires under the engine. As a result, pool fires of the fluids in conjunction with that of the molten plastic parts enhanced the burning intensity of the pool fires, resulting in rapid flame penetration into the passenger compartment (Chapters III, IV and V and Appendix B).

Temperatures of hot metal parts have been measured under various driving conditions [2]. Data for the hottest temperatures of the metal parts of vehicles are listed in Table 6-1. Data in the table show that temperatures of hottest metal parts of the vehicle increase with increase in the idle and vehicle speeds, and with uphill driving and exceed the flash point, fire point, autoignition temperature and hot surface ignition temperature of the engine compartment fluids, which are listed in Volume III. Thus, the engine compartment fluids encountering the hottest metal parts of the vehicle are expected to ignite and start the engine compartment fire.

Flame penetration into the passenger compartment depends on the heat release rate. Heat release rate from the pool fires of the hydrocarbon based engine compartment fluids can be as high as 2000 to 3000 kW/m^2 (Volume III). Heat release rate at flame penetration into the passenger compartment for engine compartment fires is estimated between about 100 to 800 kW (Chapter IV). Thus, hydrocarbon based engine compartment fluids, burning as pool fires with diameters of 30 to 90-cm, are capable of providing fire power for flame penetration, very similar to that of a gasoline pool fire (Volume III).

Heat release rates from the pool fires of the engine compartment fluids can be reduced by modifying the fluids by fire retardants. However, engine compartment fluids are used for specific functional purposes, fire retarding them may affect their performance. Furthermore, fire retardant treatments of the engine compartment fluids are not expected to be effective. Instead, fire suppression in the engine compartment during vehicle crashes, fire hardened hood blanket that will smother the fire, and fire barriers between the engine and passenger compartments are expected to be effective in delaying flame penetration into the passenger compartment and enhance the passenger survivability.

6.3 MOTOR VEHICLE PARTS AND THEIR FIRE BEHAVIOR

Vehicle parts are made of (Volume III):
1) *Aliphatic Hydrocarbon Based Plastics*:
Examples are polyethylene (PE), polypropylene (PP), nylon, polymethylmethacrylate (PMMA), polyethyleneterephthalate (PET), polyoxymethylene (POM), ethylene-propylene-diene monomer (EPDM);
2) *Aromatic Hydrocarbon Based Plastics:*
Examples are polystyrene (PS), polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), expanded polyurethane (PU) foam, fiberglass/polyester/styrene;
3*) Halogenated Hydrocarbon based Plastics*:
Example is polyvinylchloride (PVC).

Most of the automotive plastics contain variable amounts of organic and inorganic fillers and fire retardants (Volume III, Appendix A-1). However, majority of the vehicle parts are made from the aliphatic hydrocarbon based plastics. Most of the automotive plastics are inherently flammable and melt, drip and burn as pool fires.

In the intermediate-scale tests (Chapter II), automotive plastic parts melted rapidly with a a rapid-fire growth. Release rates of heat, CO and smoke were mainly due to pool fires of molten plastics. The following fire behaviors were observed for the plastic parts:

- *Melting*: 100 to 600 seconds (PP wheel liner to PE fuel tank);
- *Fire Growth*: 20 to 1420 seconds (faster growth was observed for battery with cover, master cylinder, hood liner and head liner and low growth was observed for isolated battery);
- *Molten Polymer Pool Diameter*: 15 to 60-cm;

Table 6-1. Measured Temperatures for the Hottest Metal Parts of Vehicles for Various Driving Conditions [2]

Vehicle	Idle Speed (rpm)/Vehicle Speed (mph)	Temperature (°C)						
		Catalytic Converter			Manifold		Exhaust	
		1	2	3	1	2	At Tank	Before Muffler
Stationary Idle Engine								
Ford Focus	800-3200 rpm	93-215	115-266	143-351	91-197	88-249	92-200	71-208
Dodge Caravan	750-3000 rpm	203-316	138-315	198-343	243-307	140-248	97-267	65-228
Dodge Neon	750-3000 rpm	177-343	95-274	143-387	216-417	232-487	43-162	47-184
Chevrolet Silverado	500-2000 rpm	163-397	131-348	124-325	144-271	142-376	54-248	31-97
Level Road Driving								
Ford Focus	30-70 mph	155-230	171-240	214-339	149-239	122-176	118-158	107-156
Dodge Caravan	30-70 mph	196-269	161-243	202-282	251-328	154-209	107-162	75-143
Dodge Neon	30-70 mph	222-230	176-185	220-213	340-391	374-440	106-109	115-132
Chevrolet Silverado	30-70 mph	234-286	172-244	200-235	159-169	219-283	63-55	111-174
Uphill Driving								
Ford Focus	40-70 mph	220-258	256-306	306-387	223-295	207-264	168-208	172-230
Dodge Caravan	40-70 mph	310-328	283-293	317-319	374-367	219-241	199-215	170-214
Dodge Neon	40-70 mph	308-332	259-279	312-323	409-465	496-550	143-197	195-240
Chevrolet Silverado	40-70 mph	334-390	270-315	278-302	183-210	306-366	63-66	206-273

Temperatures were measured by turning off the engine at the end of the driving range. Maximum temperatures were reached about 1 to 2 minutes after the vehicle was completely stopped and the engine turned off.

- *Heat Release Rate*: 3 to 670 kW. Flames penetrate the passenger compartment when heat release rates outside the compartment reach 100 to 800 kW (Chapter IV). Thus, several parts in the engine compartment and under the vehicle are capable of participating in the flame penetration process into the passenger compartment;
- *Fire Retardant Treatments of Automotive Plastics (PE and PP)*: the treatments reduce the flaming melting/dripping behaviors, reduce flame spread, increase time to reach the peak heat release rate and reduce the peak heat release rate;
- *Fire retardant treatments of HVAC unit*: heat release rate and generation rate of CO_2 are reduced slightly. Time for fire growth is increased by one of the fire retardants used in the test. Release rates of CO and smoke are increased significantly by the fire-retardant treatments. The treatments are ineffective in enhancing the higher resistance to ignition and burning of the HVAC unit in the vehicle burn tests.

6.4 FLAME PENETRATION INTO THE PASSENGER COMPARTMENT

Fire behavior of crashed motor vehicles was examined by performing vehicle burn tests following the vehicle crash tests. Fires were purposely started in the front in the engine compartment for the front crashed vehicles and in the rear by using the gasoline pool fire under the rear-crashed vehicles. Flame penetrated into the passenger compartment through the broken windshield, HVAC module, and seam openings on the vehicle floor, gaps, and drains holes in the floor panel, which are summarized in Table 6-2.

Based on 10 vehicle burn tests, it was found that flames penetrate the passenger compartment (between about 10 to 24 minutes) through the windshield and the dash panel openings if the fire is started in the engine compartment. If the fire is started under the vehicle by igniting the gasoline pool, flames penetrate the passenger compartment (between about 0.5 to 3.0 minutes) through the split weld seams, gaps and holes in the floor pan. Thus, it takes longer times for flames to penetrate the passenger compartment for engine compartment initiated fires, whereas it takes short times for flames to penetrate the passenger compartment for underbody initiated fires (gasoline pool fires). However, once flames penetrate the passenger compartment, fire growth in both cases becomes very rapid and untenable/flashover conditions are reached rapidly.

Table 6-2. Flame Penetration into the Passenger Compartment

<table>
<tr><th>Test #</th><th>Vehicle Burned</th><th>Flame Penetration into the Passenger Compartment</th></tr>
<tr><td colspan="3">Fires Started in the Engine Compartment</td></tr>
<tr><td>1</td><td>1996 Dodge Caravan (13/11/96)</td><td>Through broken windshield, AC evaporator and condenser-line pass-through and HVAC air intake</td></tr>
<tr><td>4</td><td>1997 Chevrolet Camaro (01/10/97)</td><td>Through windshield and HVAC module in the dash panel, both of which were broken in the crash test.</td></tr>
<tr><td>7</td><td>1998 Honda Accord (23/02/99)</td><td>Through windshield and pass-through openings in the dash panel</td></tr>
<tr><td>9</td><td>1999 Chevrolet Camaro (17/02/00)</td><td rowspan="2">Through windshield and HVAC module in the dash panel</td></tr>
<tr><td>10</td><td>1999 Chevrolet Camaro with FR-HVAC module (21/02/00)</td></tr>
<tr><td colspan="3">Fires Started Under the Vehicle in the Rear by Gasoline Pool Fire</td></tr>
<tr><td>2</td><td>1996 Plymouth Voyager (15/11/96)</td><td>Through split weld seams</td></tr>
<tr><td>3</td><td>1997 Chevrolet Camaro (30/09/97)</td><td>Through crashed induced seam openings, gap between the driver’s door and door frame, and drain hole in the floor panel</td></tr>
<tr><td>5</td><td>1998 Ford Explorer (09/06/98)</td><td>Through crashed induced seam opening, ignition of quarter trim panel by fire plume and heat conduction across the floor pan.</td></tr>
<tr><td>6</td><td>1998 Ford Explorer (11/06/98)</td><td>Through openings in the floor panel</td></tr>
<tr><td>8</td><td>1998 Honda Accord (25/02/99)</td><td>Through crashed induced seam openings</td></tr>
</table>

Estimations have been made for times to reach various events in the vehicle burn tests (Chapters III, IV and V):

- *Flame penetration*: time to flame penetration ($\mathbf{t_{fp}}$) are estimated from the observations made during the vehicle burn tests (Chapter III);

- *Flashover*: time to flashover ($\mathbf{t_{flashover}}$) is estimated from temperatures recorded by bare thermocouples below the headliner centered in the vehicle or by the array of aspirated thermocouples located below the headliner. In most cases, $\mathbf{t_{flashover}}$ is taken as the time at which there is a sudden increase in the temperature or at a time at which temperatures exceed 400 to 500 ^{o}C (Chapter IV);

- *Pain, Burn, Incapacitation, and Lethality*: time to pain ($\mathbf{t_{pain}}$), time to 2nd degree burn ($\mathbf{t_{2nd\text{-}burn}}$), time to 3rd degree burn ($\mathbf{t_{3rd\text{-}burn}}$), time to incapacitation ($\mathbf{t_{incap}}$) and time to lethality ($\mathbf{t_{lethal}}$) are estimated from the times for the Fractional Effective Dose (**FED**) to reach unity, using BURNSIM and Toxic Hazard Models. In vehicle burn tests that are terminated before the endpoints are reached, times are estimated assuming continuation of the tests to the endpoints (Chapter V);

The estimated values of times for various events in the vehicle burn tests are listed in Table 6-3 and plotted in Fig. 6-1. These data show that there are no obvious differences in results for various vehicle model designs.

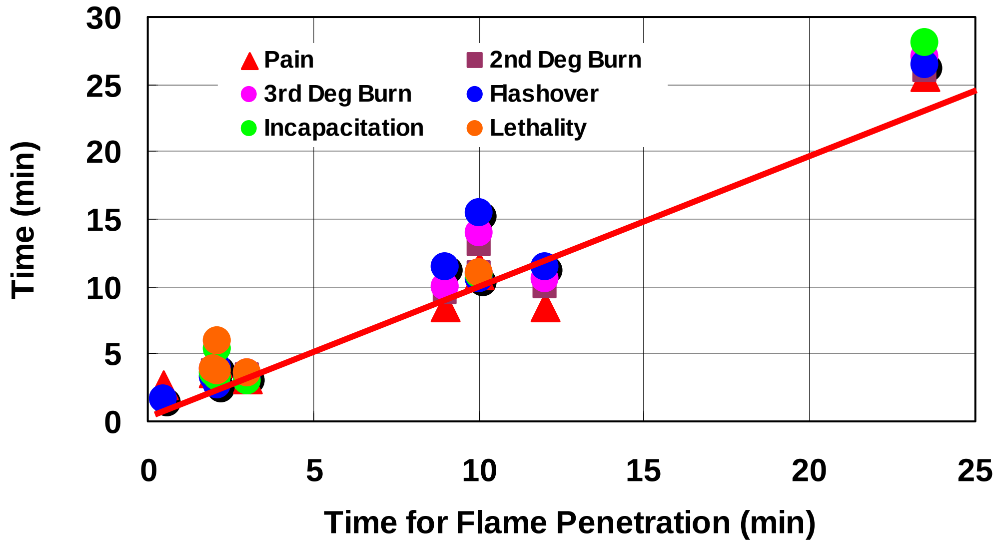

Figure 6-1. Estimated times to flashover, pain, 2nd and 3rd degree burns, incapacitation and lethality versus time to flame penetration into the passenger compartment. Data are taken from Chapters IV and V.

The following correlations are suggested by the data in Fig. 6-1:

1) $\mathbf{t_{pain} = 0.99\ t_{fp}}$; 2) $\mathbf{t_{2nd\text{-}burn} = 1.03\ t_{fp}}$; 3) $\mathbf{t_{3rd\text{-}burn} = 1.06\ t_{fp}}$; 4) $\mathbf{t_{flashover} = 1.18\ t_{fp}}$;

5) $\mathbf{t_{incap} = 1.24\ t_{fp}}$; 6) $\mathbf{t_{lethal} = 1.36\ t_{fp}}$

The above correlations indicate that once the flames penetrate into the passenger compartment, untenable conditions are reached rapidly resulting in pain, 2nd and 3rd degree burns, flashover, incapacitation, and lethality in that order.

6.5 PASSENGER COMPARTMENT ENVIRONMENT CREATED BY MOTOR VEHICLE CRASH FIRES

Data for estimated times for various events in the vehicle burn tests, listed in Table 6-3 and plotted in Fig. 6-1 suggest that in many vehicle crash fires, especially those involving front crashes, heat strokes and burns would precede asphyxiation by toxic gases and would be the main cause of lethality. For rear crashes, incapacitation by asphyxiant gases and even uptake of lethal levels may occur just before or around the same time as lethal heat and burns exposure.

Table 6-3. Estimated Times to Flame Penetration, Flashover, Pain, 2nd and 3rd Degree Burns, Incapacitation, and Lethality

Test #	Vehicle Burned	Times Post Ignition (minutes)						
		Flame Penetration	Flashover[a]	Pain[b]	Burn[b] (Degree) 2nd	Burn[b] (Degree) 3rd	Incapacitation	Lethality[b]
Fires Started in the Engine Compartment								
1	1996 Dodge Caravan (13/11/96)	10.0	10.5	10.8	11.0	11.0	10.8	11.0
4	1997 Chevrolet Camaro (01/10/97)	10.0	15.5	11.5	13.0	14.0	*	*
7	1998 Honda Accord (23/02/99)	23.5	26.5	25.5	26.0	27.0	28.0	*
9	1999 Chevrolet Camaro (17/02/00)	9.0	11.5	8.5	9.5	10.0	*	*
10	1999 Chevrolet Camaro with FR-HVAC module (21/02/00)	12.0	11.5	8.5	10.0	10.5	*	*
Fires Started Under the Vehicle in the Rear by Gasoline Pool Fire								
2	1996 Plymouth Voyager (15/11/96)	2.0	3.3	3.5	3.7	3.9	3.5	3.8
3	1997 Chevrolet Camaro (30/09/97	0.5; 3.0	3.3	3.1	3.4	3.6	3.0	3.5
5	1998 Ford Explorer (09/06/98)	2.1	2.6	none	none	none	3.3	3.7
6	1998 Ford Explorer (11/06/98)	2.1	4.0	4.3	none	none	5.3	6.0
8	1998 Honda Accord (25/02/99)	0.5	1.6	2.6	none	none	*	*

*: Incapacitation and lethality would have occurred if fires were allowed to burn longer than the fire durations of these tests.
a: Chapter IV; **b:** Chapter V.

The estimated times for various events in the vehicle burn tests in Table 6-3 are short for fire fighting and extrication by a nearby fire department even in an urban environment. Thus, prevention or delay in the flame penetration into the passenger compartment is very important for the survivability of the passengers in vehicle crash fires. Data also suggest that for engine and exterior parts, toxicity is not as relevant as high resistance to ignition and flame spread. However, for the plastic parts in the passenger compartment, in addition to resistance to ignition, flame spread and heat release, toxicity may be important especially after the heat or flame penetrates the passenger compartment.

Review of incidents of passenger vehicle crashes in North Carolina (1995-1996) suggest that on the average, drivers of vehicles involved in post-crash fires are approximately twice as likely to suffer serious injury or death and approximately four times likely to die as drivers involved in crashes of similar severity that do not involve post-crash fires (Chapter V). From the statistics of the vehicle crashes in North Carolina, when post-crash vehicle fires occurred, 82.5% of occupants (single vehicle) and 95.4% (multi-vehicle) survived without serious injury, while 4.6% and 1.6% died. Thus, for the majority of post-crash fires, the occupants escaped or are rescued before the fire becomes serious, or the fires do not become sufficiently serious to affect trapped occupants. Therefore, it is likely that even small improvements in decreasing the rapidity of fire hazard development in post-crash vehicle fires could lead to a reduction in injuries and deaths.

The clinical evaluation study of 207 fatal accidents involving post-crash fires occurring in Texas between 1990 to 1992 and in North Carolina between 1995 to 1996, provide information on the passenger compartment environment for post vehicle crash fires (Chapter V). The examination of the carboxyhemoglobin (**COHb**) concentrations in the blood of post crash fire victims shows that that the majority (72%) of fatalities had relatively low (sub-lethal) **COHb** concentrations in the blood (less than 20% **COHb**), indicating that passengers died from the effects of physical trauma or heat and burns before a significant CO uptake occurred. Others (23%) had higher **COHb** levels consistent with incapacitating but generally sub-lethal exposure to CO. Around 5% had lethal **COHb** levels (>50% COHb).

Although limitation of smoke and toxic compounds released from the automotive plastics would be beneficial, by far the most important criteria for all plastics are resistance to ignition and flame spread. For plastic parts in the engine compartment and in the exterior of the vehicle, toxicity is not relevant and applying toxicity criteria could be counter productive if plastic parts with high resistance to ignition and flame spread are rejected on the ground of toxicity. For plastic parts in the passenger compartment, in addition to higher resistance to ignition and flame spread, toxicity may also be important, especially during the early stages of the passenger compartment fires.

Summary of standards, regulations and industry guidelines for emergency response times and published response time, taken from 4, are listed in Tables 6-4 and 6-5. Average times from notification to arrival by incident year and fire department type, also taken from Ref. 4, are listed in Table 6-6. These times are guidelines and not the actual times. Note that the first responder may not have the equipment to extricate a trapped occupant.

Many of the numbers in the Tables 6-5 and 6-6 appear low. Additional work is being carried out under the MVFRI sponsorship to get better documented numbers using Automated Crash Notification (ACN) data.

Table 6-4. Summary of Standards, Regulations and Industry Guidelines for Emergency Response Times [4]

Organization	Time Specified (minutes)	Interval Description	Percentage of Calls	Emergency Service
Office of Disease Prevention and Health Promotion	5	Call to arrival	90	Urban, first responder EMS
	10	Call to arrival	80	Rural, first responder EMS
National Institute of Health	5	Dispatch to arrival	90	Life threatening calls
NFPA (1710)	4	Call to arrival	90	First engine company, career departments
NFPA (1720)	No specification	Call to arrival	None	First engine company, volunteer departments
NFPA (Proposed 450)	To be set locally	Call to arrival	To be set locally	EMS
California	10	High population density		EMS response time
	20	Medium Density		
	30	Low density		

Table 6-5. Summary of Published Response Time Values [4]

Interval	Time (minutes)	Average % of Calls Included	Data Description
Crash to notification	3.87	Average	Urban, 1996 fatal, EMS
	7.36		Rural, 1996 fatal, EMS
	4		Urban, 1997 fatal, EMS
	7		Rural, 1997 fatal, EMS
	8.4		Urban
	3.9		Urban, adjusted
Notification to arrival	4.19	Average, US cities	First unit
	4.30	80, US cities	
	0 to 10	81.7	Rural fatal, EMS
	0 to 20	94.3	Rural fatal, EMS
	0 to 10	93.8	Urban fatal, EMS
	0 to 20	97.7	Urban fatal, EMS
	6	Average	Urban, 1997 fatal, EMS
	11		Rural, 1997 fatal, EMS
	0 to 10	88.3	Urban, 1975-1993, fatal, EMS
	0 to 10	57.7	Rural, 1975-1993, fatal, EMS
	0 to 20	97.8	Urban, 1975-1993, fatal, EMS
	0 to 20	89.0	Rural, 1975-1993, fatal, EMS
	5.1	Average	2000, Fire Service
	5.3		2001, Fire Service
	5.4		2002, Fire Service
	5.3		2003, Fire Service
	0 to 7	80	2000, Fire Service
		77	2001, Fire Service
		75	2002, Fire Service
		77	2003, Fire Service

Table 6-6. Average Time in Minutes from Notification to Arrival by Incident Year and Fire Department Type [4]

Incident Year	Volunteer	Mostly Volunteer	Mostly Paid Professional Staff	All Professional Staff	Weighted Average
2000	10.4	5.3	5.1	5.3	5.1
2001	5.7	4.9	5.3	5.4	5.3
2002	7.9	5.6	5.4	5.3	5.4
2003	6.2	6.2	5.8	5.0	5.3
Weighted Average	7.2	5.5	5.3	5.2	5.3

A comparison of response times listed in Table 6-4 to 6-6 with the flame penetration and flashover times in Table 6-3 indicate that passengers could be rescued only from the front crashed vehicle fires. The flame penetration and flashover times in Table 6-3 for rear crashed vehicle fires started by gasoline pool fires under the vehicle are significantly lower than the emergency response times in Tables 6-4 to 6-6.

6.6 PASSIVE FIRE PROTECTION FOR PREVENTION OR DELAY OF FLAME PENETRATION INTO THE PASSENGER COMPARTMENT

There are varieties of methods that can be used to prevent flame penetration into the passenger compartment. For example:

1. Use of a fire wall and fire stops between the engine compartment and passenger compartment and fire hardening of underhood insulation blanket;
2. Modification of the softening and melting behaviors of plastic windshield inner linings;
3. Use of barriers to protect against flame and heat penetration from gasoline pool fires through small underbody seams and prevention of fuel leakage;
4. Fire suppression of engine compartment and undercarriage fires.

6.6.1 Use of Fire Wall (Bulkhead)

One of the automotive plastics for the bulkhead of 1996 Dodge Caravan was found to have a high resistance to flame spread [FPI = 4 $(m/s^{1/2})/kW/m)^{2/3}$, Volume III], when examined in the ASTM E2058 apparatus under simulated large-scale fire conditions (typical of vehicle crash fires). Thus, the bulkhead is expected to prevent flame penetration from the engine into the passenger compartment through the dashboard, provided there are no openings created by the crash and the windshield remains intact.

In the vehicle burn tests, flames from the engine compartment penetrated the passenger compartment through the windshield and broken HVAC unit in the bulkhead and thus fire resistance of windshield and the HVAC unit need to be enhanced.

6.6.2 Use of Fire Retarded HVAC Unit

Since in the vehicle burn tests, flames from the engine compartment were found to penetrate the passenger compartment through the HVAC unit, effectiveness of the fire retardant treatment of the plastics for the HVAC unit (PP) was evaluated. The FPI value of fire retarded PP was measured to be 13 $(m/s^{1/2})/kW/m)^{2/3}$ from the ASTM E2058 apparatus (Volume III), which is significantly higher than required for prevention of flames spread (FPI ≤ 6 $(m/s^{1/2})/kW/m)^{2/3.}$ Thus, the FPI value of the fire retardant treated PP in the HVAC unit suggests that the treatment would be ineffective in prevention flame propagation under the large-scale fire conditions, typical of vehicle crash fires. Intermediate-scale tests and vehicle burn tests also showed that the fire retardant treatment of PP in the HVAC unit was ineffective in preventing the flame penetration from the engine into the passenger compartment. Thus, there is a need to find an effective fire retardant treatment of the HVAC unit than the one used in the vehicle burn test.

6.6.3 Change in the Thermal Response of the Windshield

Flame penetration from the engine compartment to the passenger compartment through the windshield was one of the major paths in the vehicle burn tests. Falling of broken pieces of windshield and enlargement of the hole in the windshield created in the crash, due to melting of the plastic windshield inner layers, was one of the major paths for flame penetration.

Modification in the melting and softening behaviors of the plastic windshield inner layers could be beneficial in delaying the flame penetration into the passenger compartment.

6.6.4. Fire Hardening of the Underhood Insulation Blanket

The fire resistance of hood liners from the 1996 Dodge Caravan and the 1997 Chevrolet Camaro was examined in the FMVSS 571-302, ASTM E1354 and E2058 apparatuses (Volume III).

The 1996 Dodge Caravan hood liner consisted of insulation (back, made of PET, cellulose and epoxy) and face (PET) (with 1.3 to 2.4 % of inorganic fillers and 0.30% of organic fillers, 4716832A and B listed in Volume III).

The 1997 Chevrolet Camaro hood liner consisted of insulator media made of glass fiber reinforced phenol-formaldehyde (10273234B), PE top (10273234A), and nylon-PMMA-phenolic scrim (10278015) (Volume III).

The following results were found for the fire resistance of the hood liner (Volume III, Appendix A-4):

1) 1996 Dodge Caravan PET hood liner face (4716832B)

a) FMVSS 571-302: no sustained burning, passed the test;
b) ASTM E1354: very low ignition resistance (CHF = 14 kW/m^2, TRP = 114 $kW\text{-}s^{1/2}/m^2$) and low heat release rate;

c) ASTM E2058: very low ignition resistance (CHF = 10 kW/m^2, TRP = 174 $kW\text{-}s^{1/2}/m^2$), low heat release rate, but high FPI value;

2) <u>1997 Chevrolet Camaro nylon/phenolic binder hood insulator (10278015)</u>

a) FMVSS 571-302: no sustained burning, passed the test;

b) ASTM E1354: very low ignition resistance (CHF = 19 kW/m^2, TRP = 39 $kW\text{-}s^{1/2}/m^2$) and low heat release rate;

c) ASTM E2058: very low ignition resistance (CHF = 10 kW/m^2, TRP = 174 $kW\text{-}s^{1/2}/m^2$ and low heat release rate (FPI was not measured).

Although, both the hood liner faces pass the FMVSS571-302 test, results from ASTM E1354 and E2058 tests show that they have very low resistance to ignition and low heat release rate and the **FPI** value suggests rapid flame spread. In the vehicle burn tests, the flame spread on the hood insulation blanket in the engine compartment was rapid. Thus, there is a need to fire harden the hood insulation blanket and modify the method of its attachment to the hood, so that in vehicle crashes, it can cover the initial engine fire and extinguish it before it has chance to spread.

6.6.5 Intumescent Coating of the Vehicle Undercarriage and Sealing of Utility Pass-through and Drain Openings

In the vehicle burn tests, flames from the gasoline pool fire under the vehicle penetrated the passenger compartment through the electrical pass through openings and drain holes (plugs were burned), split spot weld, and seam openings. Coating the underbody with intumescent paint did not stop the flames from penetrating the passenger compartment through the electrical pass through opening, which was not covered by the paint, although time to flame penetration was slightly delayed.

It appears that use of fire hardened plugs and intumescent paints of different compositions and mode of application than used in the tests, could prevent or significantly delay the flame penetration from under the vehicle into the passenger compartment. Use of fire hardened flexible insulation that would not tear and would keep flames out is also an attractive method to significantly delay the flame penetration from under the vehicle.

6.6.6 Fire Hardening of Plastic Parts in the Engine Compartment

Fire resistance of several plastics parts in the engine compartment of the 1996 Dodge Caravan and the 1997 Chevrolet Camaro have been examined in the FMVSS 5710-302, ASTM E1354 and E2058 apparatuses, in the intermediate-scale tests and in the vehicle burn tests (Volume III). The following results were found for the fire resistance of engine compartment plastic parts.

1) 1996 Dodge Caravan Engine Compartment Plastic Parts

a) FMVSS 571-302: all plastic parts passed the test;
b) ASTM E1354: most of the plastic parts had low ignition resistance and high heat release rate;
c) ASTM E2058: most of the plastic parts had low ignition resistance, higher heat release rate and higher **FPI** values;

2) 1997 Chevrolet Camaro Engine Compartment Plastic Parts

a) FMVSS 571-302: all plastic parts passed the test;
b) ASTM E1354: most of the ordinary plastic parts had low ignition resistance and high heat release rate;
c) ASTM E2058: most of the plastic parts had low ignition resistance, higher heat release rate and higher **FPI** values.

Although the engine compartment plastic parts pass the FMVSS 571-302 test, they are expected to ignite easily, sustain flame spread and burn. It is, therefore, necessary to fire harden those plastic parts that are expected to be in initial path of the spreading flames in the engine compartment. Temperatures measured in the engine compartment at various locations (Chapters III and IV and Appendix B) provide the information for the initial path of the spreading flames in the engine compartment.

6.6.7 Other Changes

Although preventing the contact of fluids and hot metal surfaces in the engine compartment and fire retarding the fluids appear to be attractive techniques to prevent flame spread in the engine compartment, they are difficult to implement with little benefit. Shielding or insulating the manifold and catalyst could prevent ignition and might reduce the exhaust emissions.

6.7 ACTIVE FIRE PROTECTION TO PREVENT OR DELAY FLAME PENETRATION INTO THE PASSENGER COMPARTMENT VIA POST VEHICLE CRASH FIRE SUPPRESSION

The problem of post collision vehicle fires, previous suppression research in vehicles, and recent fire suppression research have been reviewed [5]. Based on the survey of opinions of companies that offer fire protection systems, technologies have been assessed for the fire safety of passengers in vehicle crashes. In the survey, relative merits of active and passive fire protection systems and fire hardening of automotive plastics and engine compartment fluids were considered. Aerosol extinguishers, conventional powder extinguishing systems, conventional water mist systems, conventional water based foam systems, and gas generator/hybrid systems were suggested for consideration for the suppression of engine compartment fires and underbody fuel-fed fires in rear end collisions. Passive fire protection systems such as self-sealing fluid lines, enhanced crashworthiness of the fuel tank and fluid shut-off devices were suggested for consideration for the fire prevention of vehicle fires.

There are very limited number of studies, where fire suppression technologies for vehicle fires have been examined [6,7,8,9,10,11]; some of these studies are discussed in the following sections.

6.7.1 National Institute of Standards and Technology's Study on the Evaluation of Active Suppression in Simulated Post-Collision Vehicle Fires

Effectiveness of fire suppressants in simulated post-collision vehicles fires were investigated for engine compartment and underbody fires [8]. Both traditional and emerging active fire suppressants were tested. These included dry powders, inert suppressants, and compressed liquefied halogenated suppressants.

The suppressants tested in the engine compartment fire suppression experiments were HFC-125 (C_2HF_5), HFC-227ea (C_3HF_7), ABC powder (mono-ammonium phosphate, $NH_4H_2PO_4$,), BC powder (sodium bicarbonate, $NaHCO_3$), a tubular suppression system, solid propellant generators and aerosol generators. The suppressants tested in the underbody fire suppression experiments were HFC-125, ABC powder, BC powder, solid propellant generators, and aerosol generators.

The results showed that it is highly improbable that an on-board fire suppression system will be able to extinguish all engine compartment and underbody fires. Many suppressant types were found to be impractical for post-collision engine compartment fire suppression, However, under certain conditions, the results showed that fire suppression is feasible. The solid propellant generator (a unique pyrotechnic device, SPGG), which rapidly delivers a gas/particulate effluent, was found to be effective suppressant tested in the full-scale engine compartment fire scenario.

Full-scale suppression experiments in the engine compartment of an un-crashed stationary vehicle in the absence of forced ventilation (radiator fan off) showed that suppression of a 200 ml/min gasoline fire (rear driver side portion of the engine manifold, about 15-cm from the front panel and 20-cm below the hood) was achievable with less than 500 g of SPGG generated compounds.

Full-scale underbody experiments showed that suppression of gasoline fire was achieved with less than 300 g of ABC and BC powder suppressants when the fuel was located under the vehicle footprint for low wind conditions. Gasoline flowed at a rate of 500 ml/min just above the middle of the rear seam of the gasoline tank. The splashing, dripping gasoline created a puddle that extended across the rear portion of the vehicle underbody, typically covering a large fraction of 1.3-m distance between the rear tires. If a fuel puddle in an underbody fire extended beyond the vehicle footprint and if moderate to high winds were present, then the powder suppression system failed to extinguish the fire. Other studies have used some of these systems and found them to be effective in suppressing the engine compartment fire [6,7] and underbody pool fires [11].

6.7.2 GM Study on the Evaluation of Active Suppression in Post-Collision Vehicle Fires

The effectiveness of solid propellant gas generator (SPGG) for the suppression of engine fire evaluated by NIST [8] was validated by a crash test, followed by static tests using a 1999 Honda Accord [9, Appendix B12]. The fire suppression system included two prototype SPGG units and optical flame detectors. The SPGG units and the optical flame detectors were bolted to the lower surface of the hood. One SPGG unit with the optical flame detector was attached to the left side and the other on the right side of the hood rearward of the crush initiator in the inner hood panel. The SPGG units were preset to deliver a concentration of about 3 kg/m^3-s of dry chemical, a limit for fire suppression established by the manufacturer (this concentration has to be maintained for long enough time so that re-ignition does not occur).

The 1999 Honda Accord with installed fire suppression system was subjected to a crash test at the GM Proving Ground, using a test protocol that resulted in a fire in the engine compartment of a similar model in a previous crash test. Fire was detected by the optical flame detector on the left at 298 ms, triggering the discharge of the SPGG unit on the left. Detector on the right did not detect fire at this time and thus the unit on the right did not discharge. The discharge of the SPGG unit on the left failed to extinguish the fire, except for a very short time in the beginning. Fire had to be extinguished manually.

Four static fire tests were performed using the crashed 1999 Honda Accord. Two new, fully charged SPGG units were installed in the vehicle before each test. The SPGG discharge did not extinguish the fire started in the engine compartment by the electrical ignition of the plastics. The SPGG discharge was also not able to extinguish a fire started in the engine compartment by the autoignition of the power steering fluid contacting a hot metal plate. SPGG discharge did extinguish a fire started by the electrical ignition of the top of the battery, where power to the igniter was turned off.

Thus, there are disagreements between the GM and NIST study about the effectiveness of the SPGG discharges to extinguish the engine compartment fires and requires a careful analysis of the results from the two institutions. The SPGG discharge could be useful for preventing the flame penetration into the passenger compartment as has been demonstrated by recent studies on the subject [6,7,10,11].

6.7.3 The Ford Motor Company Suppression System (FSS)

Ford Company has been actively evaluating fire suppression technologies to defend against ruptured fuel tanks and subsequent underbody fuel fed fires [5,11]. The work was an apparent response to the concern regarding fatalities in fires in a number of high-speed rear end impacts in parked Crown Victoria police vehicles. A pyrotechnic gas generator, similar to an air-bag deployment system, was used to deploy the combination liquid fire suppressant and surfactant. The suppressant was an aqueous film forming foam (AFFF), modified with potassium salts to lower the freezing point to below -40 ^{o}F. The study found that liquid fire suppressants combined with surfactants performed better than foams or powders, due in part, to the ability of that substance to spread like gasoline beyond the direct reach of the deployment nozzles and to cover the gasoline. Although the system was primarily designed as an automatic suppression system, a manual activation switch was provided.

For the development of the Suppression System, 80 static vehicle fire tests were performed. The full vehicle crash tests involved a Taurus striking the rear of a parked Crown Victoria Police Interceptor (CVPI) at 75 mph with a 50% overlap between the vehicles biased to the driver's side. At impact, 200 ounces of pressurized gasoline was released from a separate tank onto the front side and top of the fuel tank. The release of gasoline was completed over 22 seconds. A locally mounted rocket motor was used to ensure ignition of the gasoline.

The FSS will be sold commercially soon.

6.7.4 University of Maryland Study on Nitrogen Foam Suppression System for Automobile Under-Hood Post-Collision Fire Protection

A nitrogen foam fire suppression system has been developed to contain or extinguish fires that originate in engine compartments at the location of the battery of automobiles after front-end collisions [6,7]. The nitrogen foam creates an inert environment within the engine compartment that is sustainable for a period of at least 10 minutes. It has been shown that for an expansion ratio of 220, nitrogen foam will fill all of the voids within an engine compartment without freely flowing down and out of the engine compartment.

Seven tests were performed using five different models of vehicles, which are listed in Table 6-7. The hoods were bent to simulate possible post-collision damage. A fire size of 80 kW of gasoline using a 9 x 14-in aluminum pan, burning for 5- minutes was used in the tests. The foam application was in the range of 220 to 400 l/min with an expansion ratio of 220. foams used in the tests were from Ansul, identified as Ansulite 3 x 3, and Chemguard, Inc., identified as Ecoguard 3% F3. The results of the vehicle fire tests for fire extinguishment are presented in Table 6-7 and suggest that the foam system could be a candidate for the suppression/extinguishment of engine compartment fires to prevent flame penetration into the passenger compartment.

6.7.5 Powder Panel Fuel Tank or Fluid Reservoir Protection System from Fires

Panels are relatively simple devices composed of molded thermoplastic that contains a fire suppressant powder [5,10]. Powder panels have been applied to the lining of aircraft dry bays to provide passive, lightweight, fire protection against ballistic impact. There is a commercially available powder product marketed as Fire Panel, consisting of a shallow shell, filled with a powder fire-extinguishing agent, which is mounted on or near a fuel tank or other flammable fluid reservoir. The technology has been used for decades to protect military aircraft from ballistic-induced fuel tank –fed fires.

In the event of an impact to the fuel tank or reservoir, such as due to collision, which might rupture the tank and spill fuel to be ignited, the adjacent fire panel would also be impacted and shatter as designed. On shattering, the panel would discharge a plume of extinguishing powder to inert the space around the leaking fuel tank or the reservoir, even if the vehicle travels some distance after impact.

The panels have been tested by the Auto Safety Research Institute, in the Crown Victoria Crash Tests with Ignition Sources, in the Army's tests for tactical wheeled vehicles and for motor sports and other applications [10].

6.8 PREVENTION OR DELAY OF FLAME SPREAD IN THE PASSENGER COMPARTMENT

There are varieties of methods that can be used to prevent flame spread in the passenger compartment. For example:

2) Fire hardening of automotive plastics and parts to increase the ignition, flame spread and combustion behaviors and reduce the release of smoke and toxic compounds;
3) Modify the melting, dripping and pooling behaviors of automotive plastics and parts

In the vehicle burn tests, ignition and flame spread were observed for specific plastics located in the path of the flame entering the compartment, such as the instrument panel, carpet, seats, trim panel, and headliner. The headliner was observed to be one of the plastic parts responsible for rapid flame spread in the passenger compartment. Fire resistance of several of these plastic parts in the passenger compartment has been evaluated in the ASTM E2058 apparatus (Volume III) and in the Intermediate-scale Tests (Chapter II).

Most of the passenger compartment plastic parts had low ignition resistance, higher heat release rate and higher **FPI** values. In the intermediate-scale tests, the parts burned as high intensity pool fires. It is, therefore, necessary to fire harden those plastic parts that are expected to contribute to the flame penetration into the passenger compartment and those that are in the path of the penetrating flames into the passenger compartment.

Table 6-7. Summary of Suppression/Extinguishment of Engine Compartment Fires (6)

Test #	Vehicle Model, Ignition, and Foam Application	Results
1	1980 Ford LTD, battery is removed; fire near the battery, foam application concurrent with gasoline ignition	Ansulite 3 x 3 foam application: 200 l/min; application not sufficient to extinguish the fire; problems with leakage of nitrogen
2	1980 Ford LTD, battery is removed; fire near the battery, foam application concurrent with gasoline ignition	Ansulite 3 x 3 foam application: 400 l/min. About 3 minutes for the foam to fill the engine and about 1-minute to surround the gasoline pool fire. Flames moving away from the foam, out of the vehicle through the openings around the hood. Flames unable to spread throughout the engine compartment.
3	Saturn compact sedan; battery is removed; fire near the battery, no foam application	Ansulite 3 x 3 foam application: none; flames emerging from the gaps between the hood and the body of the vehicle. Fluctuation of the flame location between the gaps on the right side and front of the vehicle. In about 50 seconds, flames emerging from all the gaps indicating that flames are spreading from the gasoline pool to the entire engine compartment. Fire allowed to burn for 180 seconds and then extinguished with water.
4	Chrysler mid size sedan; battery is removed; fire near the battery, foam application concurrent with gasoline ignition	Ansulite 3 x 3 foam application: 400 l/min. Flames emerging from the gaps between the hood and the body of the vehicle near the gasoline pan. Foam reaches the pool fire in about 30 seconds, forms a semi-circle around the pan and in further 10 seconds extinguishes the fire. Fire is completely extinguished within about 40 to 45 seconds post ignition. At about 60 seconds, foam emerging out of the engine compartment. Foam application terminated at 70 seconds post ignition. Unburned gasoline left in the pan after the test.
5	Chrysler mid size sedan; battery is removed; fire near the battery, foam application concurrent with gasoline ignition	Ecoguard 3% F3 foam application: 400 l/min, concentration 8%. Flames emerging from the gaps between the hood and the body of the vehicle near the gasoline pan. Foam reaches the pool fire in about 25 seconds, forms a semi-circle around the pan and within 5 seconds extinguishes about 90% of the fire, rest being extinguished within 20 seconds. Fire completely extinguished within about 50 seconds post ignition. At about 60 seconds, foam emerging out of the engine compartment. Foam application terminated at 70 seconds post ignition. Unburned gasoline left in the pan after the test.

Table 6-7 continued on the next page

Table 6-7 continuing from the previous page

Test #	Vehicle Model, Ignition, and Foam Application	Results
6	Chevrolet Cavalier sedan; fire the ground below the engine compartment; foam application five minutes before ignition	Ecoguard 3% F3 foam application: 400 l/min, concentration 8%; foam generator run for 70 seconds filling areas above and around the engine. Gasoline pan under the engine compartment ignited 340 seconds after the foam generator had been started. After few seconds post ignition, flames penetrating the engine compartment and entering the headspace between the engine and the hood. After about 120 seconds, engine fire established independent of the gasoline pool fire. Fire intensity continuing to grow and after 250 seconds of burning, fire extinguished by water. No foam left in the engine compartment after the fire. Thus, the foam system was unable to protect the engine compartment fires, initiated by underbody pool fires.
7	Rollover-Mercedes Benz; fire on the hood directly below the engine; foam application concurrent with gasoline ignition	Ecoguard 3% F3 foam application: 400 l/min, concentration 8%; flames impinging directly upon the engine above. Foam dropped directly down onto the hood below the generator; engine not filled with the foam, but spreading in all directions and approaching the pool fire immediately. The foam encircled the pool and then rolled over the fire and extinguished it in about 40 seconds. The main fire extinguished after about 55 seconds. Secondary fires extinguished after 205 seconds. The foam thus was successful in extinguishing this type of roll over fire.

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APPENDIX A

SELECTED DATA FOR POST-COLLISION MOTOR VEHICLE FIRES TAKEN FROM REF. 4 (CHAPTER I)

Table A-1. Case Data for the Post-Collision Motor Vehicle Fires [4]

Vehicle	Impact Description	Fuel/Ignition Source(s)	Time to Ignition/ to Interior(minutes)	Initial Fire Location	Injuries: Fire Vehicle/Other Vehicle	Assistance in Egress from Fire Vehicle
1992 Mitsubishi Eclipse	Fontal with the front of a pickup	Engine off, coolant/ exhaust manifold, electrical or mechanical spark	<3/5 to 8	Engine compartment	Minor/none	Yes
1992 Ford Explorer	Right side in the front of the car	Coolant/electrical	Immediate/ 2 to 4	Engine compartment	Driver: ejected, broken vertebra/ Driver: cuts, broken knee, back pain	Yes (for children)
1995 BMW 5251	Frontal with a barrier, narrow	Gasoline, coolant, polymers/ electrical, exhaust manifold	2 to 5/4 to 6	Engine compartment	Driver: unconscious, passenger: spinal injuries	Yes
1996 Chrysler Sebring	Side with the side of a tractor-trailer	Most fluids except gasoline, polymers/ electrical spark, exhaust manifold	3 to 5/4 to 6	Engine compartment	Driver: lacerations	No
1991 Plymouth Acclaim	Frontal with the side of a pickup truck	Coolant/ electric motor	8 to 10/ extinguished 9 to 11 with no spread to interior	Engine compartment	None	No
1997 Plymouth Voyager	Frontal with the side of a van, under ride	Gasoline, other fluids/electrical or mechanical spark, exhaust manifold	Immediate/4 to 6	Engine compartment	Driver: broken hand/Driver: cuts to head	No

Table A-1 continuing on the next page

Table A-1 continuing from the previous page

Vehicle	Impact Description	Fuel/Ignition Source(s)	Time to Ignition/ to Interior(minutes)	Initial Fire Location	Injuries: Fire Vehicle/Other Vehicle	Assistance in Egress from Fire Vehicle
1991 Mitsubishi Eclipse	Override of a culvert, rollover	Engine oil/exhaust pipe, mechanical spark	Immediate/ extinguished without spread to interior	Exhaust system, car inverted.	Driver: back pain, bruises, scratches	No
1990 Lincoln Town Car	Rear-end by the front of a 3/4 ton van	Gasoline from tank/ electrical, mechanical spark	Immediate/ fully engulfed within 9	Rear end and/or interior	Driver: fatality from blunt force injury. Passenger: fatality from unknown cause/Driver: none, five passengers: minor and major injuries	Driver remained 'm the vehicle, passenger partially ejected
1994 Mazda 323	Rear-end by the front of a passenger car	Gasoline from tank/ electrical, mechanical spark, exhaust manifold	Immediate/< 2	Rear end and/or interior	Driver: fatality due to fire/ minor injuries	Driver remained in the vehicle
1995 Ford Escort	Frontal with rear of a pickup	Engine oil and coolant/exhaust manifold and electrical	< 2/extinguished in 5 to 10 with no spread to interior	Engine compartment	None	No
1991 Toyota Previa	Override of a tow dolly	Gasoline from tank/ mechanical spark	Immediate/ immediate to exit paths	Pool fire under driver door	Driver and passenger burn injuries	No

Table A-1 continuing on the next page

Table A-1 continuing from the previous page

Vehicle	Impact Description	Fuel/Ignition Source(s)	Time to Ignition/ to Interior(minutes)	Initial Fire Location	Injuries: Fire Vehicle/Other Vehicle	Assistance in Egress from Fire Vehicle
1990 Dodge Caravan	Frontal impact with a tree	All fluids/ electrical, mechanical spark, exhaust manifold	Immediate/1 to 3	Engine compartment	Driver: burns. Passengers: one fatal with unrelated burns, two seriously injured	Yes
1968 Plymouth Sundance	Undercarriage impact and rollover	Unknown fluid(s)/ Unknown	<5/ fully engulfed within 10	Between front wheels on inverted car	Driver: non-incapacitating. Passenger: none	Yes
1993 Honda Prelude	Frontal with a utility pole	Coolant, power steering fluid, polymers/ electrical	5/<10	Engine compartment	Driver: incapacitating injuries	Yes
1994 Toyota Camry	Frontal with a narrow object	Coolant, brake fluid, polymers /electrical, mechanical, spark, exhaust manifold	1 to 2/<5	Engine compartment	Driver: bruised chest	Yes
1994 Saturn	Rear by front of a passenger car	Gasoline from tank/ electrical, mechanical spark	Immediate/1 to 3	Passenger compartment	Driver: fatal, cause unknown, likely due to trauma/ two passengers: minor	Driver remained in the vehicle

Table A-1 continuing on the next page

Table A-1 continuing from the previous page

Vehicle	Impact Description	Fuel/Ignition Source(s)	Time to Ignition/ to Interior(minutes)	Initial Fire Location	Injuries: Fire Vehicle/Other Vehicle	Assistance in Egress from Fire Vehicle
1992 Chevrolet Sports Van	Rear by front of an under riding pickup	Gasoline from tank/ electrical, mechanical spark	Immediate/ fully engulfed within 11	Rear end	Driver: concussion, back injuries, burned arm. three passengers: minor injuries	Yes
1993 Chevrolet Silverado Pickup	Frontal with the rear of a van	Power distribution box, coolant, brake fluid/ electrical-, mechanical spark	Unknown/ extinguished with no spread to interior	Engine compartment	Driver: fatal from impact	Driver remained the in vehicle
1995 Chevrolet K-1 5 Pickup	Frontal with a tree	Coolant, brake fluid, polymers/electrical, mechanical spark, exhaust manifold	Unknown/3 to 7	Engine compartment	Driver: fatal, cause unknown	Driver remained in the vehicle
1995 Toyota Camry	Frontal with a guard rail	Coolant, transmission fluid, polymers/ electrical, mechanical spark, exhaust	1 to 4/fully engulfed within 9	Engine compartment	Driver, passenger both had visible injuries	Yes
1994 Dodge Caravan	Override of a steel road plate	Gasoline from tank/ mechanical spark	Immediate/ immediate to exit paths	Pool fire under passenger compartment	Driver: burn injuries. two passengers: none	Unknown

Table A-1 continuing on the next page

Table A-1 continuing from the previous page

Vehicle	Impact Description	Fuel/Ignition Source(s)	Time to Ignition/ to Interior(minutes)	Initial Fire Location	Injuries: Fire Vehicle/Other Vehicle	Assistance in Egress from Fire Vehicle
1991 Ford Escort	Frontal with the rear of a car and tree	All fluids/exhaust manifold, electrical, mechanical spark	<3/6 to 10	Engine compartment	Driver fatal due to internal injuries/None	Yes
1988 Mercury Sable	Frontal with a deer	Coolant, power steering, transmission fluid/exhaust manifold, electrical sparks	5/unknown	Engine compartment	None	No
1991 Ford Ranger	Frontal with the rear of a minivan, rollover	Coolant, transmission fluid, polymers/ exhaust manifold, electrical, mechanical spark	1 to 2/2 to 3	Engine compartment	Driver: several broken bones/ driver: possible injuries	No
1993 Jeep Grand Cherokee	Frontal with a barrier after side impact from a car	Coolant, gasoline/exhaust manifold, electrical, mechanical spark	Immediate/ unknown	Engine compartment	Minor injuries/one passenger killed, other four occupants had varieties of injuries	Yes

Table A-1 continuing on the next page

Table A-1 continuing from the previous page

Vehicle	Impact Description	Fuel/Ignition Source(s)	Time to Ignition/ to Interior(minutes)	Initial Fire Location	Injuries: Fire Vehicle/Other Vehicle	Assistance in Egress from Fire Vehicle
1992 Oldsmobile 98	Frontal with the side of a pickup truck	Coolant, transmission fluid, brake fluid, polymers/ exhaust manifold, electrical, mechanical spark	Unknown/unknown	Engine compartment	Driver: non-incapacitating injuries/ Driver: non-incapacitating injuries	Yes
1995 Nissan Pathfinder	Sideswipe by a truck and rollover	Gasoline from filler neck/electrical, mechanical spark	Immediate/ immediate	Right rear	Driver: injured arm and singed hair; passenger: possible injuries/none	Driver assisted passenger
1990 Ford Tempo	Front with the rear of a minivan	Most fluids, polymers/ electrical, mechanical spark	Immediate/ extinguished <2 with no spread to interior	Engine compartment	Driver and two passengers: minor cuts and bruises/ unknown	No
1998 Subaru Legacy	Override of a culvert and rollover	Engine oil, brake fluid, coolant, polymers/exhaust components, electrical	Unknown/unknown	Lower engine compartment	Fractured back, multiple bruises, abrasions, and lacerations	Yes
1995 Ford Taurus	Frontal with a barrier after side contact with a truck	Power steering and coolant, polymers/ exhaust manifold, electrical	5 to 15/unknown	Engine compartment	Possible hip injury/ none	No

Table A-1 continuing on the next page

Table A-1 continuing from the previous page

Vehicle	Impact Description	Fuel/Ignition Source(s)	Time to Ignition/ to Interior(minutes)	Initial Fire Location	Injuries: Fire Vehicle/Other Vehicle	Assistance in Egress from Fire Vehicle
1999 Pontiac Grand Am	Non-collision	Power steering fluid, coolant, gasoline/exhaust manifold	N/A/ extinguished without spread to interior	Engine compartment	None	No
1990 Ford Bronco II	Frontal with the rear of a tractor trailer	Most fluids/exhaust manifold, electrical, mechanical spark	Immediate/3 to 5	Engine compartment	Driver and three passengers: minor cuts, abrasions, and bruises/ none	No
1993 Chevrolet Cavalier	Frontal with a tee	Coolant, brake fluid, polymers/ electrical, mechanical spark, exhaust manifold	Immediate/10 to 15	Engine compartment	Driver: minor injuries; one passenger: no injuries, second passenger: non-incapacitating	No
1993 Mitsubishi LRV minivan	Non-collision	gasoline/electrical spark	spread to interior	Engine compartment		No
1997 Jeep Cherokee	Non-collision	Gasoline, power steering fluid, transmission fluid, polymers/ electrical, exhaust manifold	N/A / extinguished before spreading to interior	Engine compartment	None	No

APPENDIX B

LARGE SCALE VEHICLE BURN TESTS AND DATA

(REFERENCES IN CHAPTER III)

B.1 PROPAGATION OF AN ENGINE COMPARTMENT FIRE IN A 1996 DODGE CARAVAN: TEST # 1

The information included in this appendix is taken from the report entitled "Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 3: Propagation of an Engine Compartment Fire in a 1996 Passenger Van", by Jeffrey Santrock, NHTSA Docket Number: 3588; Document Number: NHTSA-1998-3588-119, www.nhtsa.dot.gov [1].

The fire propagation test was performed on November 13, 1996 at FM Global using a 1996 Dodge Caravan that was crashed at the GM Proving Ground. The crash test consisted of a stationary vehicle struck in the left front (driver's side) by a moving barrier. The driver's side window was broken, but other windows remained intact in the crash. Engine compartment fluids were spilled around the engine compartment and under the vehicle. Because of the crash, a fire was started in the area of the battery and the power distribution center (PDC), about 5-minues after the impact. In the crash test, the fire was allowed to burn for about five minutes and then extinguished with a hand held fire extinguisher. The cause of the fire was determined to be due to series of shorts in the electrical system of the vehicle. The environmental housing around the battery, the battery case, the PDC, and the left headlamp assembly were ignited. Figure B-1-1 shows these parts and the locations of the thermocouples used to monitor the flame spread.

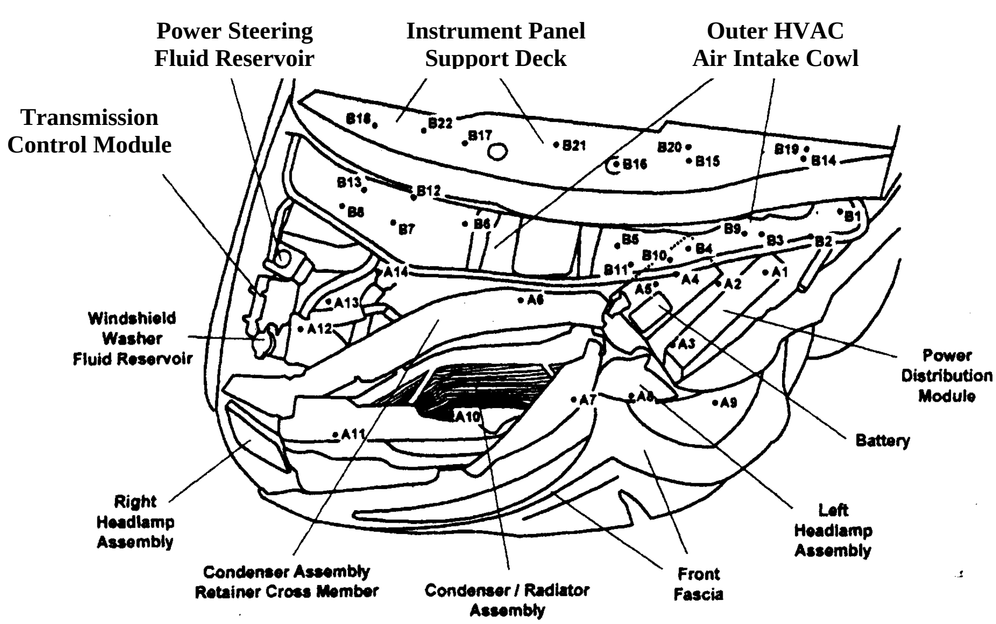


Figure B-1-1. Top view of the front of the test vehicle showing approximate locations of the thermocouples in the engine compartment, in the HVAC air intake cowl and on the instrument panel support deck. Figure is taken from Ref. 1.

For the propagation tests, spilling of engine compartment fluids observed in the crash test was simulated as follows:

1) 7.8 liters of 1:1 mixture of antifreeze and water was poured over the front of the engine compartment;
2) 3.85 liters of washer fluid was added to the broken windshield washer fluid reservoir and allowed to drain onto the ground;
3) 0.95 liter of transmission fluid was poured onto the concrete paving blocks under the transaxle housing;
4) 0.95 liter of motor oil was added to the engine through engine oil filler neck and allowed to drain onto the ground through the broken oil pan;
5) 0.47 liter of brake fluid was poured into the engine compartment at the location of the brake fluid reservoir.

B-1-1 Ignition in the Engine Compartment

Fire was started in the engine compartment in a manner very similar to that observed in the crash test by placing an electrical igniter between the batter and PDC. The following were observed:

1. Smoke rising from the ignition area within 5 seconds of the start of the test and continuing for about next 600 seconds;
2. Ignition of the vapors occurring in about 602 seconds, flames being observed first by the video in the area above the battery and PDC and thermal radiation from the objects in the engine compartment and temperatures increasing with time;
3. Heated gas venting from the rear edge of the hood in 3 seconds after ignition.
4. A small flame emerging from the rear of the hood in about 15 seconds after ignition.

B-1-2 Flame Spread in the Engine Compartment

The temperature-time relationships in the engine compartment are shown in Fig. B-1-2. Post ignition times to reach 30 ^oC, 50 ^oC, 100 ^oC, 200 ^oC, 300 ^oC, 400 ^oC, 500 ^oC, 600 ^oC and the maximum temperature are listed in Table B-1-1. Maximum temperatures recorded at these locations are also included in the table. The temperature data in Table B-1-1 are arranged in groups based on their locations- near the ignition location (battery and PDC on the left), near headlamp assembly on the left and near the windshield washer fluid, transmission control module and power steering fluid.

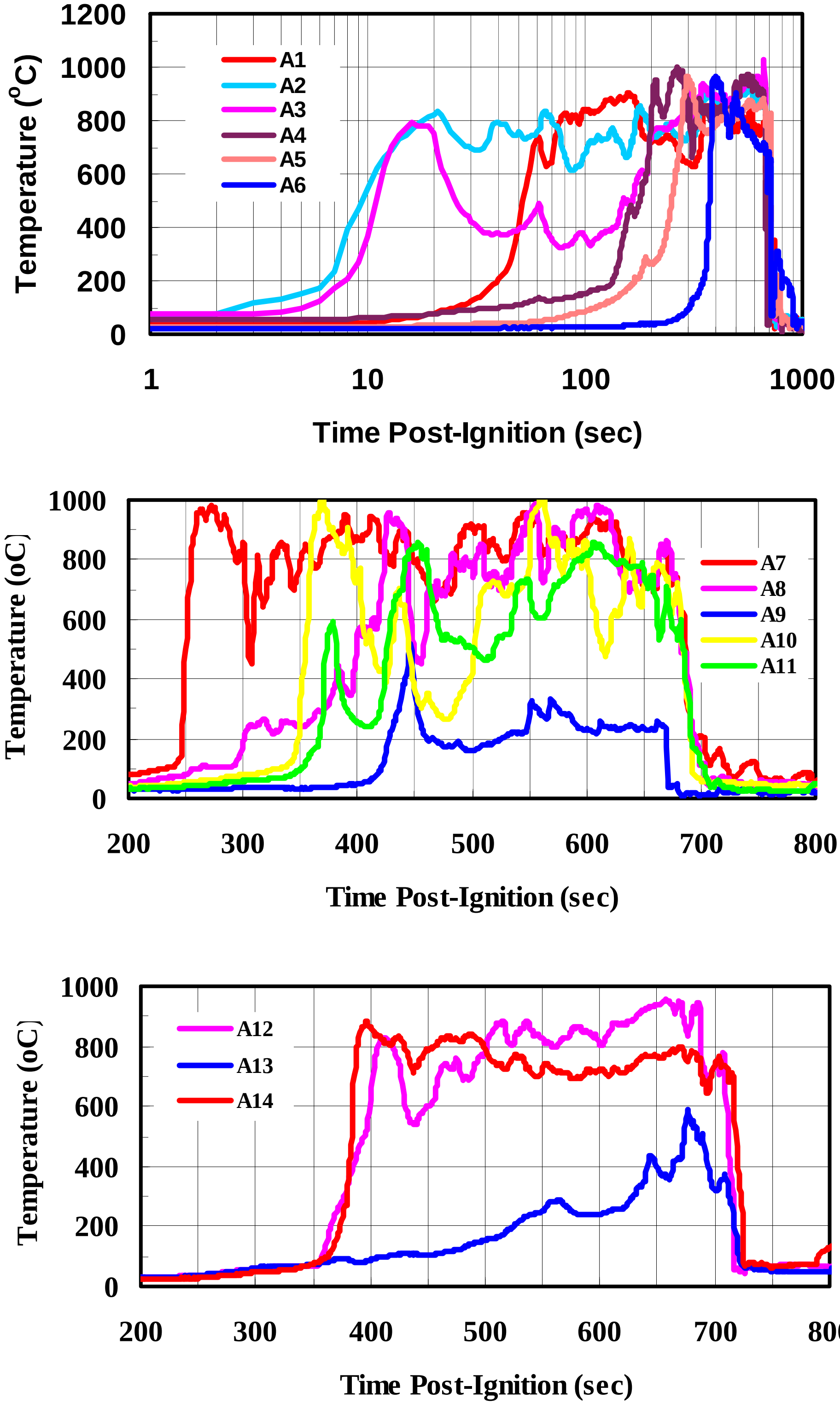


Figure B-1-2. Temperature versus time at various locations A1 in the engine compartment. Data are taken from Ref. 1.

Table B-1-1. Time-Temperatures Relationships at Various Locations in the Engine Compartment

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time (s)	Temp (°C)
Near the Battery and Power Distribution Module (Ignition Location)										
A1		12	26	40	47	51	53	56	158	902
A2			3	7	8	9	10	11	585	934
A3				8	10	11	11	12	669	1030
A4			41	134	145	155	179	193	266	1000
A5	13	63	112	169	222	240	251	262	296	965
A6	122	249	305	351	365	370	375	378	402	962
Near Left Headlamp Assembly										
A7	42	99	229	247	249	249	250	252	273	982
A8	80	201	258	302	372	381	399	414	555	985
A9	196	403	421	428	437	442	446	N/A	446	516
A10	104	245	328	349	351	353	355	357	563	1001
A11	122	282	351	367	370	371	373	430	607	859
Near the Windshield Washer Fluid Reservoir										
A12	165	281	359	366	377	386	395	400	658	954
A13	165	281	412	525	629	642	674	N/A	676	589
A14	258	303	363	374	380	383	384	385	397	882

The following were observed outside the passenger compartment in the test [1]:

1. About 15 Seconds Post Ignition: flames were localized to the front of the battery and PDC. The hood liner[1] above the battery and PDC appeared to have ignited. Flaming melted plastic dripping from the burning battery and PDC appeared to have ignited the air cleaner housing, which was broken and pushed under the battery during the crash test

2. About 60 Seconds Post Ignition: fire had grown slightly in the area of the battery and PDC, but fire on the hood liner had grown toward the front and rear of the vehicle. Flames were attached to the hood liner 13 to 15-cm forward of where the fire plume from the battery contacted the hood liner. Hood liner was burning from the rear-edge of the hood to about 15-cm forward of the battery and PDC. Maximum width of the burning area of the hood liner was about 30 cm. Flames had also started to spread along the HVAC air intake cowl. The cowl was ignited by the flames of the burning battery and PDC and other components burning under the battery. These components included the

[1] The hood liner was made of polyester and glass fiber mat with a cotton-felt (cotton-shoddy) backing.

battery tray, the air intake resonator, the air cleaner housing, the air intake boot, and the brake fluid reservoir;

3. <u>About 60 to 120 Seconds Post Ignition</u>: there was a direct contact of the flames with the windshield along its lower edge. The fire plume grew to about half the height of the windshield with lower half of the plume making contact with the exterior surface of the glass slightly to the left of the center of the windshield. The hood liner had detached from the front side of the hood;

4. <u>About 160 Seconds Post Ignition</u>: hood liner started to separate from the hood, allowing cotton shoddy to ignite and burn;

5. <u>About 180 Seconds Post Ignition</u>: most of the battery, the PDC and the forward edge of the HVAC air intake cowl in the left sides of the engine compartment were burning. There was downward flame spread aided by the flaming melted plastics in the left side of the engine compartment (flaming streams of molten plastics were seen flowing downward and forward from the site of ignition, igniting the headlamp assembly). The left front wheelhouse, the left frame rail, the transaxle housing and the bumper reinforcement appeared to have impeded the downward flow of molten plastics and preventing the formation of a significant plastic pool fire on the ground until 360 seconds post ignition. The molten plastics on various parts, however, strengthen the fire in the upper engine compartment;

6. <u>About 210 to 240 Seconds Post Ignition:</u> flames had spread to the center of the air intake cowl and further to the right along the hood liner. The inner layer of windshield consisting of vinyl butyral/vinyl alcohol copolymer was ignited.

7. <u>About 300 to 360 Seconds Post Ignition</u>: the hood fell on top of the engine. Flames were observed in the right hand side of the engine compartment. Flames had spread into the left hand lamp assembly. Burning molten plastics flowing forward in the left side of the engine compartment entered the rear of the headlamp assembly through crash induced fractures. The bumper fascia and the energy absorber started to burn below the left head light. Flame started to spread downward on the bumper fascia and bumper energy absorber. A small melt/drip fire fueled by melted plastic dripping from the bumper fascia and bumper energy absorber also began to form on the ground below the left front corner of the test vehicle at this time. Flames were inside the windshield at this time;

8. <u>About 450 Seconds Post Ignition</u>: flames were visible along the entire length of a tear on the left side of the bumper fascia that occurred in the crash test of this vehicle.

9. The lateral flame spread velocity along different paths in the engine compartment was very similar (4 mm/s), as shown in Fig. B-1-3.

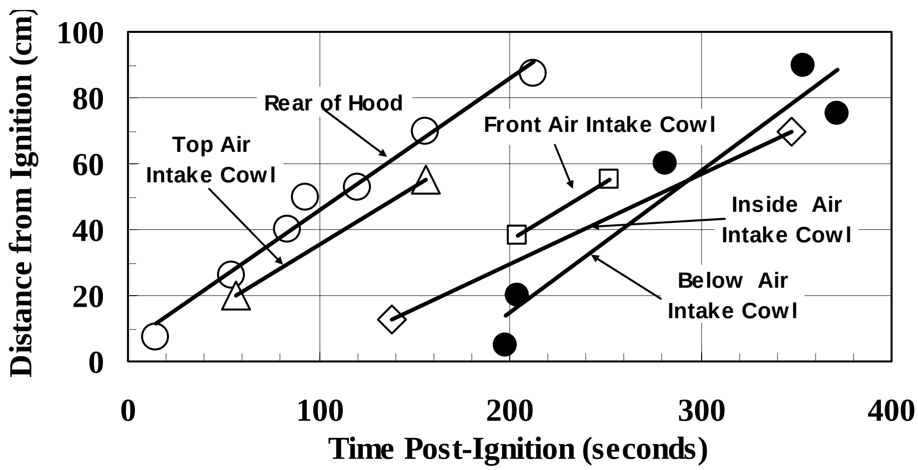


Figure B-1-3. Lateral flame spread along different paths in the engine compartment in the fire test involving a 1996 Dodge Caravan with electrical ignition near the battery and PDC [1].

B-1-3 Flame Spread in the Passenger Compartment

Flames entered the passenger compartment mainly through the broken windshield. The flames also entered the passenger compartment through AC evaporator and condenser-line pass-through (closures had dislodged in the crash test) and HVAC air intake (recirculation door had been dislodged in the crash test). Thermocouple locations used for monitoring the flame spread are shown in Figs. B-1-4, B-1-5 and B-1-6. The temperatures measured at these locations are shown in Figs. B-1-7 to B-1-9. Table B-1-2 lists the measured time-temperature data.

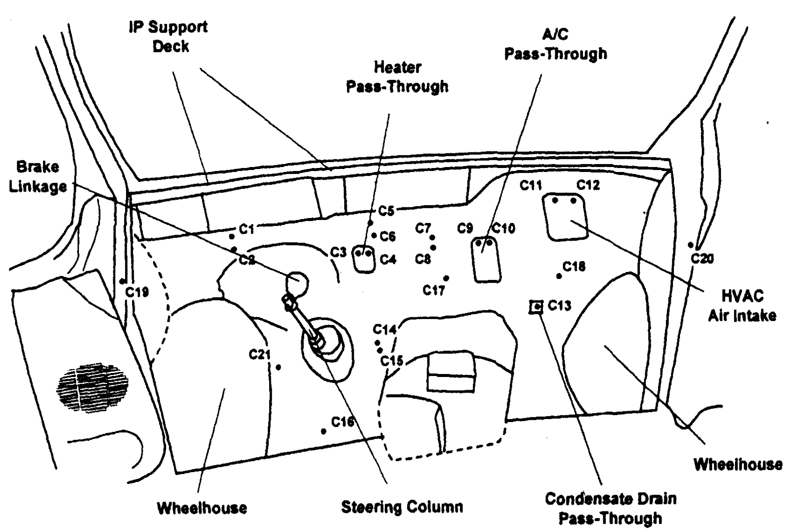


Figure B-1-4. Interior view of the front of the 1996 Dodge Caravan showing the approximate locations of thermocouples on the dash panel. Figure is taken from Ref. 1.

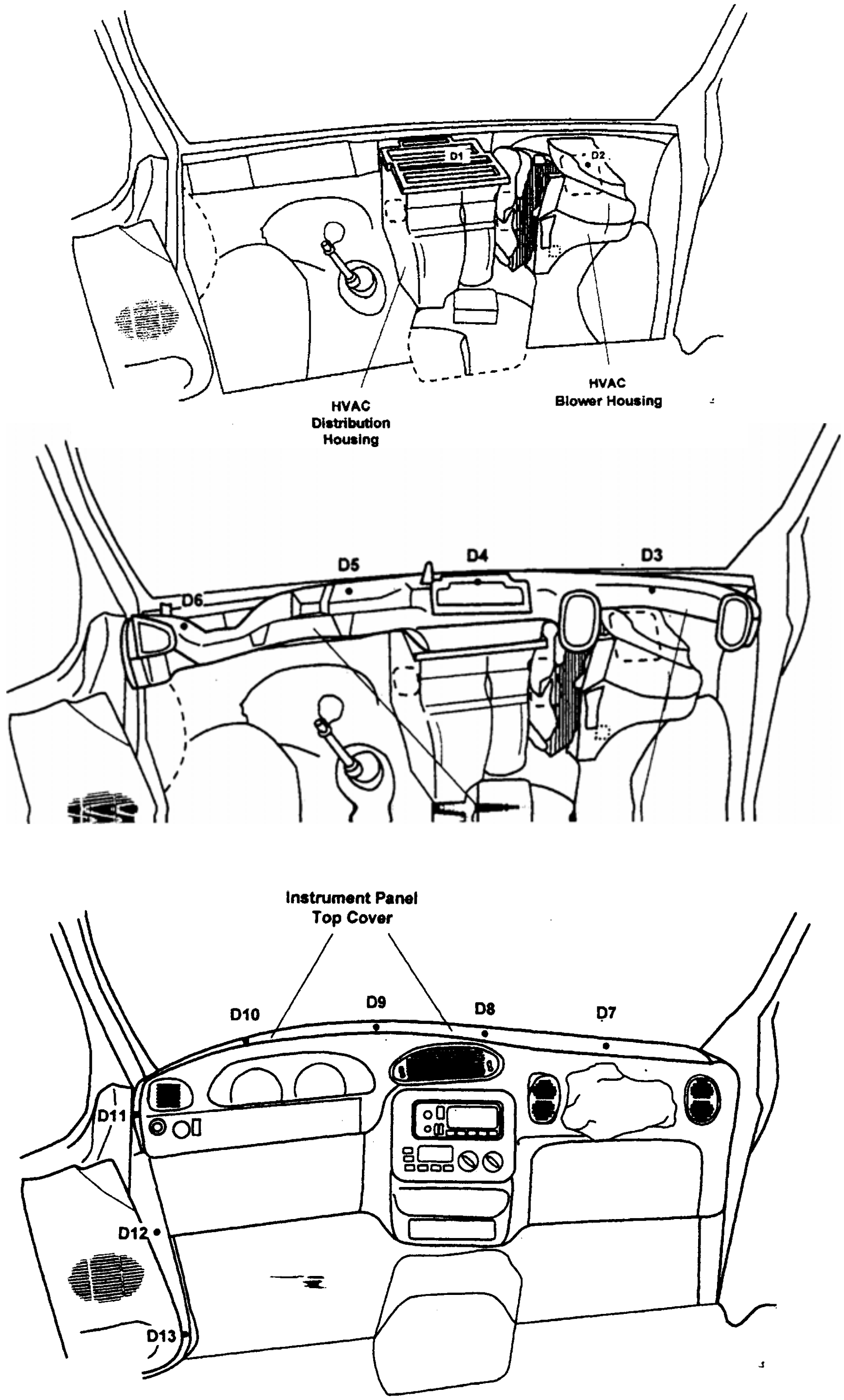


Figure B-1-5. Interior view of the front of the test vehicle showing approximate locations of thermocouples in the HVAC blower and distribution housing and ducts and on the instrument panel top cover and the gap along the forward edge of the driver's door. Figures are taken from Ref. 1.

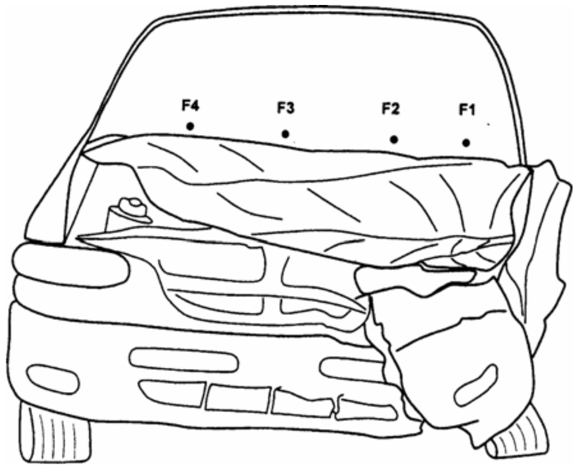


Figure B-1-6. Approximate locations of thermocouples on the exterior surface of the windshield. Figure is taken from Ref. 1.

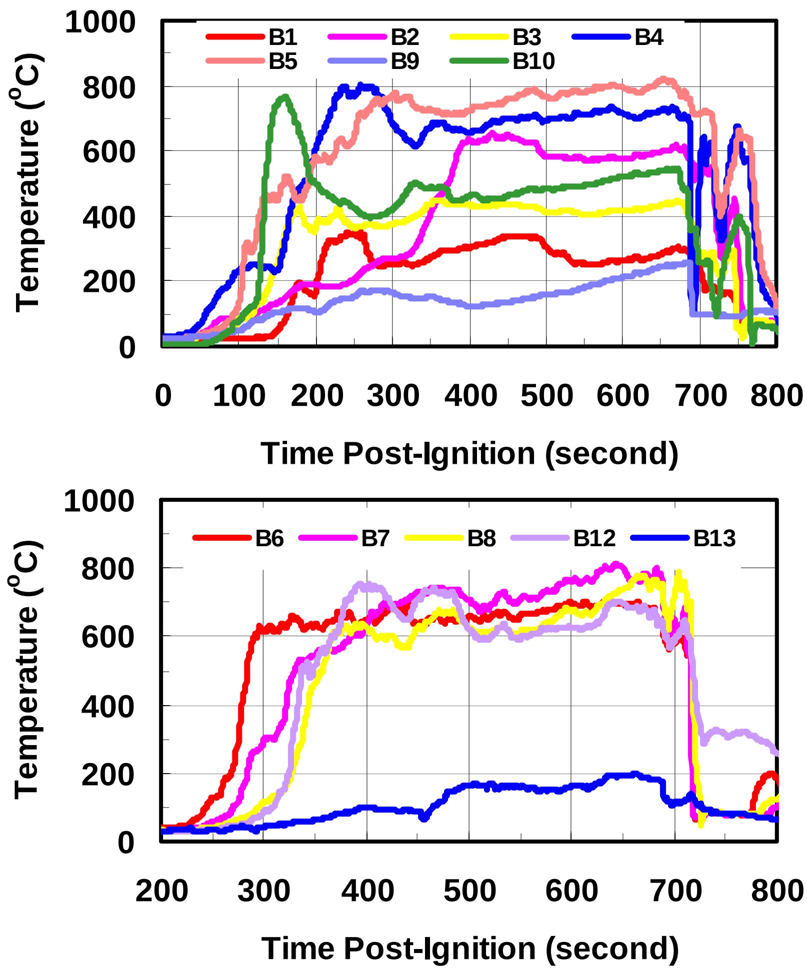


Figure B-1-7. Temperature versus time at various locations in the outer HVAC air intake cowl. Data are taken from Ref. 1.

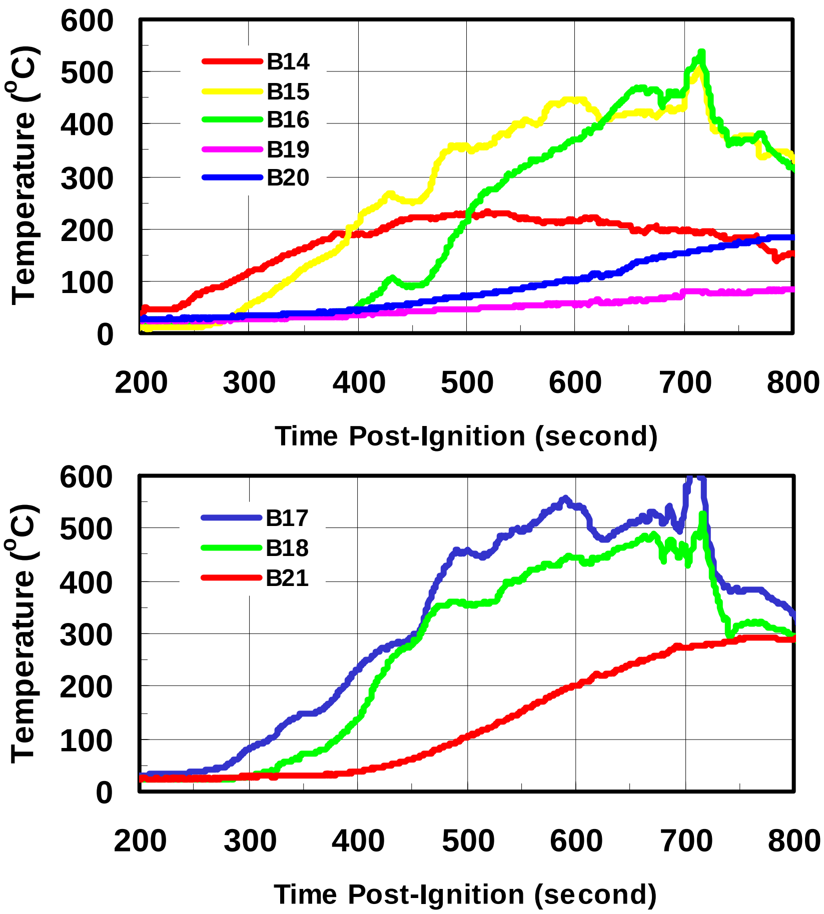


Figure B-1-8. Temperature versus time at various locations on instrument panel support deck. Data are taken from Ref. 1.

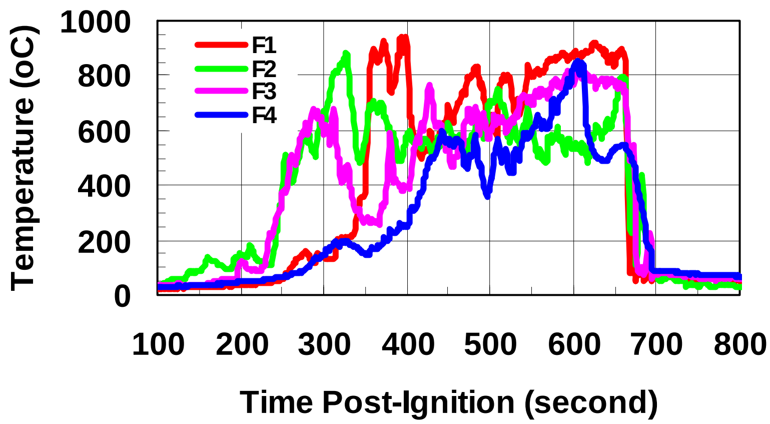


Figure B-1-9. Temperature versus time at various locations on the exterior surface of the windshield. Data are taken from Ref. 1.

Table B-1-2. Time-Temperatures Relationships at Various Locations on the HVAC Air Intake Cowl, Instrument Panel Support Deck and Exterior Windshield Surface

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time (s)	Temp (°C)
Left Outer HVAC Air Intake Cowl (Close to the Ignition Location)										
B1	125	150	163	201	212	N/A	N/A	N/A	256	357
B2	36	59	121	245	327	347	372	385	429	656
B3	51	93	118	140	155	169	N/A	N/A	357	449
B4	2	40	56	89	158	165	184	199	257	801
B5	42	68	94	104	107	127	158	225	652	823
B9	42	99	142	576	N/A	N/A	N/A	N/A	683	257
B10	75	90	107	126	129	131	133	138	159	769
Right Outer HVAC Air Intake Cowl										
B6	121	227	243	268	274	278	283	291	633	703
B7	165	244	271	284	300	322	330	385	642	812
B8	177	263	294	327	338	344	356	366	704	787
B12	164	278	309	325	328	333	336	366	401	754
B13	147	312	464	662	N/A	N/A	N/A	N/A	662	200
Left Instrument Panel Support										
B14	2	234	285	421	N/A	N/A	N/A	N/A	518	231
B15	283	297	335	391	469	545	712	N/A	716	507
B16	296	399	427	495	537	624	703	N/A	716	539
B19	330	519	N/A	N/A	N/A	N/A	N/A	N/A	937	92
B20	203	421	588	895	N/A	N/A	N/A	N/A	1042	264
Right Instrument Panel Support										
B17	121	280	319	387	452	473	545	704	709	632
B18	301	328	382	414	457	539	714	NA	715	529
B21	309	428	495	597	N/A	N/A	N/A	N/A	831	299
Exterior Windshield Surface										
F1	151	238	262	316	341	350	352	353	394	944
F2	24	114	156	243	246	251	253	294	327	881
F3	2	169	198	234	246	257	260	277	599	819
F4	95	200	280	373	404	421	429	551	605	857

The following were observed in the passenger compartment in the test [1]:

1. About 270 Seconds Post Ignition: a triangular section of the windshield fell onto the top of the instrument panel, leaving a roughly 15-cm wide hole in the windshield in front of the steering wheel. The size of the hole increased horizontally by a factor of about three and vertically by a factor of about two as several pieces of windshield fell inward over the next 120 seconds;

2. About 360 to 420 Seconds Post Ignition: the instrument panel ignited and flames spread laterally to the right and to the left and downward into to the underlying defroster duct assembly over next several seconds. The hot gases were drawn out of the passenger compartment through the windshield hole reducing the flame spread rate in the passenger compartment. Smoke from the engine compartment entered the passenger compartment through the openings in the forward bulkhead;

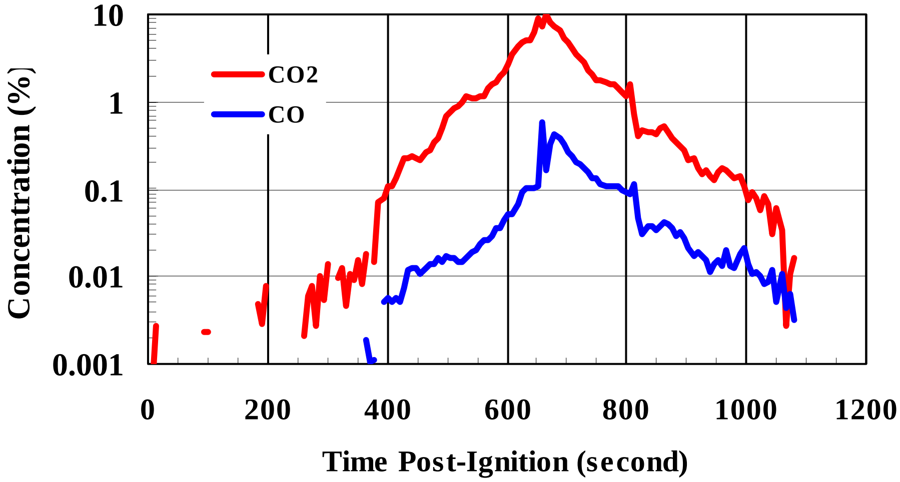
3. About 420 to 480 Seconds Post Ignition: pieces of flaming windshield fell into the right side of the passenger compartment, igniting the top of the instrument panel, the carpet in front of the passenger seat, the deployed passenger airbag, and in the inboard armrest of the passenger seat. The air temperature between the driver and the passenger in the front, 2.5-cm below the headliner increased from about 50 ^{o}C to > 100 ^{o}C, whereas the temperature 41-cm below the headliner was only 32 ^{o}C. The gas concentrations measured 15-cm below the headliner, also between the driver and the passenger in the front, started to increase;

4. About 540 to 630 Seconds Post Ignition: the vapors in the passenger compartment ignited and flames began to emerge from the driver's door window stating at 600 seconds. Rapid expansion of gases in the burning zone led to an efflux of gases through the top of the window opening in the driver's door and inflow of air through the bottom of the window opening;

5. About 645 to 660 Seconds Post Ignition: interior of the vehicle was approaching the flashover stage when the test was ended.

B-1-4 Temperature and Concentrations of Products in the Passenger Compartment of the Burning 1996 Dodge Caravan

The concentrations of products and temperatures inside the passenger compartment of the burning 1996 Dodge Caravan are shown in Figs. B-1-10 and B-1-11. The concentrations and temperatures were measured between the driver and the front passenger seats. The concentrations were measured 10-in below the headliner and the temperatures were measured 1-in, 4-in, 7-in, 10-in, 13-in, and 16-in below the headliner by the aspirated thermocouples.



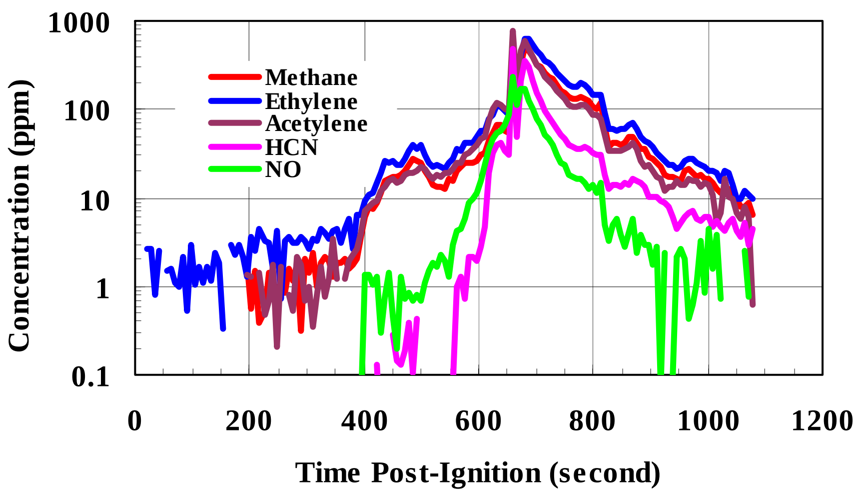


Figure B-1-10. Concentration versus time for products inside the passenger compartment in the 1996 Dodge Caravan burn test. Data are taken from Ref. 1.

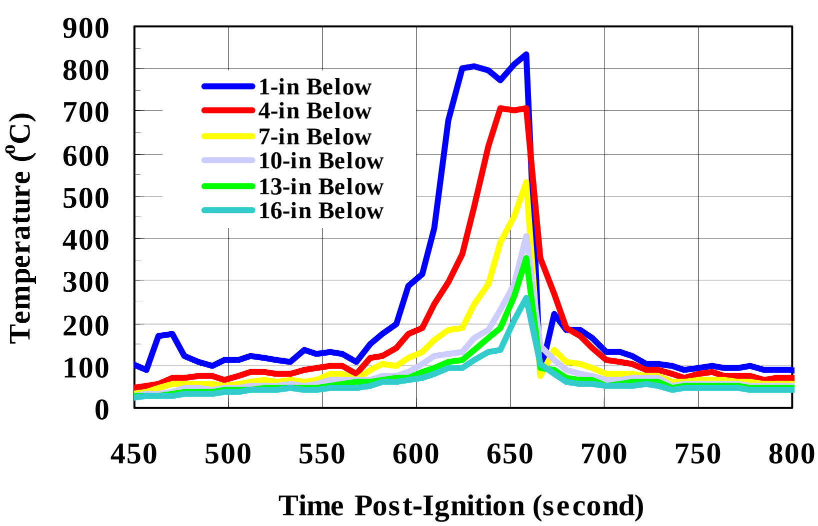


Figure B-1-11. Temperature versus time at various distances below the headliner between the driver and the front passenger seats. Data are taken from Ref. 1.

B-1-5 Release Rates of Heat and Products Measured in the Fire Plume over the Burning 1996 Dodge Caravan

The heat release rate and generation rates of CO and CO_2 measured in the fire plume over the burning vehicle are shown in Figs. B-1-12 and B-1-13.

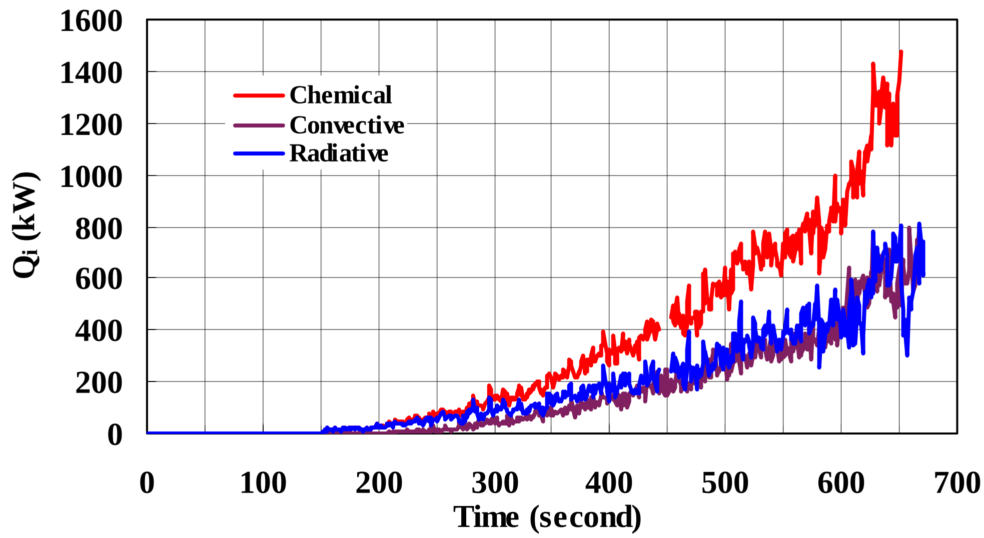


Figure B-1-12. Heat release rate measured in the fire plume over the burning 1996 Dodge Caravan. Data are taken from Ref. 1.

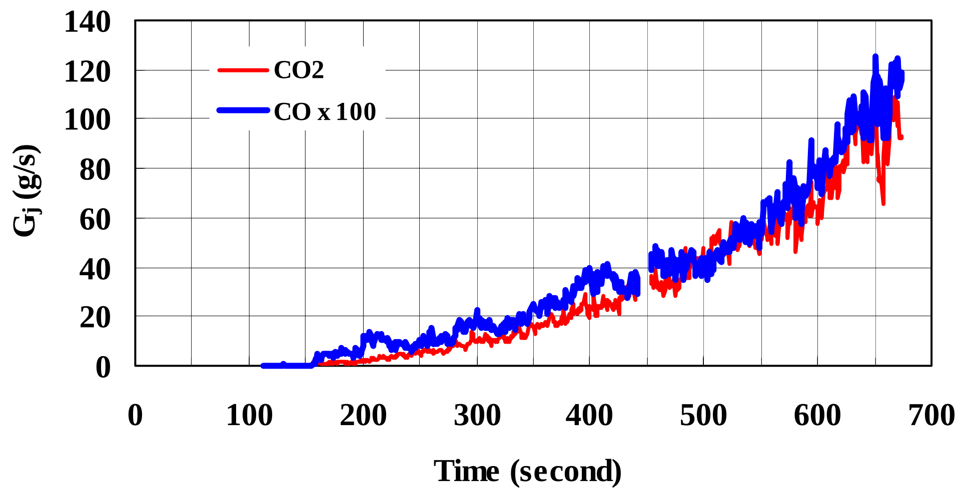


Figure B-1-13. Release rates of CO and CO_2 measured in the fire plume over the burning 1996 Dodge Caravan. Data are taken from Ref. 1.

B-1-6 Ventilation Conditions in the Passenger Compartment of the Burning 1996 Dodge Caravan

The CO and CO_2 concentrations ratios (C_{CO}/C_{CO2}) measured in the plume over the burning vehicle and inside the passenger compartment are shown in Fig. B-1-14. The ratio in the passenger compartment decreases from about 0.066 (fuel rich) to 0.02 (fuel lean), where it becomes similar to the ratio in the fire plume. However, it increases to 0.066 just before untenable/flashover conditions are reached in the passenger compartment.

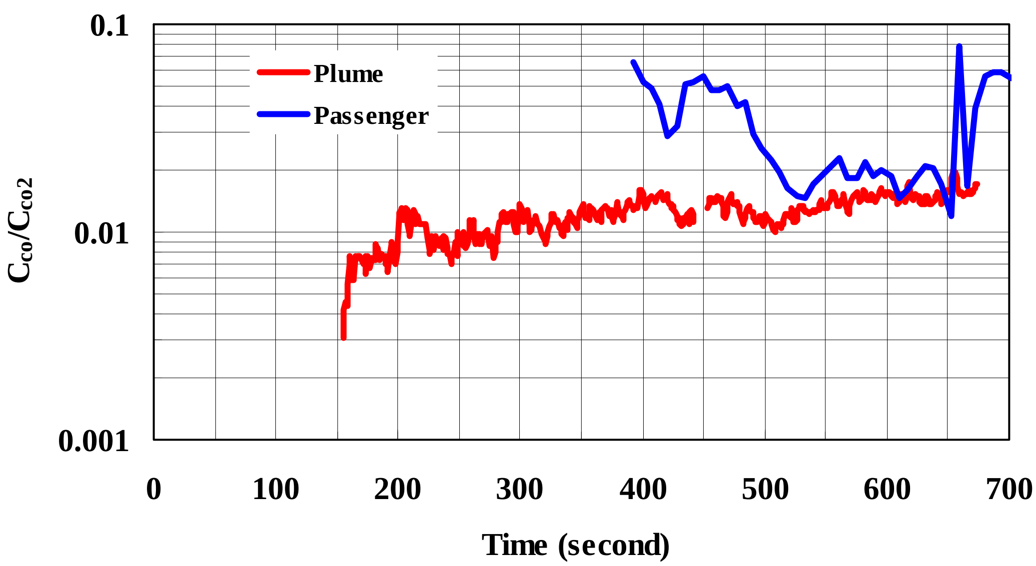


Figure B-1-14. Ratios of the CO to CO_2 concentrations in the fire plume and inside the passenger compartment of the burning 1996 Dodge Caravan. Data are taken from Ref. 1.

B.2 PROPAGATION OF UNDERBODY GASOLINE POOL FIRE IN A 1996 MODEL OF PLYMOUTH VOYAGER: TEST #2

The information included in this appendix is taken from the report entitled "Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 4: Propagation of an Underbody Gasoline Pool Fire in a 1996 Passenger Van", by Jeffrey Santrock, NHTSA Docket Number: 3588, Document Number: NHTSA-1998-3588-143, www.nhtsa.dot.gov [2].

The fire propagation test was performed on November 15, 1996 at FM Global using a 1996 model of Plymouth Voyager that was crashed at the GM Proving Ground. The crash test consisted of a stationary vehicle struck in the left rear by a moving barrier. No leaks were detected in the fuel system of the test vehicle during the crash test or the subsequent roll test performed after the test. No fire was observed during the crash test, nor was there evidence of fire present in the test vehicle after the crash test. However, for the fire propagation test, it was assumed that there was a leak in the fuel tank with gasoline spilling onto the ground, getting ignited and burning as a pool fire. The vehicle underbody and exterior and interior parts are shown in Figs. B-2-1 and B-2-2.

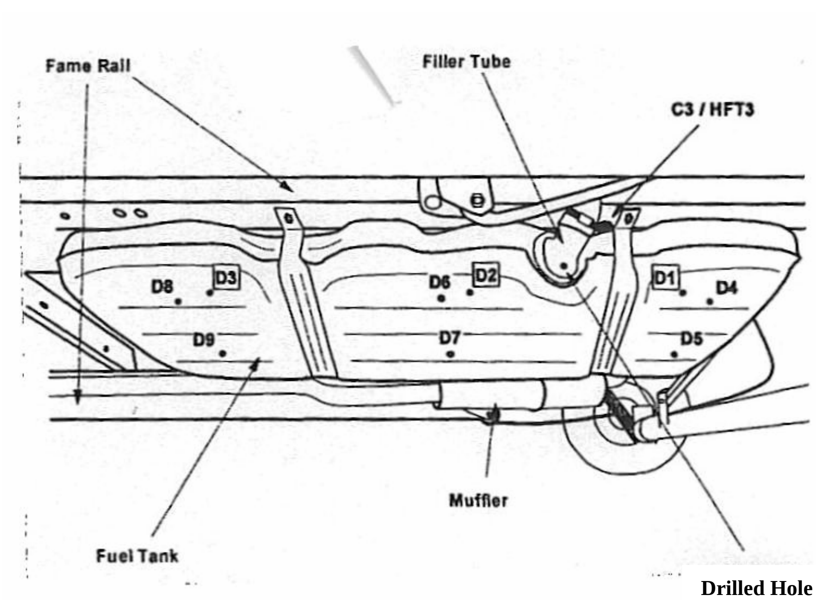


Figure B-2-1. Underbody of a 1996 Plymouth Voyager. Thermocouples D1 through D3 are inside and D4 through D9 are outside the fuel tank. Figure is taken from Ref. 2.

For the fire propagation test, all the doors and windows of the crashed vehicle were closed, except those that were damaged or broken in the crash test. The left rear vent window was wedged open and could not be closed. The rear hatch window was broken in the crash test and was not replaced. A 3-mm diameter hole was drilled in the base of the filter neck, where it connected to the fuel tank, as shown in Fig. B-2-1.

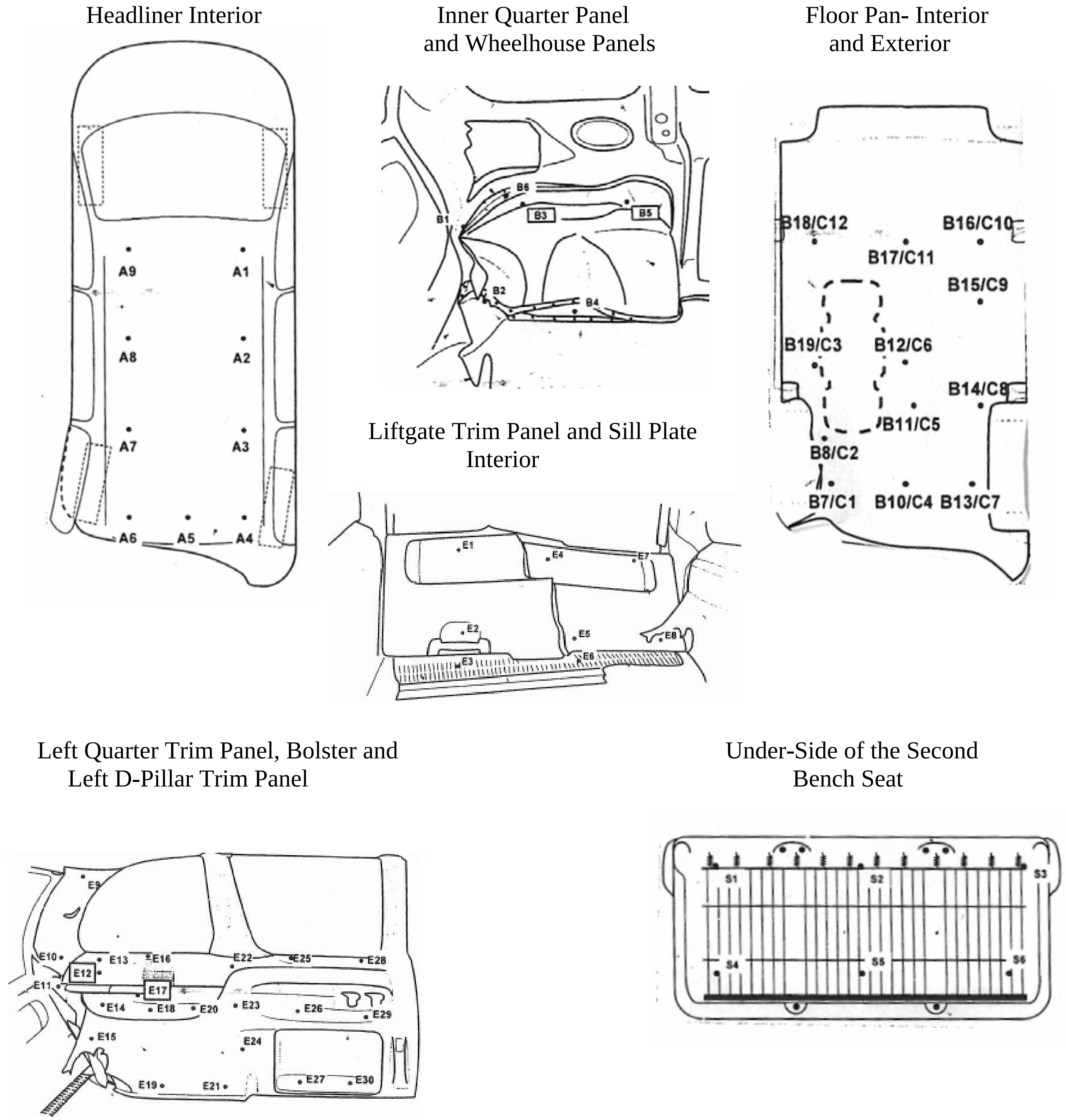


Figure B-2-2. View of the exterior and interior parts of a 1996 Plymouth Voyager and approximate locations of the thermocouples. Figures are taken from Ref. 2

A short piece of nylon rod was inserted into the hole. About 10 gallons of gasoline were added to the fuel tank and the filter cap was replaced. The plug was removed from the hole and not reinserted into the hole at any time during the fire test. Gasoline was allowed to flow out of the hole drilled in the filler tube onto the ground. The flow rate of gasoline from the drilled hole was about 243 ml/min. The fuel tank and floor pan of the test vehicle were 15 to 30 cm above the pool. Locations of thermocouples on various inside and outside parts of the 1996 Plymouth Voyager are shown in Figs. B-2-1 and B-2-2. The thermocouples were used to monitor the flame spread in the vehicle burn test.

B-2-1 IGNITION OF THE GASOLINE POOL IN THE REAR OF THE VEHICLE

In the test, gasoline spilled onto the ground was ignited by a hand-held propane torch, 32 seconds after removing the plug from the hole drilled in the filler tube of the fuel tank. The estimated diameter of the gasoline pool at 30 seconds was about 40 cm. The pool diameter remained approximately constant for about 90 seconds. Between 80 and 200 seconds, the pool diameter increased from about 40 to 80 cm. The flames spread radially along the lower surface of the gasoline tank and upward around its sides onto the floor pan. The heat flux to the area of the floor pan that was just above the filler (the approximate center) was about 75 kW/m^2. The source of additional fuel that caused the size of the burning pool under the test vehicle to increase appeared to be due to dripping and burning of the polyethylene fuel tank.

An increase in the flame volume in the area between the spare tire and floor pan was observed between 200 and 205 seconds post ignition. The diameter of the pool fire below the vehicle did not indicate an increase at this time. The size and intensity of the fire plume below the vehicle did not change appreciably between 180 and 200 seconds post ignition. Starting at about 200 seconds post ignition, an area with temperature greater than 700 ^{o}C appeared to the right of the fuel tank and spread forward and rearward along the longitudinal center-line of the floor pan over the next 10 seconds.

The fuel tank contained 38.5 liters (10 gallons) of gasoline at the start of the test. By 200 seconds post ignition, the fuel tank had lost about 833 ml of gasoline. At 213 seconds post ignition, there was an increase in the fire size at the left of the test vehicle, as solid materials (possibly rocker molding or the molding on the left) were burning and falling. At the end of the test, it was estimated that about 9.5 gallons of gasoline were present in the fuel tank. After the test, it was found that the exterior surface of the bottom of the tank was melted and charred, but interior surface was not melted or charred due to the cooling effect of gasoline. Two sections were missing from the bottom of the tank. The top the fuel tank also charred. The time-temperature relationships inside and outside the fuel tank and below the floor pan (D- and C-thermocouples in Figs. B-2-1 and B-2-2) are shown in Fig. B-2-3.

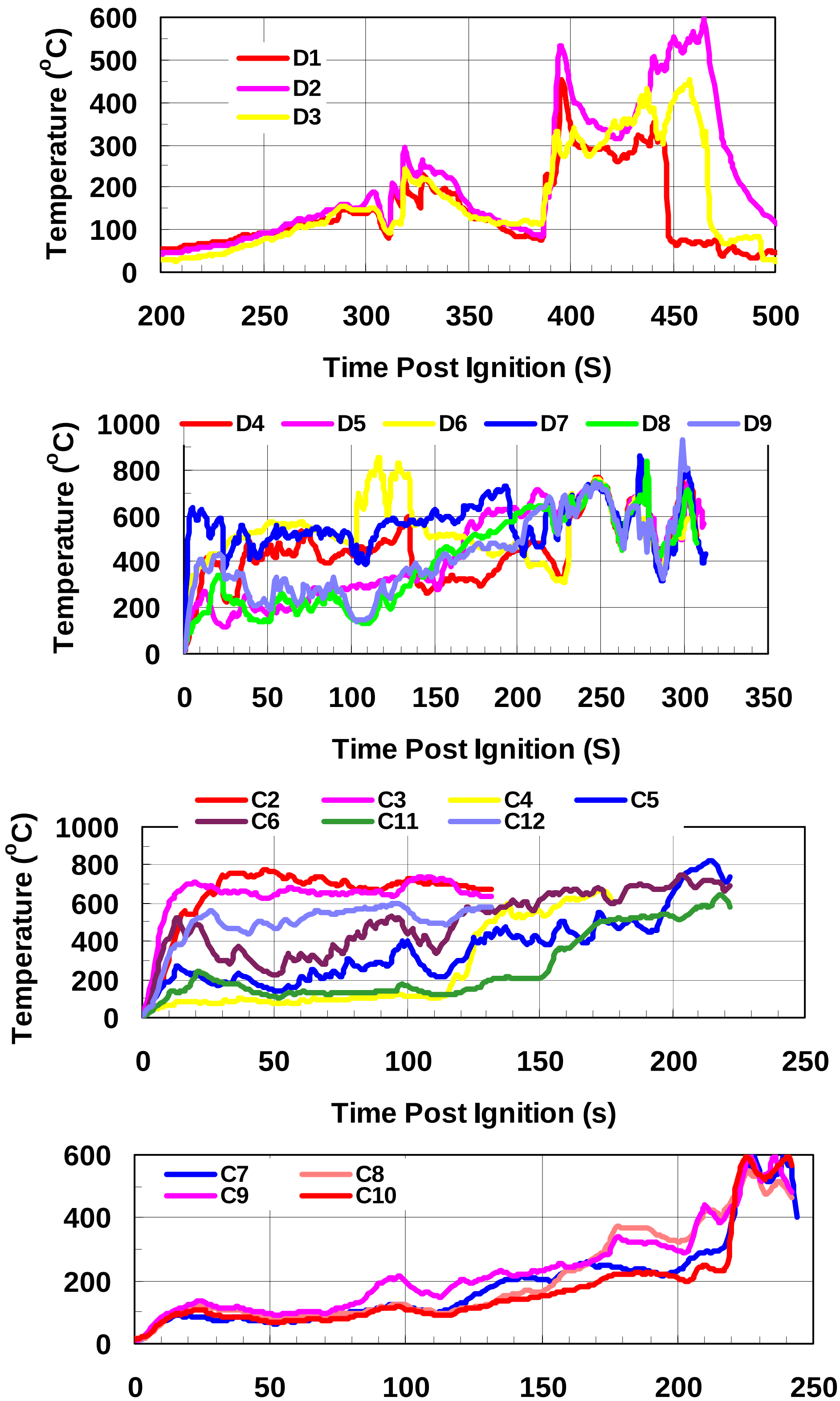


Figure B-2-3. Temperature versus time profiles for the inside (D1 to D3) and outside (D4 to D9) of fuel tank and 1-cm below the exterior of the floor pan in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

Post ignition times to reach 30 °C, 50 °C, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C and the maximum temperature inside and outside the fuel tank and below the floor pan are listed in Table B-2-1. Maximum temperatures recorded at these locations are also included in the table.

Table B-2-1. Time-Temperatures Relationships at Various Locations Inside and Outside the Fuel Tank and Upper (Inside) and Lower (Outside) the Floor Pan

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time s	Temp °C
Inside the Fuel Tank in Liquid Gasoline										
D1	154	189	262	313	395	396	N/A	N/A	396	452
D2	154	212	258	313	392	393	395	N/A	465	599
D3	186	235	265	319	392	435	N/A	N/A	458	453
Outside on the Lower Surface of the Fuel Tank										
D4	2	3	5	8	11	13	69	134	299	770
D5	2	2	3	7	105	158	169	179	277	793
D6	1	1	2	3	4	15	29	105	117	853
D7	1	1	1	2	2	2	3	4	273	864
D8	2	2	5	16	18	150	172	199	277	834
D9	2	2	2	4	7	10	204	208	299	933
1-cm Below the Exterior (Lower) Surface of the Floor Pan										
C2	2	3	5	8	11	12	15	22	47	772
C3	1	2	3	4	6	7	8	11	109	738
C4	3	6	79	118	124	126	131	159	214	745
C5	2	3	5	11	77	98	158	199	215	823
C6	2	3	4	6	7	9	13	139	276	770
C7	5	8	81	136	216	221	223	N/A	228	598
C8	6	9	18	156	174	209	224	312	326	648
C9	4	6	14	93	176	208	224	227	326	661
C10	6	8	20	172	220	221	222	N/A	241	598
C11	3	5	10	20	155	164	173	216	326	787
C12	2	3	5	8	10	16	19	96	264	740
Interior (Upper) Surface of the Floor Pan										
B1	6	11	22	41	45	49	96	102	182	910
B2	7	11	20	31	44	95	98	105	175	865
B3	5	6	10	19	30	38	90	157	192	844

Table B-2-1 continued on the next page

Table B-2-1 continuing from the previous page

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time s	Temp °C
B4	31	40	46	94	101	104	107	110	127	756
B5	5	7	11	21	52	69	73	88	172	715
B6	9	13	33	92	133	160	173	N/A	191	547
B7	96	135	175	275	300	301	301	N/A	302	584
B8	30	42	70	123	175	251	253	300	301	772
B9	22	35	61	115	179	299	299	299	302	763
B10	58	119	142	184	220	N/A	N/A	N/A	303	379
B11	37	78	145	216	302	302	N/A	N/A	303	465
B12	23	39	100	168	216	302	N/A	N/A	302	417
B13	125	188	302	303	303	N/A	N/A	N/A	304	341
B14	112	197	301	302	302	302	N/A	N/A	303	447
B15	139	221	281	302	302	302	N/A	N/A	303	482
B16	173	233	286	302	302	303	N/A	N/A	303	422
B17	22	89	169	207	252	300	302	N/A	302	525
B18	20	29	65	131	179	221	299	300	302	784

In the period from 40 to 120 seconds post ignition, the fire plume appeared to have been localized to areas directly under the fuel tank and the floor pan to the left of the fuel tank as indicated by the temperature contours in Fig. B-2-4, which are estimated from the C-thermocouple data.

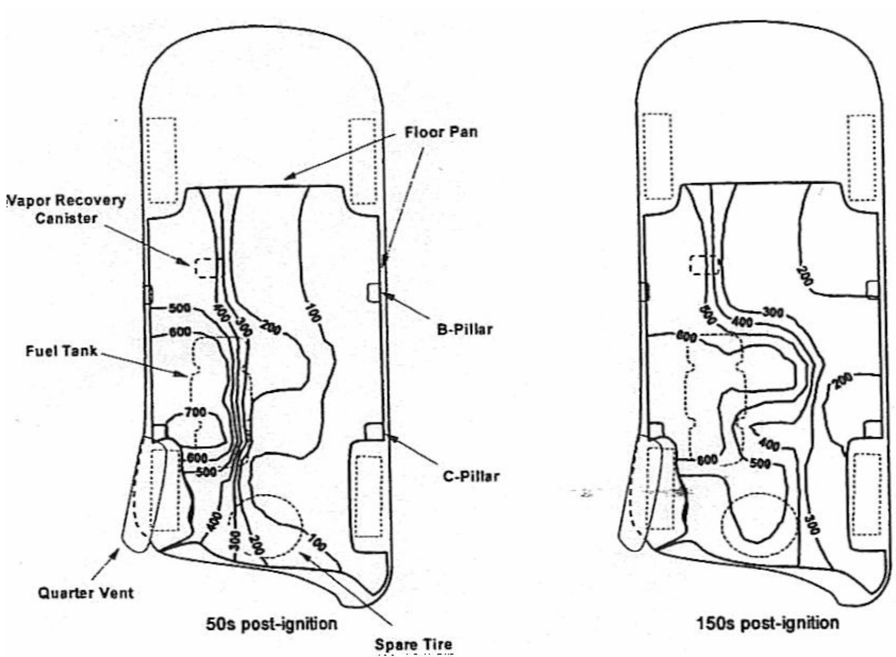


Figure B-2-4. Temperature contours below the floor pan. Figures are taken from Ref. 2.

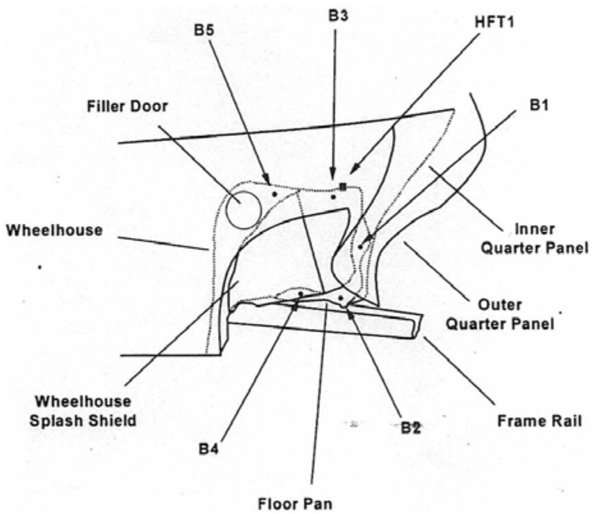


Figure B-2-5. Left rear wheelhouse of the 1996 Plymouth Voyager. Figure is taken from Ref. 2.

Figure B-2-5 shows the left rear wheelhouse, where the major combustion occurred and flames first entered the passenger compartment through the split weld seams around it between 80 and 120 seconds. Locations of five B-thermocouples and one heat flux transducer/radiometer (HFT) assembly are also shown in the figure. The B-thermocouples in this figure (detail in Fig. B-2-2 -floor pan interior and exterior) were inside on the upper surface of the floor pan opposite to the C-thermocouples that were 1-in below the exterior (lower) surface of the floor pan.

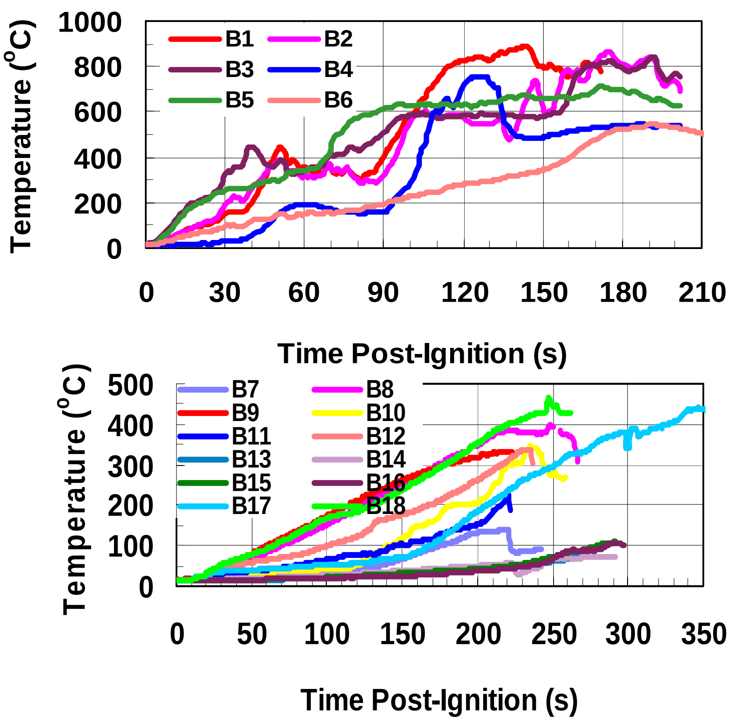


Figure B-2-6. Temperature versus time at the interior (upper) surface of the floor pan in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

The temperature time relationships for B locations are shown in Fig. B-2-6. The post ignition times to reach 30 °C, 50 °C, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, and the maximum temperature at B locations for the interior (upper) surface of the floor pan are listed in Table B-2-1 along with the temperature recorded at C locations. Maximum temperatures recorded at B locations are also included in the table.

B-2-2. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

Flames and hot gases flowed across the bottom and up around the sides of the fuel tank. Because of a slight upward tilt of the vehicle towards its left rear corner, the fire plume was channeled rearward between the left frame rail and the left rocker, into the left wheelhouse (Fig. B-2-5):

1. Between 10 and 15 Seconds Post Ignition: flames began to emerge in the wheelhouse, impinging directly upon the wheelhouse splash shield;
2. About 60 Seconds Post Ignition: polypropylene was observed dripping from the splash shield (2-mm thick polypropylene + 2% inorganic filler with a melting point of 166 ^{o}C);
3. About 60 to 90 Seconds Post Ignition: the splash shield sagged onto the left rear tire. Flames began to fill the left rear wheelhouse. A fire plume was observed outside the left rear wheelhouse. Hot gases started to enter weld-seams around the left rear wheelhouse, heating the upper left corner of the back panel of the second bench seat cover and left edge of the window opening in the liftgate;
4. About 80 to 120 Seconds Post Ignition: flames spread from the splash shield to the left rear tire and ignited it. The height of the fire plume emerging from the wheelhouse also increased. The top of the flames reached the lower edge of the quarter vent glass. Flames entered the passenger compartment through the split weld-seams around the left rear wheelhouse and through the left quarter vent. The flames ignited the second bench seat and the left quarter trim panel. A thick gray plume of smoke started to emerge from the inside of the test vehicle. The density of smoke column increased over the next 20 to 25 seconds;
5. By about 130 Seconds Post Ignition: flames along the interior surface of the vent glass sporadically reached the top of the quarter vent. The angled glass appeared to direct a portion of the fire plume into the passenger compartment through the left quarter vent;
6. Between 135 to 140 Seconds Post Ignition: flames were visible through the left side of the liftgate;
7. About 150 Seconds Post Ignition: some plastics inside the passenger compartment had ignited;
8. By about 155 Seconds Post Ignition: the tops of the flames were consistently above the top of the test vehicle and flames appeared to enter the left quarter vent continuously;
9. Between about 170 and 180 Seconds Post Ignition: flames started to spread laterally to the right across the rear of the headlining;
10. By 190 Seconds Post Ignition: the flame front had moved forward along the headlining to a line above the backs of the front seats;
11. Between 180 and 195 Seconds Post-Ignition: flames moved from the left to the right side of the headlining. Flames had disappeared from the left side of the headlining by 195 seconds. Most of the combustible in the headlining was consumed in about 20 to 30 seconds after its ignition.
12. About 210 Seconds Post Ignition: manual fire suppression using a water spray and a dry powder fire suppressant was started.

These observations are summarized in Table B-2-2.

Table B-2-2. Observations from the 1996 Plymouth Voyager Burn Test #2

Time Post Ignition (s)	Event
Shortly ignition	Smoke and flames observed near the left rear wheelhouse.
10-15	Flames began to emerge in the wheelhouse, impinging directly upon the wheelhouse splash shield. The fire plume in the wheelhouse increased. Flames were visible through the open spot weld seam along the lower edge of the wheelhouse side panel. The lower surface of the floor pan was exposed to flames and continued to be exposed until the test was ended and burning gasoline pool was extinguished. The heat flux to the lower surface of the floor pan ranged from about 75 kW/m^2 shortly after ignition to about 35 kW/m^2 just before fire suppression.
60	Polypropylene dripping from the splash shield
60-90	Splash shield sagged onto the left rear tire. Flames began to fill the left rear wheelhouse and a fire plume was observed outside the wheelhouse. Heat flux to the top of the wheelhouse increased to about 85 kW/m^2 and flames first entered the passenger compartment through the split weld seams around the left wheelhouse between 80 and 120 seconds. The lower edge of the left quarter trim panel appeared to have ignited between 90 and 110 seconds.
105-110	A thick gray plume of smoke started to emerge from the inside of the test vehicle. Flames had entered the split spot weld seams at the rear of the wheelhouse by 100 seconds. The density of smoke increased over the next 20 to 25 seconds until flames became visible through the left side of the liftgate window between 135 and 140 seconds post ignition.
120-140	Flames spread from the splash shield to the upper surface of the left rear tire and ignited it. Fire in the left rear wheelhouse splash grew substantially. A plume of dark gray smoke emanated from the lower left corner of the test vehicle by about 130 seconds. Sections of left quarter trim panel closest to the split spot weld seams and the left side of the second bench seat cushion were exposed directly to flames between 120 and 130 seconds.

Table B-2-2 continued on the next page

Table B-2-2 continuing from the last page

Time Post Ignition (s)	Event
140-155	Interior components around the left rear wheelhouse started to burn. Hot gases and flames that entered the split spot weld seams around the wheelhouse ignited the second bench seat and the left quarter trim panel (by 150 seconds). Flames spread to the back of the second bench seat, the liftgate trim panel, the C- and D-pillar moldings and the headlining. Radiation from these fires ignited the back panel of the seat cover on the first bench seat. By 155 seconds, the tops of the flames were consistently above the top of the test vehicle and appeared to enter the left quarter vent continuously. Between 130 and 150 seconds, flames were spreading along the lower surface of the foam pad in the seat cushion. The transition from the thermal decomposition to flaming ignition for the foam pad occurred around 130 seconds. The flames were concentrated on the left side of the seat cushion and seatback..
170-180	Flames started to spread laterally to the right across the rear of the headlining. Flames spread out radially along the lower surface of the headlining over the next 20 seconds. The exposed surfaces of the left quarter trim panel, the left bolster, and the left D-pillar trim were burning by 170 seconds.
185-195	Flames moved from the left to the right side of the headlining. By 190 seconds, the flame front had moved forward along the headlining to a line above the backs of the front seats. Also, the foam pad in the second bench seat cushion appeared to have ignited by 190 seconds, with flames spreading along its lower surface toward the right side of the test vehicle. By 195 seconds, flames had disappeared from the headlining. Fire consumed most of the combustible materials in the headlining within about 20 to 30 seconds after its ignition.
210	Manual fire suppression using a water spray and a dry powder fire suppressant was started.
Post Observations	The rear half of the left quarter trim panel, the left C- and D-pillar trim panels and the left edges of the liftgate trim panel and liftgate sill plate had ignited by the time flames in the interior of the test vehicle were extinguished. The fire damage was localized to the left rear corner and headlining. Plastics covering the front-surface of the left C-pillar appeared to have melted and sagged, but did not ignite. Fire damage to the first bench seat indicated that the top and rear panels of the cover on the first bench seat back were ignited by radiation from the flames in the left rear corner of the test vehicle and flames on the headlining. Sections of the back and side panels in the seat back covers of the driver's and front passenger's seats were melted and charred. The back panel in the driver's seat back cover appeared to have been ignited by radiation from the flames in the left rear corner of the test vehicle. The fire damage pattern to the lower surface of the carpet pad indicated that over the most of the floor pan, conduction through the floor pan did not result in the ignition of the carpet before the fire was extinguished.

The post ignition times to reach 30 ^oC, 50 ^oC, 100 ^oC, 200 ^oC, 300 ^oC, 400 ^oC, 500 ^oC, 600 ^oC and the maximum temperature at various locations in the passenger compartment and maximum temperatures at these locations are listed in Table B-2-3. The locations are E (left quarter trim panel, bolster, left D-pillar trim panel, liftgate trim panel and sill plate interior), S (below the seat cushion of the second bench seat) and A (lower surface of the headlining). Temperature equal to greater than 600 ^oC is assumed to indicate the presence of a flame at that location. The time-temperature relationships for these locations, where presence of flame is indicated are shown in Figs. B-2-7, B-2-8 and B-2-9.

Table B-2-3. Time-Temperatures Relationships for Various Locations in the Passenger Compartment

Location	Time-to-Reach (s)								T_{max}	
	30 ^oC	50 ^oC	100 ^oC	200 ^oC	300 ^oC	400 ^oC	500 ^oC	600 ^oC	Time s	Temp ^oC
Liftgate Trim Panel and Still Plate Interior										
E1	169	182	206	NA	NA	NA	NA	NA	206	100
E2	200	204	NA	NA	NA	NA	NA	N/A	205	61
E3	188	NA	NA	NA	NA	NA	N/A	N/A	242	47
E4	164	177	194	216	N/A	N/A	N/A	N/A	237	202
E5	159	172	NA	NA	NA	NA	N/A	N/A	199	99
E6	179	222	273	273	273	N/A	N/A	N/A	275	368
E7	144	158	172	195	202	210	N/A	N/A	271	473
E8	140	153	158	193	274	300	N/A	N/A	270	431
Left Quarter Trim Panel, Bolster and Left D-Pillar Trim Panel										
E9	108	124	138	150	156	158	165	169	171	642
E10	25	41	104	180	186	187	NA	N/A	188	429
E11	40	91	127	163	NA	NA	NA	NA	188	217
E12	153	173	246	273	274	NA	N/A	N/A	274	306
E13	122	138	159	174	178	179	180	182	185	668
E14	112	136	158	161	162	164	169	171	178	803
E15	120	142	157	160	161	161	163	167	182	743
E16	91	123	158	168	171	171	182	186	186	613
E17	75	114	152	185	186	N/A	N/A	N/A	200	375
E18	120	142	160	162	164	166	168	173	194	713
E19	100	117	132	147	163	169	175	178	189	692

Table B-2-3 continuing on the next page

Table B-2-3 continued from the previous page

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time s	Temp °C
E20	83	115	143	147	149	165	166	167	177	818
E21	119	140	143	145	148	148	149	150	155	782
E22	119	149	155	165	180	182	N/A	N/A	183	486
E23	125	142	160	171	N/A	N/A	N/A	N/A	172	252
E24	114	134	155	171	179	181	182	183	189	956
E25	160	166	177	300	300	301	N/A	N/A	302	434
E26	171	185	N/A	N/A	N/A	N/A	N/A	N/A	440	90
E27	221	246	N/A	N/A	N/A	N/A	N/A	N/A	252	54
E28	159	164	N/A	N/A	N/A	N/A	N/A	N/A	205	167
E29	180	N/A	N/A	N/A	N/A	NA	NA	N/A	208	59
E30	219	246	301	N/A	N/A	N/A	N/A	N/A	301	117
Second Bench Seat- Below the Seat Cushion										
S1	12	25	46	105	110	115	120	123	168	832
S2	109	128	142	154	158	166	N/A	N/A	174	433
S3	152	166	178	186	200	N/A	N/A	N/A	201	305
S4	29	68	112	123	126	128	132	142	161	809
S5	56	108	125	133	141	144	150	N/A	183	566
S6	108	126	137	149	168	185	N/A	N/A	198	435
Headliner Interior										
A1	135	145	162	173	177	183	242	243	243	657
A2	113	143	159	168	174	177	182	192	194	653
A3	109	140	153	169	174	183	188	191	197	674
A4	134	146	151	162	166	169	173	175	196	780
A5	115	142	149	160	164	168	171	174	188	813
A6	69	134	143	152	158	161	167	169	182	813
A7	108	140	154	161	163	167	171	173	183	834
A8	134	146	158	166	171	173	175	178	184	716

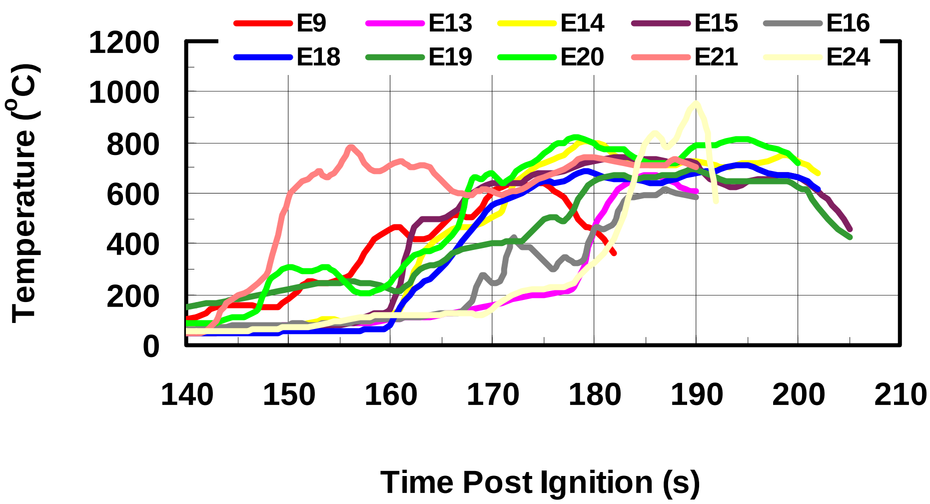


Figure B-2-7. Temperature versus time at E locations where flame was present inside the passenger compartment in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

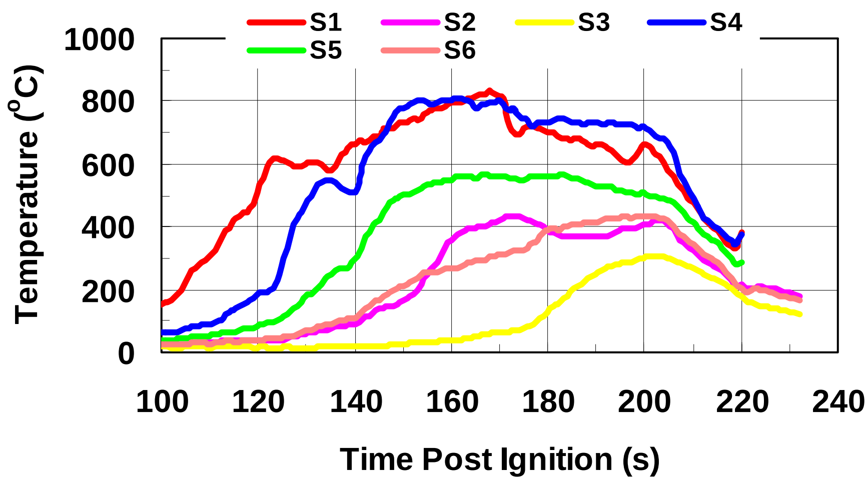


Figure B-2-8. Temperature versus time below the seat cushion of the second bench seat in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

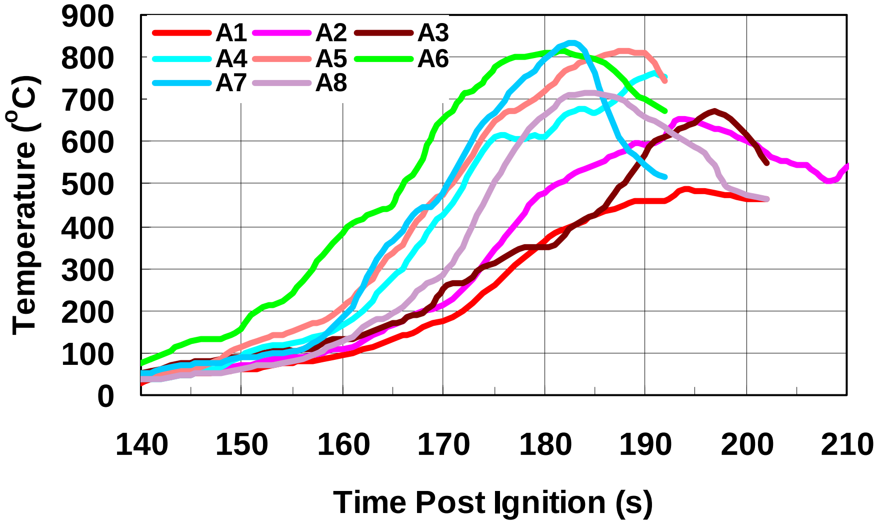


Figure B-2-9. Temperature versus time below the lower surface of the headlining in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

B-2-3. TEMPERATURE, CONCENTRATIONS AND RELEASE RATES OF HEAT AND PRODUCTS FROM THE 1996 PLYMOUTH VOYAGER BURN TEST

The concentrations of products and temperature profiles between the driver and front passenger seats are shown in Figs. B-2-10 and B-2-11. The concentrations were measured 10-in below the headliner and the temperatures were measured at by aspirated thermocouples at various heights below the headliner. The release rates of heat, CO, CO_2, and smoke measured in the fire plume are shown in Figs. B-2-12 and B-2-13 and the CO to CO_2 concentration ratios in the passenger compartment and in the fire plume are shown in Fig. B-2-14.

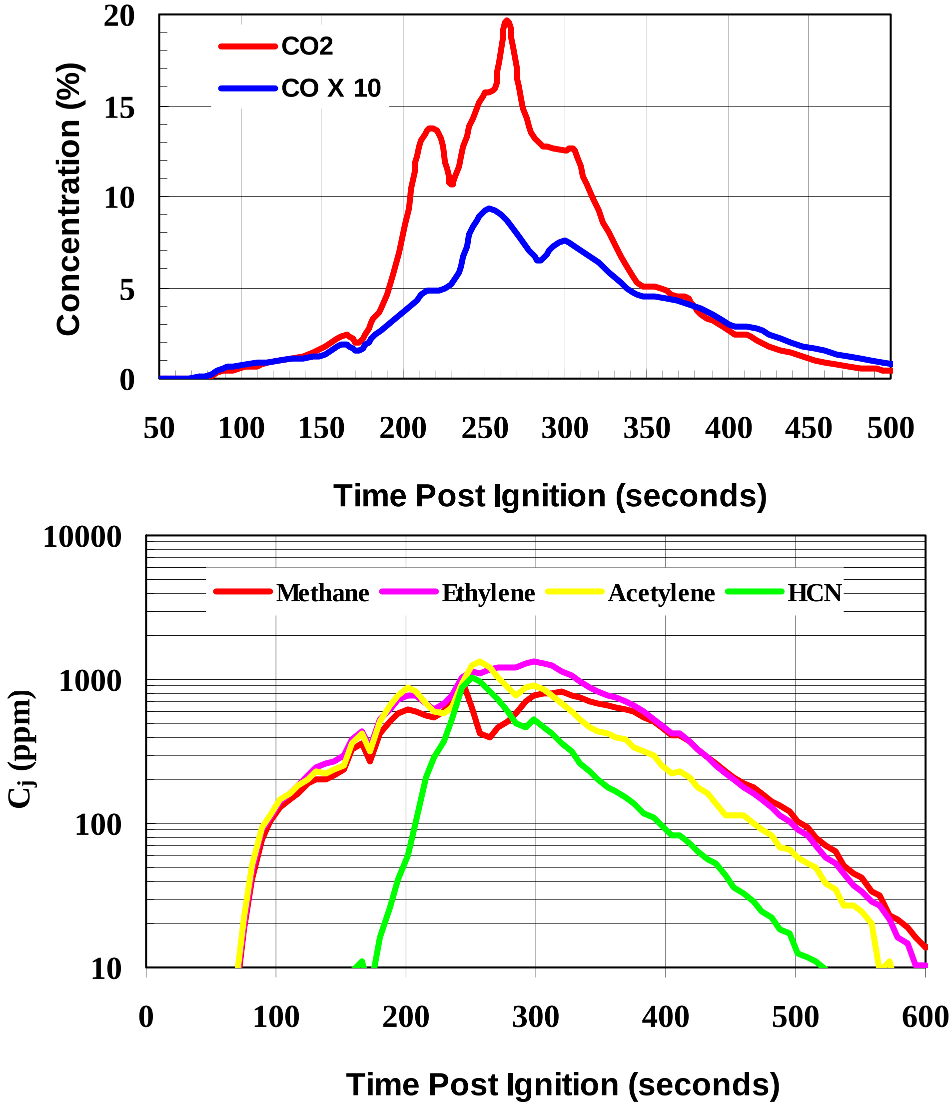


Figure B-2-10. Concentration versus time for products between the driver and front passenger seats inside the passenger compartment in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

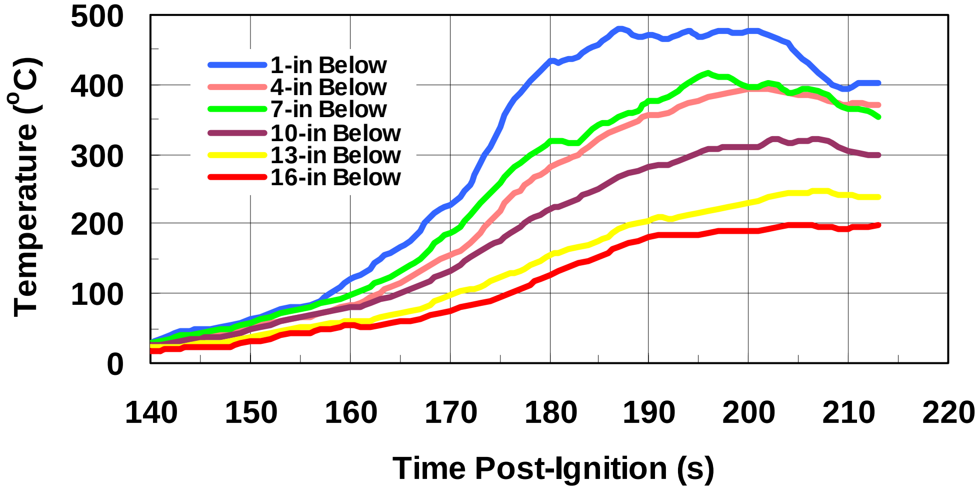


Figure B-2-11. Temperature profiles between the top of the driver and passenger seats in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

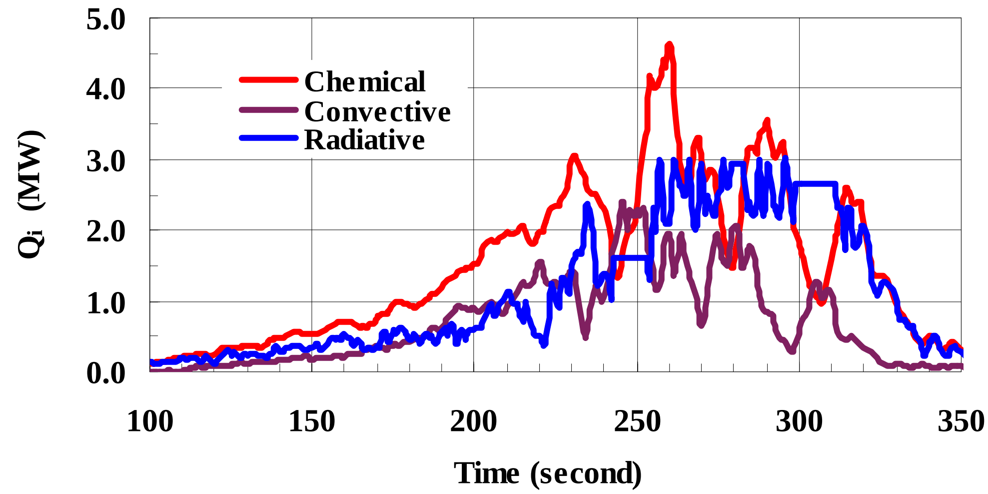


Figure B-2-12. Heat release rates in the burn test for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

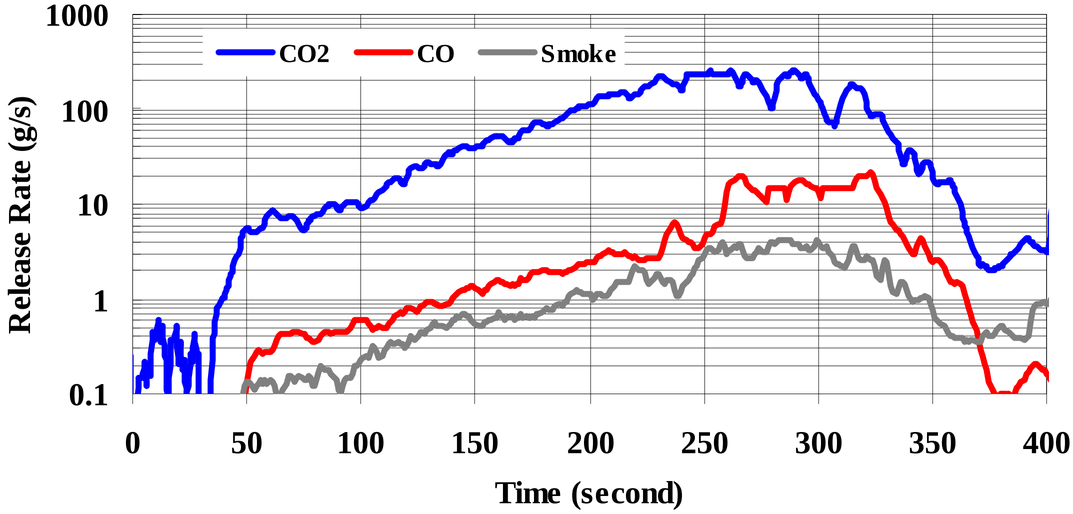


Figure B-2-13. Release rates of CO_2, CO, and smoke in the burn tests for the 1996 Plymouth Voyager. Data are taken from Ref. 2.

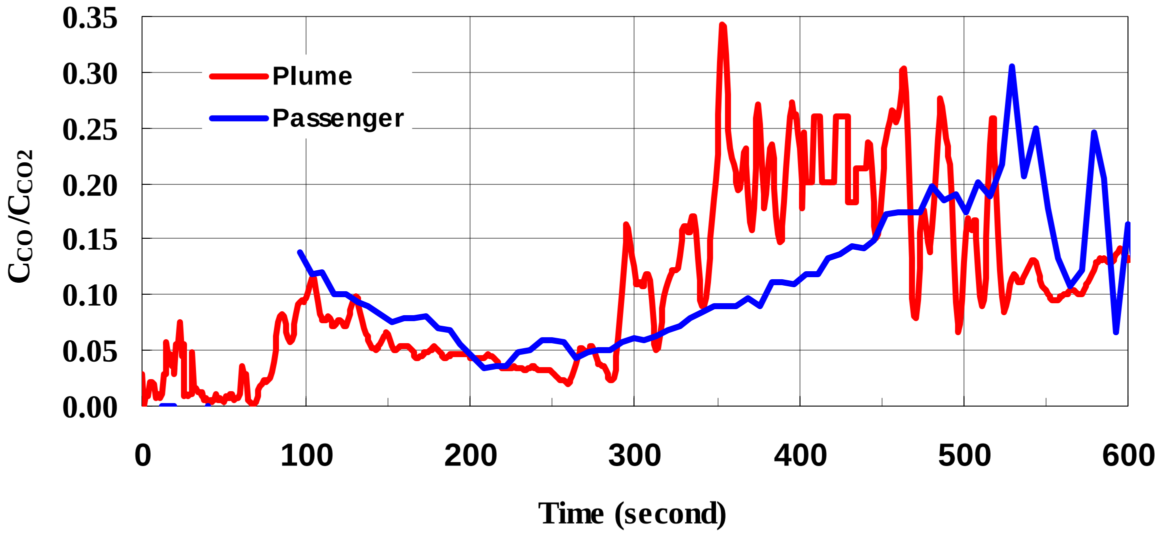


Figure B-2-14. Ratio of CO to CO_2 concentrations in the plume and in the passenger compartment from the burning of 1996 Plymouth Voyager. Data are taken from Ref. 2.

B.3 PROPAGATION OF UNDERBODY GASOLINE POOL FIRE FOR A 1997 CHEVROLET CAMARO: TEST #3

The information included in this appendix is taken from the report entitled "Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 6: Propagation of an Underbody Gasoline Pool Fire in a 1997 Rear Wheel Drive Passenger Car", by Jeffrey Santrock, NHTSA Docket Number: 3588, Document Number: NHTSA-1998-3588-158, www.nhtsa.dot.gov [3].

The fire propagation test was performed on September 30, 1997 at FM Global using a 1997 Chevrolet Camaro that was crashed at the GM Proving Ground on January 8, 1997. The crash test consisted of a stationary vehicle struck in the left rear (driver's side) by a moving barrier. The following vehicle damages were noted:

- Residue crush to vehicle was 1080-mm on the left side and 610 mm on the right side;
- Left side door window was shattered;
- Rear compartment lift window panel was broken and the glass was shattered;
- Left quarter interior trim finishing panel was dislodged and pushed forward;
- Left door was pushed outward slightly creating a gap between the bottom of the door and lower section of the door frame;
- Carbon absorbent from the ruptured evaporative emission canister was spilled onto the ground in the front of the left rear tire;
- A seam opened between the rear floor pan and the left inner quarter panel;

No leaks were detected in the fuel system of the test vehicle during the crash test or the subsequent roll test performed after the test. No fire was observed during the crash test, nor was there evidence of fire present in the test vehicle after the crash test. However, for the fire propagation test, it was assumed that there was a leak in the fuel tank with gasoline spilling onto the ground, getting ignited and burning as a pool fire.

For the fire propagation test, all the doors and windows of the crashed vehicle were closed, except those that were damaged or broken in the crash test. The left side door and rear glasses were broken in the crash test and were not replaced. Charcoal from the vapor recovery canister of the 1997 Chevrolet Camaro was removed, soaked with gasoline, and placed on the concrete surface of the fluid containment pan in front of the left rear tire just before the start of the burning test.

Gasoline was delivered at a constant flow rate of 515 ml/s from a pressurized external reservoir by a tube located at the lower left edge of the fuel tank, below the area where the fuel filler tube entered the fuel tank. Gasoline was allowed to flow onto the concrete surface of the fluid containment pan for about 31 seconds before it was ignited by a propane torch. At ignition, gasoline vapors were burning under most of the rear section of the test vehicle within few seconds of ignition.

The flame spread outside and within the passenger compartment was monitored by cameras and thermocouples. Figures B-3-1, B-3-2, and B-3-3 show the locations of thermocouples on various parts inside and outside the 1997 Chevrolet Camaro. The thermocouples were used to monitor the flame spread in the vehicle burn test.

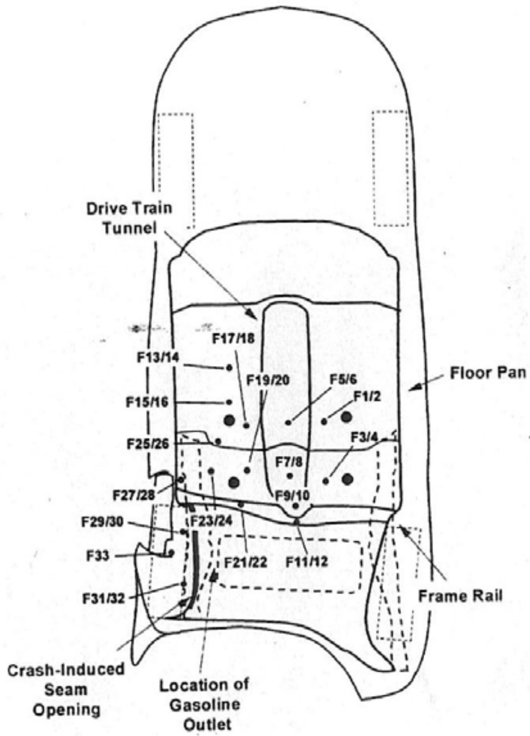
B-3-1. IGNITION OF THE GASOLINE POOL UNDER THE REAR OF THE VEHICLE

In the test, gasoline spilled onto the ground was ignited by a hand-held propane torch, 31 seconds after allowing the gasoline to flow from the external tank. The gasoline pool was elongated, spreading out along a seam between two of the cement boards under and parallel to the rear axle of the test vehicle. The gasoline pool length remained at about 1.1-m for 200 seconds post ignition.

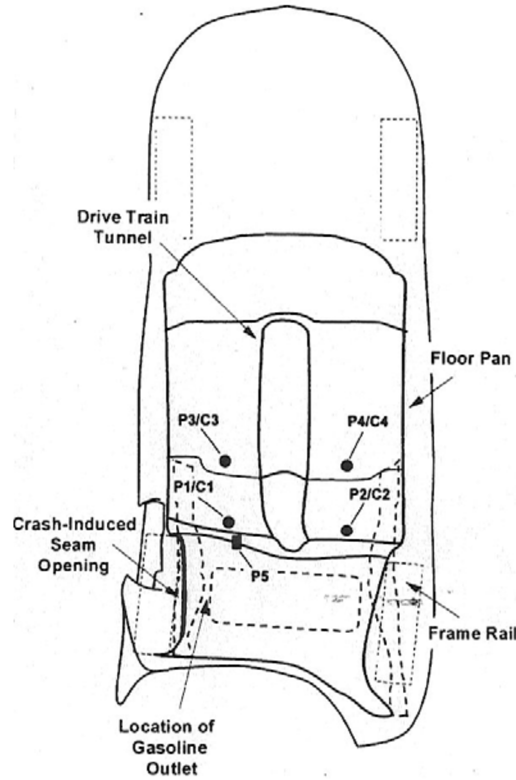
Thermocouple data indicated that heated gases started to spread forward along the left side (driver’s side) of the floor panel at about the time of ignition and to a pocket under the rear left seat created as the floor panel buckled during the crash test. Heated gases and flames appeared to accumulate in the rear section of the drive train tunnel, but not to have spread beyond to the right side of the floor panel. By 50 seconds post ignition, the area of the floor panel exposed to flames (reached 600 ^{o}C) increased to include an adjacent section of the drive train tunnel and a section just forward of the rear left seat cushion. By 75 seconds post ignition, flames were present on the floor panel just forward of the rear left seal well. By 100 seconds post ignition, section of flexible nylon fuel pipe under the rear left seat started to sag and burn. By 150 seconds post ignition, flames spread forward along the fuel lines to the in-line fuel filter under the rear left seat and fell onto the surface of the fuel containment panel.

Table B-3-1 summarizes the events during the burning of the 1997 Chevrolet Camaro.

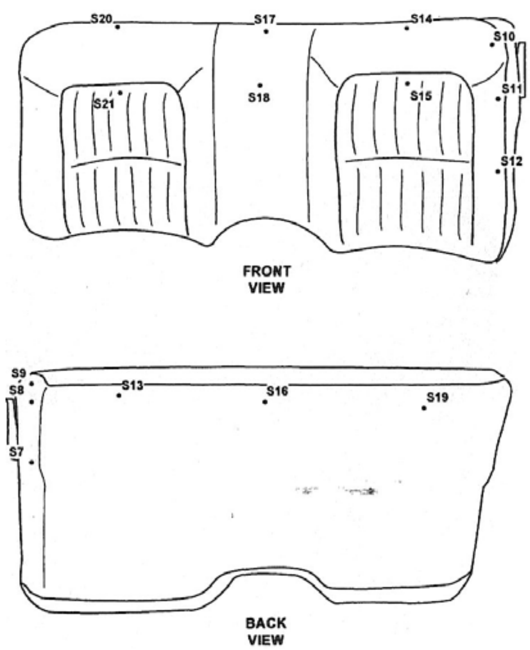
Floor Pan



Floor pan drain hole plugs and carpet



Seat Back



Rear Bumper Energy absorber Liftgate

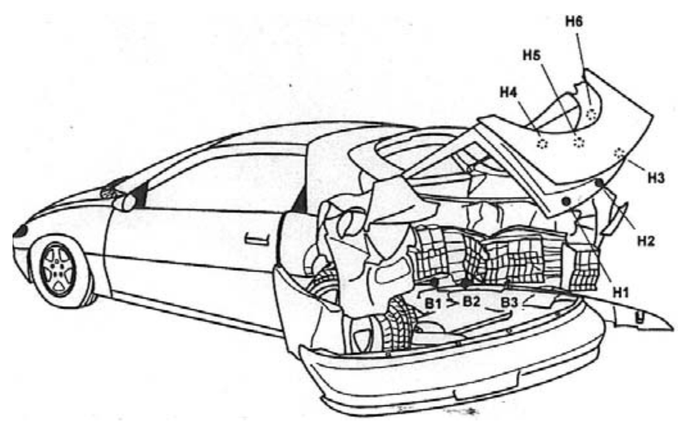
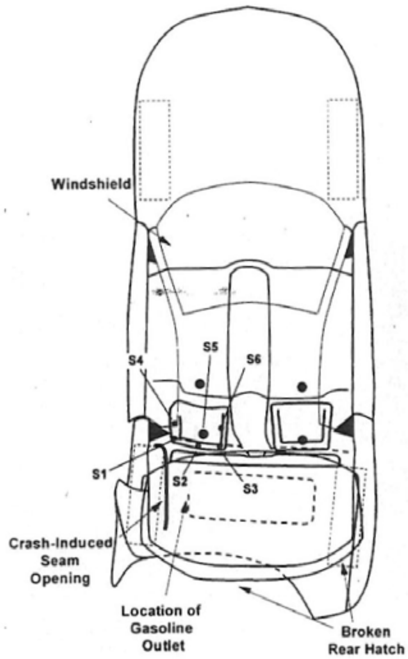
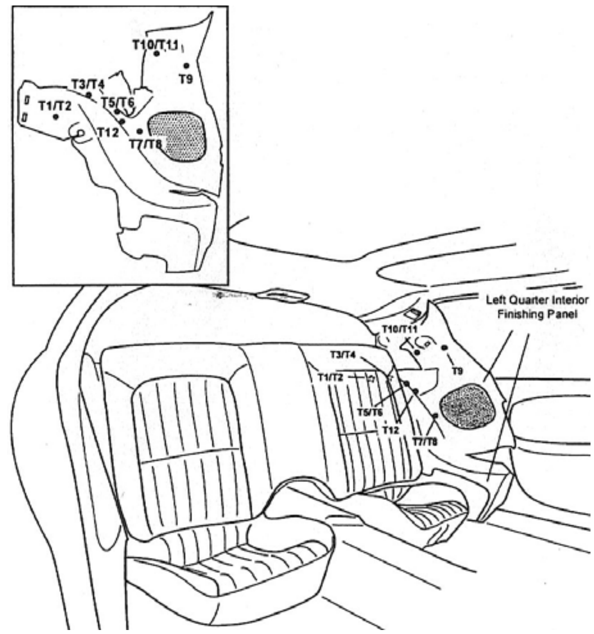


Figure B-3-1. Approximate locations of thermocouples on the floor pan, floor drain hole plugs, carpet, rear bumper energy absorber, rear liftgate and seat back. Figure is taken from Ref. 3.

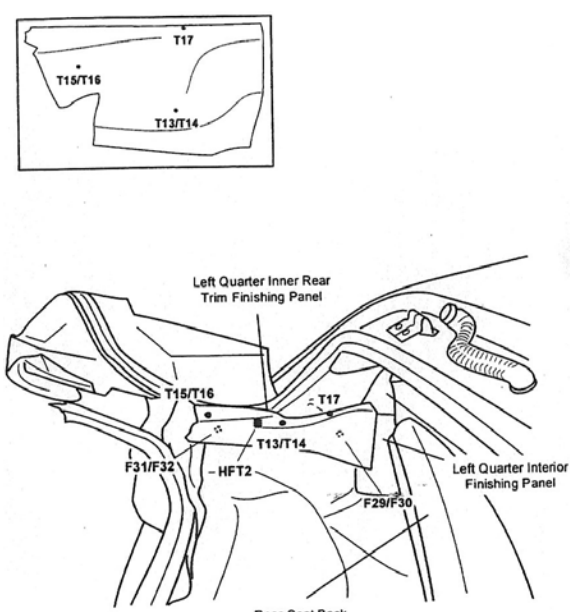
Rear left seat cushion



Left quarter interior finishing panel



Left quarter inner rear trim finishing panel



Headliner

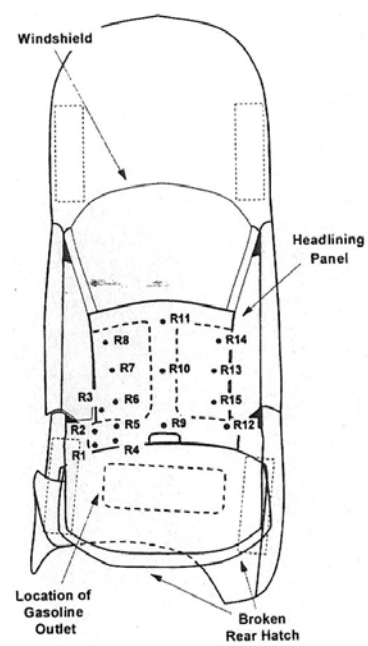


Figure B-3-2. Approximate locations of thermocouples on the rear left seat cushion, left quarter interior finishing panel, left quarter inner rear trim finishing panel and headliner. Figure is taken from Ref. 3.

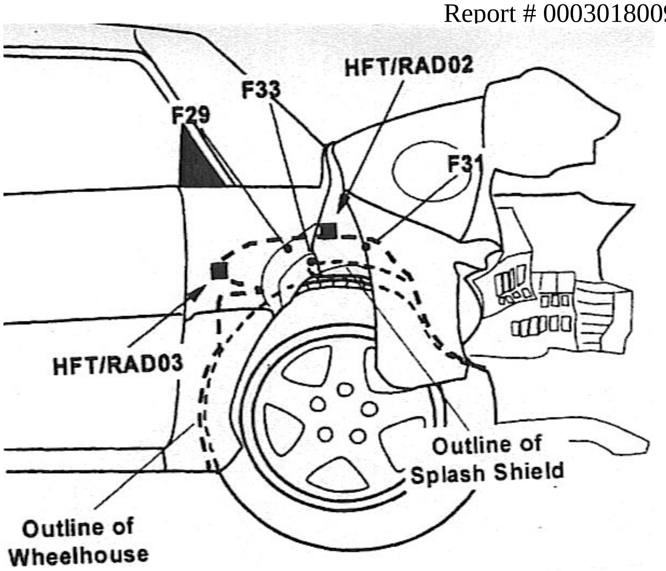


Figure B-3-3. Approximate locations of thermocouples on the inside of the wheelhouse. Figure is taken from Ref. 3.

The estimated diameter of the gasoline pool at 30 seconds was about 40 cm. The pool diameter remained approximately constant for about 90 seconds. Between 80 and 200 seconds, the pool diameter increased from about 40 to 80 cm. The flames spread radially along the lower surface of the gasoline tank and upward around its sides onto the floor pan. The heat flux to the area of the floor pan that was just above the filler (the approximate center) was about 75 kW/m^2. The source of additional fuel that caused the size of the burning pool under the test vehicle to increase appeared to be due to dripping and burning of the polyethylene fuel tank.

Table B-3-1. Summary of Fire Development during the Vehicle Burn Test [3]

Time (s)	Event
-30	Start of gasoline flow
0	Gasoline vapor under the vehicle was ignited by a propane torch
5	Temperature on top of the floor pan drain hole plug under the left rear seat cushion started to increase
7	Flames from the burning gasoline pool entered the passenger compartment through the seam opening around the left rear wheel house
12	Flames from the burning gasoline were visible in the left rear corner of the vehicle
40 to 45	The fire plume disappeared from the left rear corner of the vehicle
100 to 110	Flames from the burning gasoline pool ignited the rear bumper energy absorber
150 to 170	Ignition of the left quarter interior trim finishing panel
160	Flames burned through the floor pan drain hole plug locates under the rear left seat cushion
175	Flames began to reach the left rear corner of the headlining panel
188	Flames burned through the carpet in the area between the rear seat cushions
199	Fire suppression signal given

An increase in the flame volume in the area between the spare tire and floor pan was observed between 200 and 205 seconds post ignition. The diameter of the pool fire below the vehicle did not indicate an increase at this time. The size and intensity of the fire plume below the vehicle did not change appreciably between 180 and 200 seconds post ignition. Starting at about 200 seconds post ignition, an area with temperature greater than 700 ^{o}C appeared to the right of the fuel tank and spread forward and rearward along the longitudinal center-line of the floor pan over the next 10 seconds.

The fuel tank contained 38.5 liters (10 gallons) of gasoline at the start of the test. By 200 seconds post ignition, the fuel tank had lost about 833 ml of gasoline. At 213 seconds post ignition, there was an increase in the fire size at the left of the test vehicle, as solid materials (possibly rocker molding or the molding on the left) were burning and falling. At the end of the test, it was estimated that about 9.5 gallons of gasoline were present in the fuel tank. After the test, it was found that exterior surface of the bottom of the tank was melted and charred, but interior surface was not melted or charred due to the cooling effect of gasoline. Two sections were missing from the bottom of the tank. The top the fuel tank also charred. These observations are summarized in Table B-3-1.

B-3-2. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

Flames into the passenger compartment propagated simultaneously along three pathways due to elongated shape and location of the gasoline pool fire under the vehicle:

1. Through the crash-induced seam openings between the rear floor pan panel and left rear inner quarter panel;
2. Through a gap between the back of the driver's door and the door frame that was created by damage to the vehicle sustained during the crash test;
3. Through a drain hole in the floor panel.

1. Flame Spread into the Rear Left Corner of the Passenger Compartment through Seam Openings and a Gap

Between 10 and 20 seconds post ignition, flames entered the passenger compartment in the area behind the displaced left quarter interior trim finishing panel (T thermocouples, Fig. B-3-2, top right figure). Flames appeared along the top edge of the trim panel. By 30 seconds post ignition, flames had reached the left rear corner of the headlining panel (R thermocouples, Fig. B-3-2, lower right figure) and had started to spread forward and to the right along its lower surface. By 45 seconds post ignition, no flames were visible inside the passenger compartment.

Post ignition times to reach 30 ^{o}C, 50 ^{o}C, 100 ^{o}C, 200 ^{o}C, 300 ^{o}C, 400 ^{o}C, 500 ^{o}C, 600 ^{o}C and the maximum temperature at left quarter interior finishing panels and under the headliner are listed in Table B-3-2.

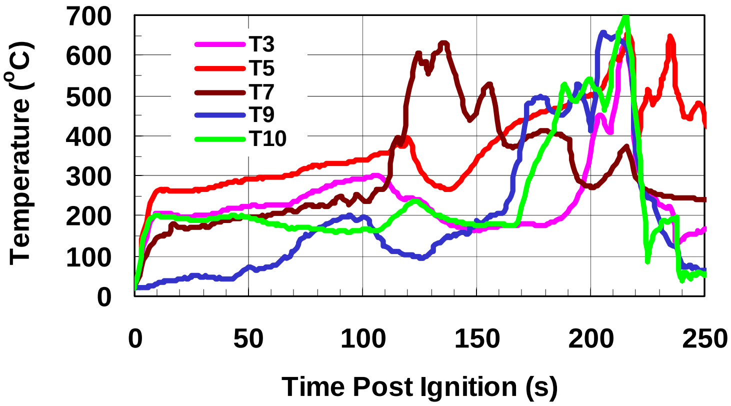
Table B-3-2. Time-Temperatures Relationships at Various Locations on the Left Quarter Interior Finishing Panel and Under the Headliner of the 1997 Chevrolet Camaro

Location	Time-to-Reach (s)								T_{max}	
	30 ^{o}C	50 ^{o}C	100 ^{o}C	200 ^{o}C	300 ^{o}C	400 ^{o}C	500 ^{o}C	600 ^{o}C	Time s	Temp ^{o}C
Behind the Panel (Back-Side)										
T1	12	13	14	15	17	N/A	N/A	N/A	18	352
T3	1	2	4	9	198	202	212	214	215	641
T5	1	2	3	6	67	161	200	214	217	653
T7	1	2	5	53	112	118	121	124	136	630
T9	10	26	68	95	167	171	193	204	206	657
T10	1	2	3	9	174	183	188	211	216	712
T13	1	2	4	14	17	N/A	N/A	N/A	21	375
T15	4	7	13	15	16	18	22	N/A	23	511
On the Exterior Surface (Front-Side)										
T2	23	39	209	N/A	N/A	N/A	N/A	N/A	216	124
T4	17	34	88	139	157	198	201	215	216	628
T6	1	26	71	131	150	167	211	N/A	217	595
T8	1	1	1	2	2	2	3	4	273	864
T11	24	51	132	182	188	195	211	214	216	724
T12	1	1	170	N/A	N/A	N/A	N/A	N/A	238	191
T14	12	14	23	N/A	N/A	N/A	N/A	N/A	220	163
T16	16	25	153	221	N/A	N/A	N/A	N/A	286	221
T17	2	3	6	108	121	186	N/A	N/A	198	472
10-cm Below the lower Surface of the Headliner										
R1	6	12	14	24	189	191	193	196	216	743
R2	4	13	14	16	18	22	24	26	216	754
R3	9	13	13	14	16	18	26	196	217	660

Table B-3-2 continued on the next page

Table B-3-2 continuing from the previous page

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time s	Temp °C
R4	13	14	17	22	192	199	210	N/A	216	547
R5	6	13	13	16	19	21	187	194	213	733
R6	18	27	130	200	217	N/A	N/A	N/A	218	305
R7	7	13	14	15	17	23	208	217	217	608
R8	10	13	15	21	24	210	216	N/A	217	519
R9	9	14	18	155	181	184	208	216	217	631
R10	13	14	15	21	190	200	215	N/A	217	520
R11	13	14	15	19	189	196	205	N/A	215	574
R12	14	18	177	186	213	N/A	N/A	N/A	217	359
R13	14	14	18	185	194	205	215	N/A	217	518
R14	13	14	16	25	187	193	204	N/A	211	564
R15	13	15	18	183	193	211	216	N/A	217	543



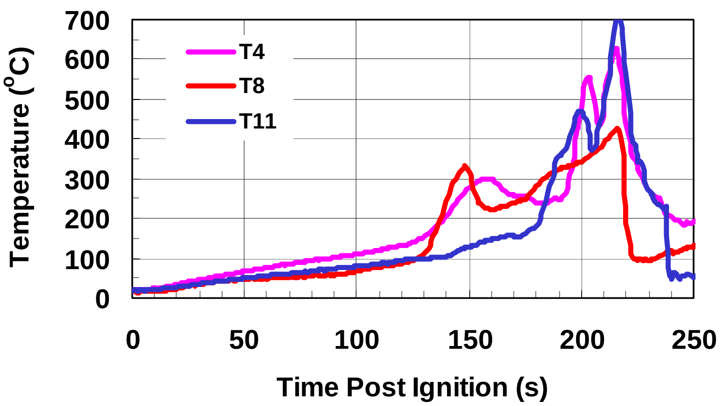


Figure B-3-4. Temperature versus time at the left quarter interior trim finishing panel (flame entered the passenger compartment) Data are taken from Ref. 3.

The temperatures measured at left quarter interior finishing panels reaching ≥ 600 °C are plotted in Fig. B-3-4. The temperatures measured 10-cm below the lower surface of the headliner are plotted in Fig. B-3-5.

Flames had reached the headliner location R2 in 30 seconds post ignition where temperature exceeded 600 °C (Fig. B-3-5). Flames had disappeared from the passenger compartment by 45 seconds post and temperature below the headliner decreased as indicated in Fig. B-3-5. Flames were observed behind the left interior quarter trim finishing panel between 160 and 170 seconds post ignition (T1 to T15 in Table B-3-2 and Fig. B-3-4. These flames did not contact the headliner at this time. By 180 seconds post ignition, flames were visible between the front of the left interior quarter trim finishing panel and the driver's seat back. The headliner temperatures were between 300 to 400 ^{o}C at this time (Fig. B-3-5). By 190 seconds post ignition, flames started to spread forward and to the right along the headlining panel.

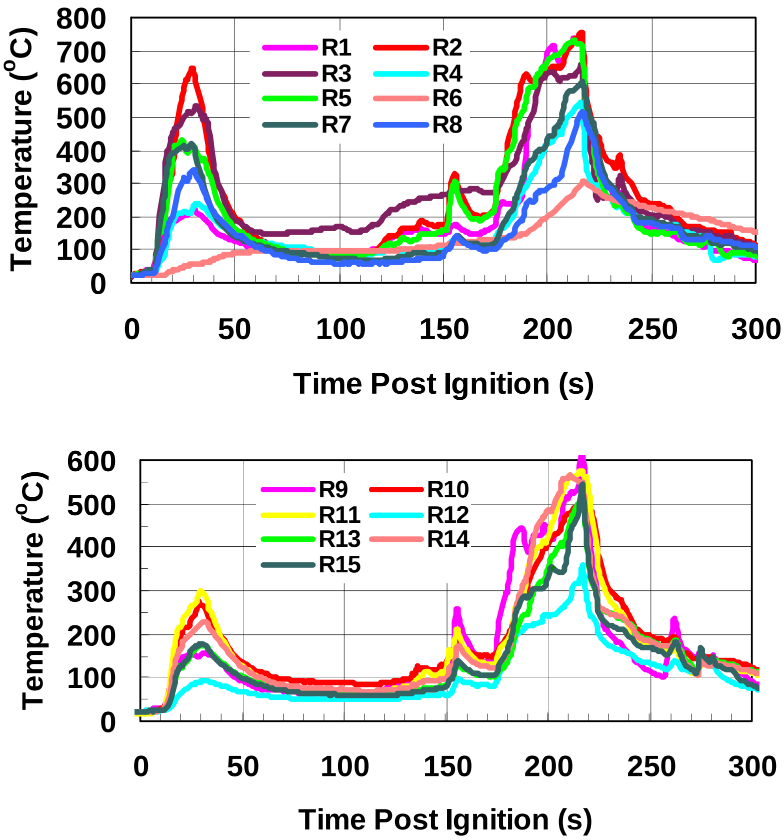


Figure B-3-5. Temperature versus time below the headliner. Data are taken from Ref. 3.

The presence of flames behind the interior quarter trim finishing panel was possibly through the seam openings around the left rear wheelhouse. Flames were present at this location during the first 30 seconds post ignition and again between 150 to 160 seconds post ignition, leading to the ignition of the quarter trim panel and the left rear section of the headlining panel. The flames entered the left rear wheelhouse and the seam openings around the wheelhouse between 200 to 210 seconds post ignition.

The test data, video recordings and physical examination after the burn test, indicated that flames had spread to the rear of the driver's door. The headlining panel had burned and charred in areas where the estimated temperature was > 500 ^{o}C at 210 seconds post ignition. The left side of the driver's seat, left side and top of the rear seat back and section of the interior trim panel on the driver's door that was behind the displaced interior quarter trim finishing panel were burned.

The upper section of the interior quarter trim finishing panel appeared to have melted and burned. Solidified plastics from the panel was observed on the lower portion of the inner quarter panel, the carpet on the vertical section of floor pan behind the rear seat back and the package shelf in the rear compartment. Other examinations indicated that the upper section of the section interior quarter trim finishing panel was exposed to flame at about 190 seconds post ignition and had ignited.

2. Flame Spread into the Middle of the Passenger Compartment through the Floor Pan Drain Hole

Between about 185 and 200 seconds, flames were visible in front of the middle of the rear seat back (indicated by thermocouples P1 through P4 and F19 in the Fig. B-3-1 located on the upper surfaces of drain plugs in the floor pan). Three other drain-hole plugs in the front floor pan were not damaged and remained in place. The temperatures below the left side of the floor pan were > 600 ^{o}C at the end of the test, where paint was charred with a red or white oxide layer. This area was exposed to flame from about 15 seconds post ignition until the end of the test. The time-temperature relationships for the floor pan (locations F in Fig. B-3-1) are plotted in Fig. B-3-6 and the times to reach 30 ^{o}C, 50 ^{o}C, 100 ^{o}C, 200 ^{o}C, 300 ^{o}C, 400 ^{o}C, 500 ^{o}C, 600 ^{o}C and the maximum temperature on and below the floor pan and at various locations of the rear left seat and cushion are listed in Tables B-3-3 and B-3-4.

The temperature recorded by thermocouple P1 indicates that the left rear floor pan drain-hole plug burned through between 155 and 170 seconds post ignition. Heated gases and flames that entered the drain-hole under the left rear seat cushion appeared to have followed channels between the floor pan and the carpet created during the crash test. Flames spread between the carpet and the floor pan to the right and upward along the vertical section of the pan behind the rear seat back. The C1 thermocouple located on the upper surface of the carpet just above the drain-hole plug, reached a maximum of 306 ^{o}C at 209 seconds post ignition. This temperature indicates that flames did not burn through the section of carpet directly above the drain-hole.

Flames appeared to have burned through the inboard side of the left seat cushion. The fabric over and foam pad in the rear seat back and rear seat cushions were charred and discolored above areas of the carpet that were burned and charred. Table B-3-4 show that only few locations reached temperatures greater than 300 ^{o}C (S3, S5, S6, S8, S9, and S18).

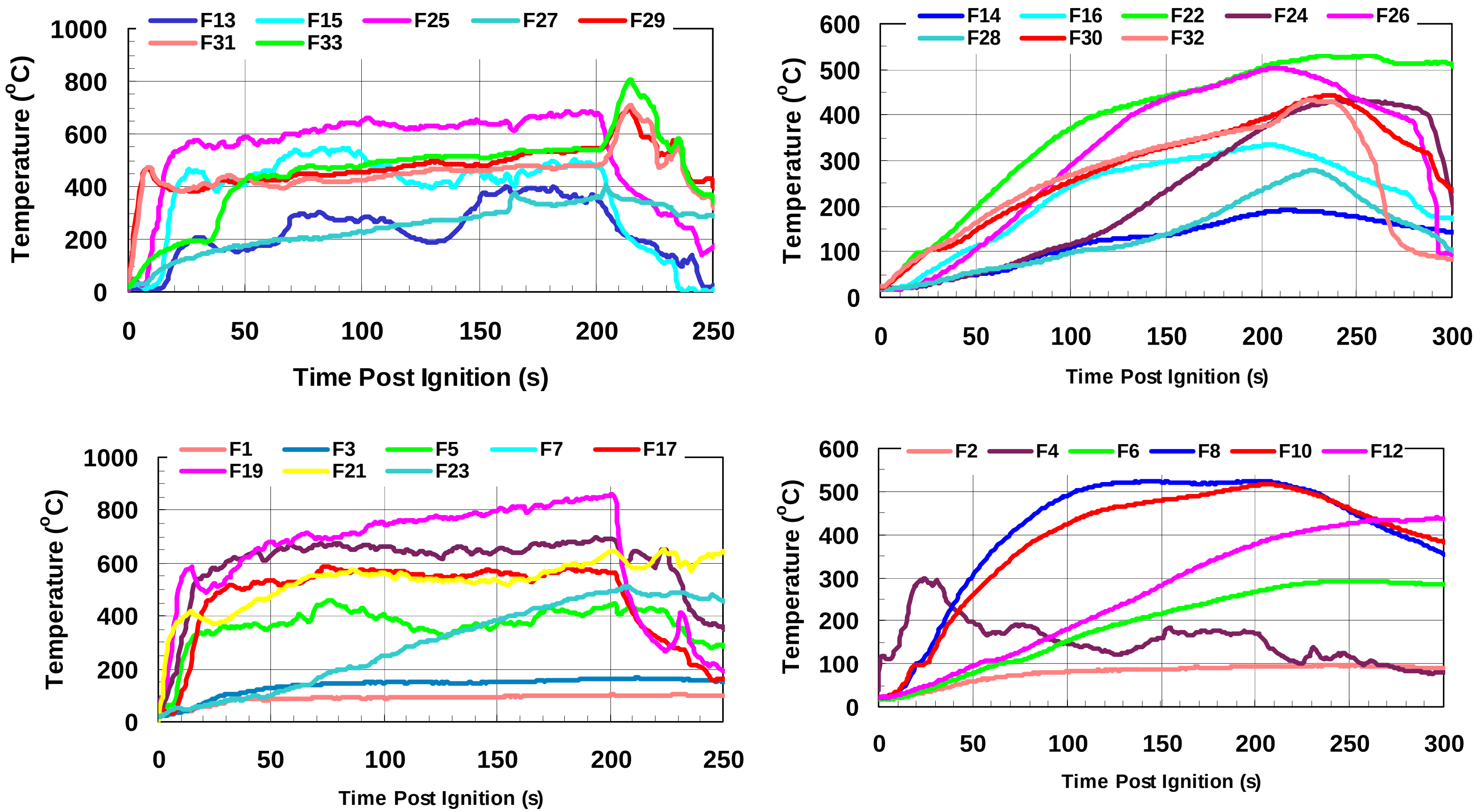


Figure B-3-6. Temperature versus time for the floor pan during the burning of the 1997 Chevrolet Camaro model. The even-odd number thermocouples were located at the same position. The even numbered thermocouples were attached to the upper surface of the floor pan and the odd numbered thermocouples were located about 1-cm below the lower surface of the floor pan. Data are taken from Ref. 3.

Table B-3-3. Time-Temperatures Relationships in the Vehicle Burn Test at Various Locations On and Below the Floor Pan

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time (s)	Temp (°C)
Upper Surface of the Floor Pan										
F2	20	41	N/A	N/A	N/A	N/A	N/A	N/A	241	96
F4	2	2	2	15	N/A	N/A	N/A	N/A	25	297
F6	19	33	65	135	N/A	N/A	N/A	N/A	250	293
F8	9	14	21	35	50	70	105	N/A	201	525
F10	9	13	26	39	60	89	181	N/A	208	517
F12	13	26	53	111	158	219	N/A	N/A	297	439
F14	27	49	95	N/A	N/A	N/A	N/A	N/A	214	192
F16	17	23	44	85	151	N/A	N/A	N/A	204	335
F18	12	19	28	52	72	98	N/A	N/A	206	493
F20	2	8	15	36	48	61	82	111	203	755
F22	5	10	23	51	77	114	198	N/A	235	530
F24	27	49	86	139	175	213	N/A	N/A	250	432
F26	22	31	49	77	103	132	203	N/A	209	503
F28	25	44	102	184	N/A	N/A	N/A	N/A	226	279
F30	5	11	25	73	128	207	N/A	N/A	237	444
F32	4	9	25	65	123	212	N/A	N/A	225	434
F34	2	2	86	179	284	NA	N/A	N/A	289	300
1-cm Below the Lower Surface of the Floor Pan										
F1	2	17	185	N/A	N/A	N/A	N/A	N/A	232	107
F3	7	16	30	N/A	N/A	N/A	N/A	N/A	212	166
F5	2	2	9	10	14	63	N/A	N/A	75	462
F7	2	2	4	9	10	14	16	30	194	697
F9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	193	22
F13	2	16	18	24	70	158	N/A	N/A	162	425
F15	2	2	15	16	18	20	25	N/A	82	597
F17	2	2	2	13	16	18	22	67	74	642
F19	2	2	2	3	6	7	8	10	201	940
F21	2	2	2	3	4	8	44	82	276	745

Table B-3-3 continued on the next page

Table B-3-3 continued from the previous page

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time (s)	Temp (°C)
F23	4	8	51	83	116	156	205	N/A	206	509
F25	2	2	9	10	13	15	16	25	194	735
F27	5	10	18	71	158	204	N/A	N/A	204	405
Wheelhouse										
F29	2	2	2	3	4	6	162	207	214	696
F31	2	2	2	3	5	6	205	209	215	708
F33	2	4	8	36	40	48	116	206	215	805
F35	2	2	NA	NA	NA	NA	NA	NA	235	95
Upper Surfaces of Drain Plug in the Floor Pan										
P1	9	15	27	51	83	139	161	166	208	866
P2	23	49	198	N/A	N/A	N/A	N/A	N/A	247	104
P3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	236	23
P4	63	N/A	N/A	N/A	N/A	N/A	N/A	N/A	319	49
Behind the Rear Seatback in Electrical Pass-through										
P5	78	124	195	N/A	N/A	N/A	N/A	N/A	305	140
Upper Surfaces of the Carpet above the Drain Plugs in the Floor Pan										
C1	124	161	164	174	203	N/A	N/A	N/A	209	306
C2	175	222	N/A	N/A	N/A	N/A	N/A	N/A	279	59
C3	189	N/A	N/A	N/A	N/A	N/A	N/A	N/A	298	43
C4	219	N/A	N/A	N/A	N/A	N/A	N/A	N/A	272	46

Table B-3-4. Time-Temperatures Relationships for Various Locations of Rear Left Seat and Cushion

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time (s)	Temp (°C)
1-cm Below the Lower Surface of the Foam Pad of the Rear Left Seat Cushion										
S1	82	177	208	N/A	N/A	N/A	N/A	N/A	275	152
S2	165	276	N/A	N/A	N/A	N/A	N/A	N/A	378	78
S3	85	117	131	220	258	N/A	N/A	N/A	278	331
S4	184	224	N/A	N/A	N/A	N/A	N/A	N/A	343	78
S5	97	134	151	164	181	257	N/A	N/A	265	441
S6	56	69	103	116	127	144	209	N/A	265	507
Outer Surface of the Left Side Panel of the Seat Cover										
S7	29	120	206	213	N/A	N/A	N/A	N/A	217	238
S8	12	13	28	31	35	N/A	N/A	N/A	44	389
S9	4	13	13	14	20	28	30	N/A	32	572
Outer Surface of Left Side Panel of the Seat Cover										
S10	18	26	188	209	N/A	N/A	N/A	N/A	216	247
S11	23	177	195	216	N/A	N/A	N/A	N/A	218	222
S12	64	184	193	216	N/A	N/A	N/A	N/A	218	252
S14	216	N/A	N/A	N/A	N/A	N/A	N/A	N/A	216	30
S15	23	182	199	N/A	N/A	N/A	N/A	N/A	217	171
S17	23	183	200	N/A	N/A	N/A	N/A	N/A	217	175
S18	36	188	190	195	200	206	209	0	216	623
S20	139	204	N/A	N/A	N/A	N/A	N/A	N/A	217	77
S21	156	194	214	N/A	N/A	N/A	N/A	N/A	216	117
Outer Surface of the Front Panel of the Seat Cover										
S13	7	20	195	N/A	N/A	N/A	N/A	N/A	219	155
S16	31	201	N/A	N/A	N/A	N/A	N/A	N/A	224	75
S19	126	199	N/A	N/A	N/A	N/A	N/A	N/A	220	68

The temperature recorded at various locations at the rear bumper energy absorber and the liftgate in the burning of the 1997 Chevrolet Camaro, listed in Table B-3-5 indicate low temperatures except at location B1.

Table B-3-5. Time-Temperatures Relationships in the Burn Test for Rear Bumper Energy Absorber and Rear Liftgate of the 1997 Chevrolet Camaro

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time (s)	Temp (°C)
Below the Lower Surface of the Rear Bumper Energy Absorber										
B1	2	2	2	2	79	92	102	107	125	748
B2	2	2	152	N/A	N/A	N/A	N/A	N/A	152	172
B3	2	2	5	104	106	107	108	110	118	764
Lower Outside Edge of the Rear Lift Glass Outer Panel										
H1	2	227	229	N/A	N/A	N/A	N/A	N/A	229	176
H2	227	229	N/A	N/A	N/A	N/A	N/A	N/A	229	62
H3	2	226	229	N/A	N/A	N/A	N/A	N/A	229	114
Inside Surface of the Rear Lift Glass Inner Panel										
H4	2	191	226	N/A	N/A	N/A	N/A	N/A	229	143
H5	2	152	227	229	N/A	N/A	N/A	N/A	229	215
H6	152	218	229	N/A	N/A	N/A	N/A	N/A	230	158

B-3-3. TEMPERATURE AND CONCENTRATION OF PRODUCTS IN THE PASSENGER COMPARTMENT AND RELEASE RATES OF HEAT AND PRODUCTS IN THE FIRE PLUME

The concentrations of products and temperature profiles between the driver and front passenger seats during the burning of the 1997 Chevrolet Camaro are shown in Fig. B-3-7. The concentrations were measured 10-in below the headliner and the temperatures were measured at by aspirated thermocouples at various heights below the headliner. Release rates of heat, CO, CO_2 and smoke measured in the fire plume over the burning 1997 Chevrolet Camaro are shown in Fig. B-3-8. Ratio of the measured CO to CO_2 concentrations versus time in the plume of the burning vehicle and inside the passenger compartment are shown in Fig. B-3-9.

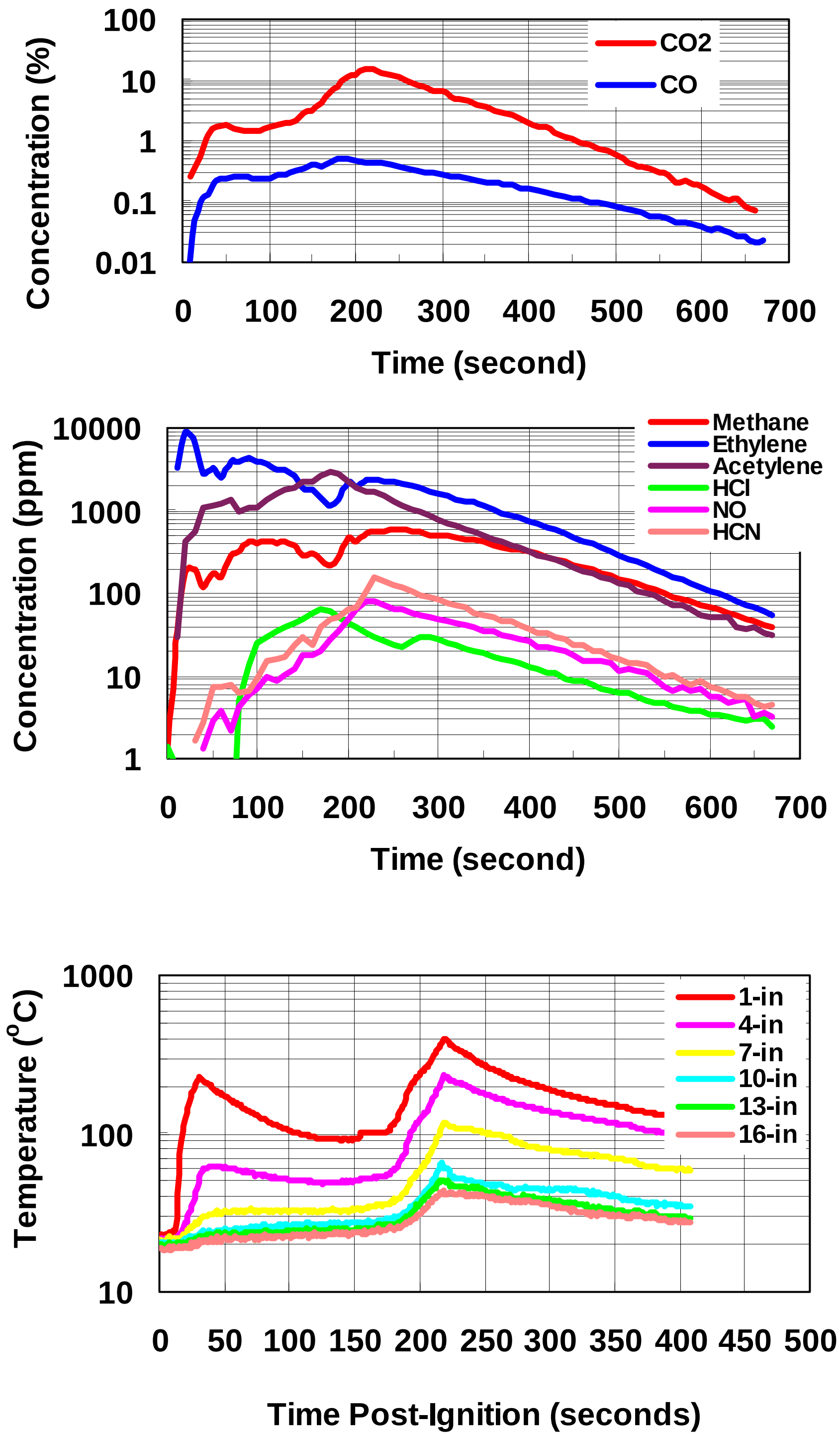


Figure B-3-7. Concentration and temperature versus time between the driver and front passenger seats inside the passenger compartment in the burn test for the 1997 Chevrolet Camaro. Data are taken from Ref. 3.

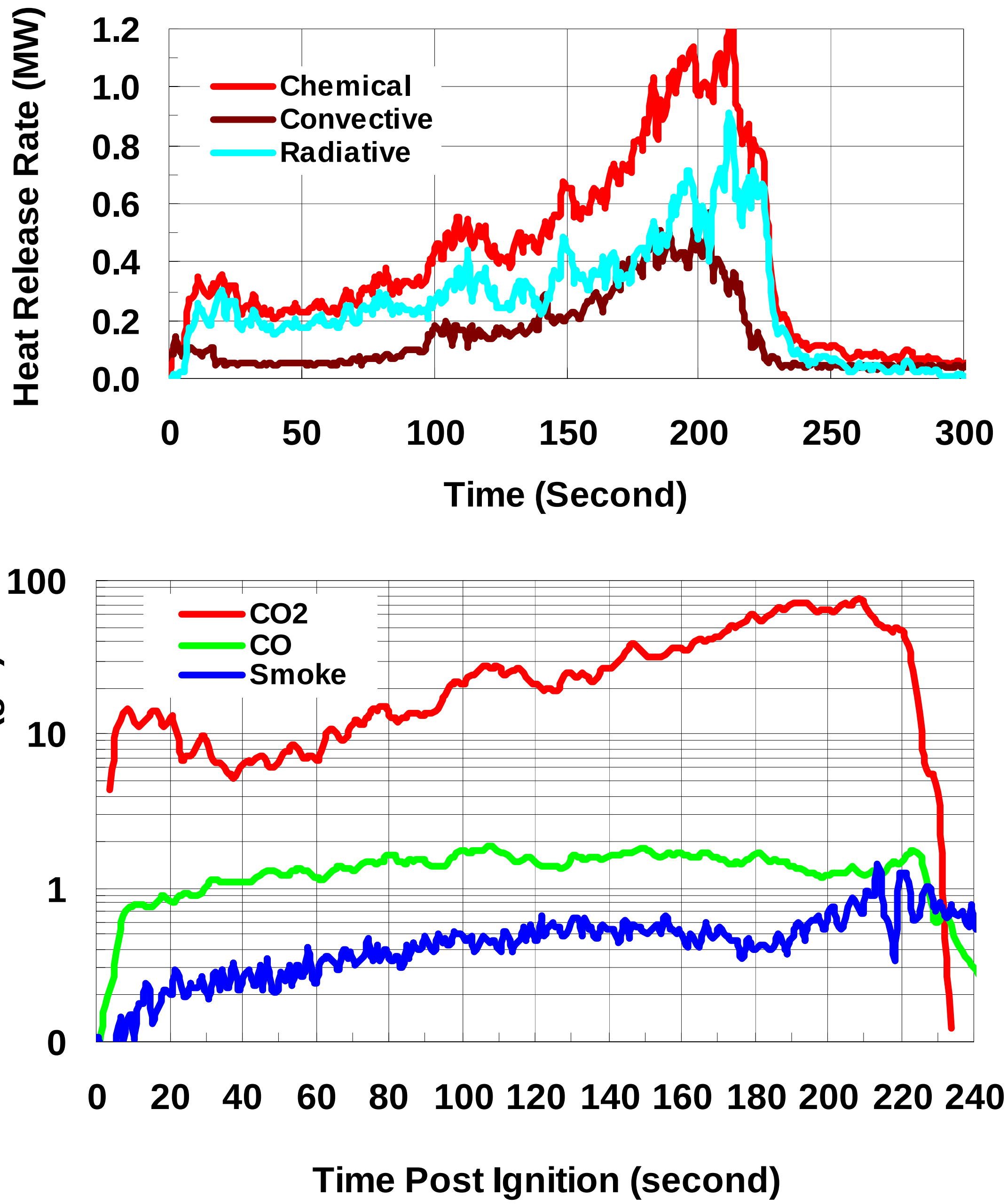


Figure B-3-8. Release rates of heat, CO, CO_2 and smoke in the burn test for the 1997 Chevrolet Camaro. Data are taken from Ref. 3.

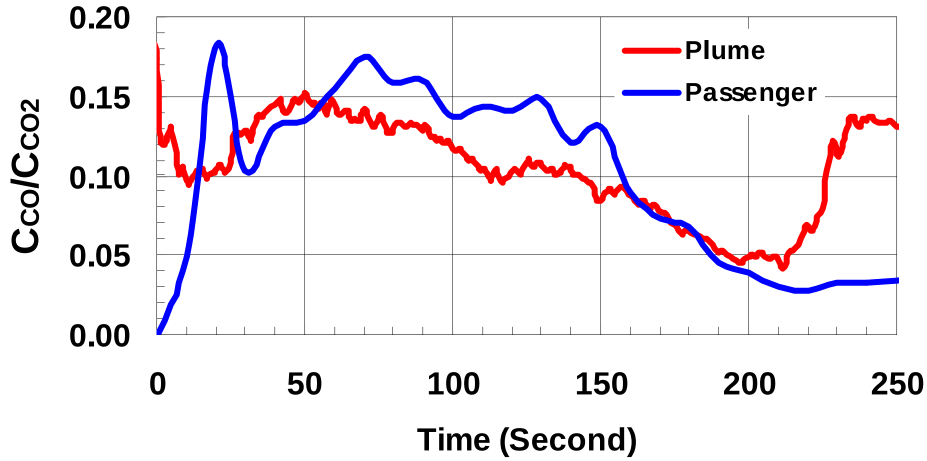


Figure B-3-9. Ratios of the CO to CO_2 concentrations versus time in the plume and in the passenger compartment of burning 1997 Chevrolet Camaro. Data are taken from Ref. 3.

B.4 PROPAGATION OF AN ENGINE COMPARTMENT FIRE FOR A 1997 CHEVROLET CAMARO: TEST #4

The information included in this appendix is taken from the report entitled "Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 7: Propagation of an Engine Compartment Fire in a 1997 Rear Wheel Drive Passenger Car", by Jeffrey Santrock, NHTSA Docket Number: 3588, Document Number: NHTSA-1998-3588-178, www.nhtsa.dot.gov [4].

The fire propagation test was performed on October 1, 1997 at FM Global using a 1997 Chevrolet Camaro model that was crashed at the GM Proving Ground on May 14, 1997. The crash test consisted of a towing the vehicle into a fixed steel pole at a speed of 55.3 km/h. The point of contact between the test vehicle and the pole was on the front bumper fascia 305-mm to the right of the vehicle longitudinal centerline. The crash test did not result in a fire or a fuel system leak in the test vehicle. Following damages to the vehicle were noted:

- Hood and right fender were crushed;
- Windshield and window in the right door were broken;
- The left side of the front bumper fascia was detached from the test vehicle;
- The engine and transmission were displaced rearward;
- Two of the bolts securing the transmission case to the rear of the engine punctured the dash panel in two places;
- The upper and lower cases of the HVAC module were broken and the heat exchanger and A/C evaporator were displaced rearward;
- A section of the weld seam between the floor pan and inner rocker panel separated during the crash test.

For the fire propagation test, all the doors and windows of the crashed vehicle were closed, except those that were damaged or broken in the crash test. A mixture of 3 quarts of automatic transmission fluid, 1 quart of motor oil, and 1 quart of brake fluid was heated to a temperature of about 150 ^{o}C and poured onto the cement board surface under the engine compartment just before the start of the test. About 2 liter of a mixture of antifreeze and water (1:1) heated to about 80 ^{o}C was sprayed onto the hood lining.

A propane ring burner with holes was used to start the fire in the engine compartment. The propane burner was in the right side of the engine compartment so that the flames from the burner impinged on the lower and upper cases of the HVAC module. A heated coiled Nichrome wire was used to ignite the propane issuing from the burner. Flame spread outside and within the passenger compartment was monitored by cameras and thermocouples. Locations of the thermocouples at various inside and outside parts of the 1997 Chevrolet Camaro model are shown in Figs. B-4-1 and B-4-2. The thermocouples were used to monitor the flame spread along with the video and IR cameras in the vehicle burn test.

Summary of fire development during the vehicle burn test with fire started in the engine compartment of the 1997 Chevrolet Camaro is listed in Table B-4-1.

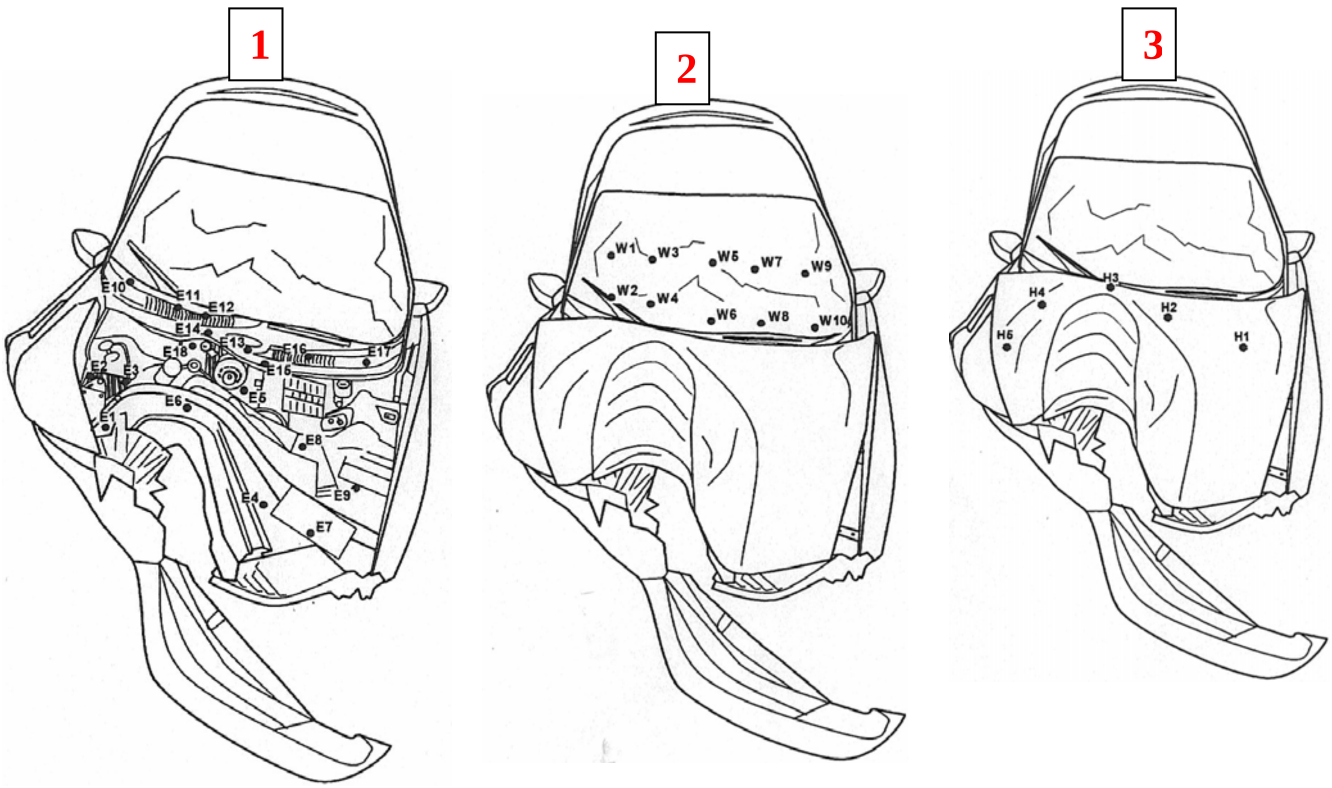


Figure B-4-1. Locations of thermocouples: 1) in the engine compartment, 2) on the windshield and 3) on the hood of the crashed the 1997 Chevrolet Camaro. Figures are taken from Ref. 4.

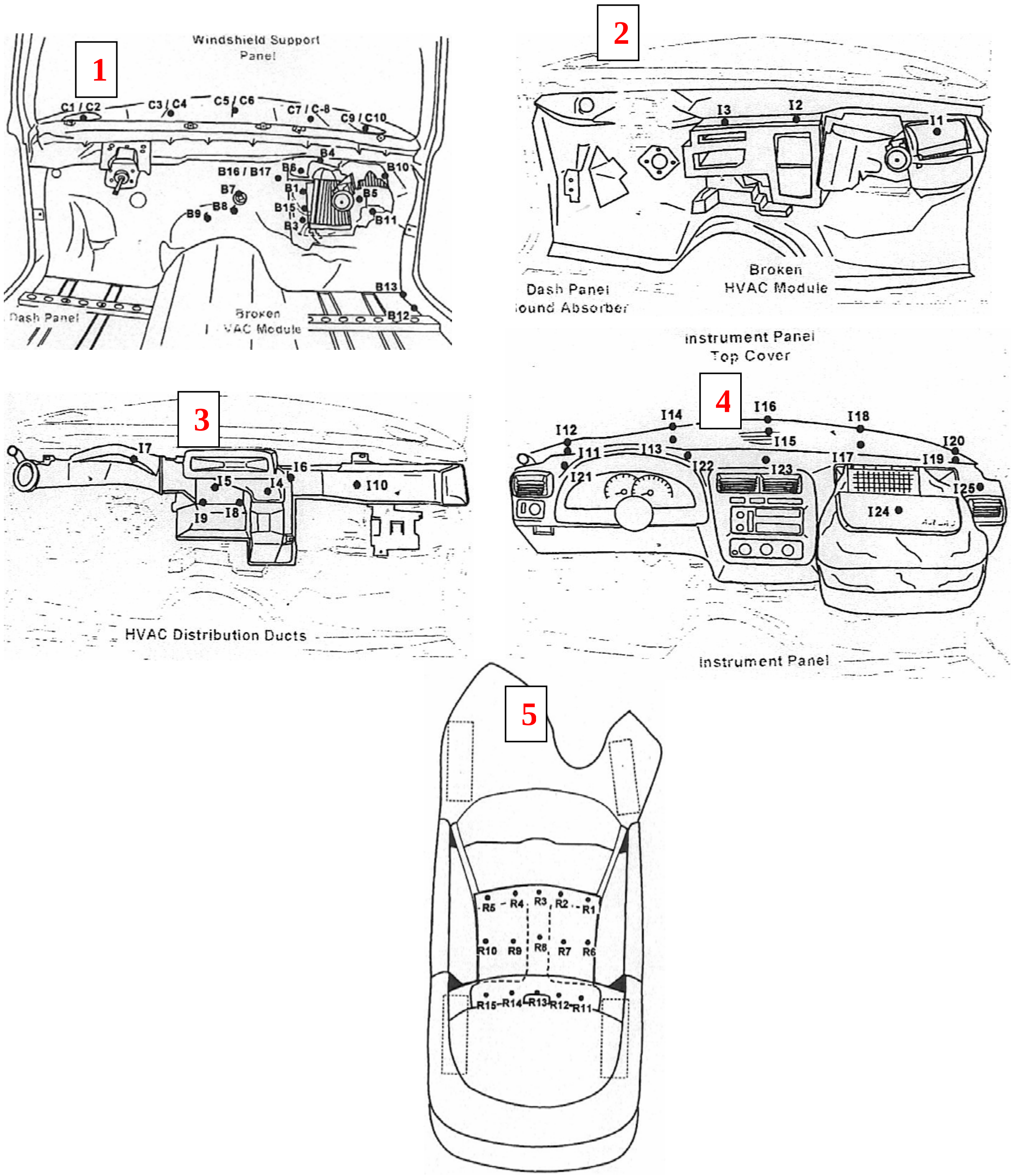


Figure B-4-2. Locations of thermocouples: 1) on the windshield support panel, dash panel, and HVAC module, 2) on the HVAC module, 3) on the HVAC distribution duct assembly, 4) on the instrument panel and its top cover, and 5) on the headlining panel of the crashed 1997 Chevrolet Camaro. Figures are taken from Ref. 4.

Table B-4-1. Summary of Fire Development in the Burn Test with Fire Started in the Engine Compartment of the 1997 Chevrolet Camaro [4]

Time (sec)	Event
0	Ignition of the propane torch
120	Propane torch tuned off
135	Flames visible on the right air inlet screen
240-360	Flame spread laterally in the engine compartment
666	Sections of the windshield fall into the instrument panel upper trim panel
480-540	A measurable pressure differential develops across the dash panel
780-900	Deployed passenger airbag ignites and burns
895	Flames emerge through the defroster outlet in the instrument panel trim panel
950	Test ended

B-4-1. IGNITION AND FLAME SPREAD IN THE ENGINE COMPARTMENT AND UNDER THE VEHICLE

To start the test, propane was allowed to flow through the ring burner and electrical power was supplied to the Nichrome wire to ignite the propane-air mixture flowing through the burner. The propane flow to the burner was stopped 2-minutes after ignition. The propane ring burner flames were extinguished by 5 seconds after the flow of propane was turned off. Around 125 seconds post ignition, plastics and fluids in the engine compartment were burning. By 150 seconds post ignition, flames from the propane torch had not spread to components in the upper engine compartment. Observations for the flame spread in the engine compartment are listed in Table B-4-2.

Table B-4-2. Flame Spread Observations in the Engine Compartment of the 1997 Chevrolet Camaro Burn Test

Time Post Ignition (s)	Events
180-240	Emergence of flames from under the upper dash extension panel above the area where propane torch was located
210	Flames reaching the air inlet screen at the base of the windshield in the area above the propane torch
240-280	Flames spreading laterally at the rear of the engine compartment along the air inlet screen and forward from the areas where the propane torch was located
360-480	Ignition of the broken inner edge of the right front fender
480-510	Flames emerging from the forward edge of the left upper dash extension panel under the dislodged battery top
540-600	Flames spreading to the left air inlet screen above the dislodged battery top
600 - 660	Ignition of the right front wheelhouse panel liner
600 to 960	Laterally and forward spreading of flame in the right and left sides of the engine compartment
960	Test ended

Between 90 and 180 seconds post ignition, burning plastic melt was observed dripping periodically onto the inboard section of the HVAC upper case, right exhaust manifold heat shield, and right valve cover. By 180 seconds post ignition, flames were visible under the dash upper extension panel to the left of the engine and a section of the HVAC upper case near one of the heater hose. Burning of pool of plastic melt was observed on the right exhaust manifold heat shield around 180 seconds; however, by 300 seconds flames were extinguished. Between 180 and 360 seconds post ignition, flames spread to the lower HVAC module as burning plastic melt flowed downward on the upper case.

Pieces of burning plastics fell into the mixture of petroleum oils, brake fluid, and engine coolant that was pooled under the engine compartment at about 510 seconds post ignition. Some of the burning plastics extinguished shortly after falling into the fluid mixture pool. Flames did not spread across the surface of the pooled fluids away from the burning plastics that fell from the vehicle.

Post ignition times to reach 30 ^oC, 50 ^oC, 100 ^oC, 200 ^oC, 300 ^oC, 400 ^oC, 500 ^oC, 600 ^oC and the maximum temperature at various locations in the engine compartment are listed in Tables B-4-3 and B-4-4. These data provide information about flame spread in the engine compartment, on the windshield and on the hood of the engine compartment. A temperature value of 600 ^oC was taken as the threshold to indicate the presence of flame.

Table B-4-3. Time-Temperatures Relationships at Various Locations in the Engine Compartment, Windshield and the Hood in the 1997 Chevrolet Camaro Burn Test

Location	**Time-to-Reach (s)**								**T_{max}**	
	30 ^oC	**50 ^oC**	**100 ^oC**	**200 ^oC**	**300 ^oC**	**400 ^oC**	**500 ^oC**	**600 ^oC**	**Time s**	**Temp ^oC**
Engine Compartment (Fig. B-4-1)										
E1	785	824	863	889	893	896	899	908	949	771
E2	289	323	381	456	471	543	620	644	943	835
E3	251	287	325	415	428	430	433	530	837	860
E4	552	799	N/A	N/A	N/A	N/A	N/A	N/A	967	97
E5			465	629	632	636	638	641	669	735
E6		763	942	N/A	N/A	N/A	N/A	N/A	955	185
E7	453	607	712	819	917	921	952	N/A	959	508

Table B-4-3 continued on the next page

Table B-4-3 continued from the previous page

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time s	Temp °C
E8	333	437	526	557	629	645	653	681	846	923
E9		613	663	772	789	971	N/A	N/A	977	447
E10	79	151	167	174	178	182	188	197	217	640
E11	35	98	116	171	185	195	199	201	924	926
E12	25	135	221	244	249	254	257	260	747	884
E13	1	9	68	284	326	329	333	335	740	835
E14		274	313	327	333	339	347	357	379	870
E15		64	296	341	377	417	463	540	947	771
E16		266	334	381	537	547	556	562	600	939
E17	286	379	506	556	572	586	625	659	896	871
Windshield (Fig. B-4-1)										
W1	233	391	561	950	957	N/A	N/A	N/A	957	318
W2	230	330	374	653	801	807	817	N/A	939	568
W3	276	375	867	913	922	932	934	944	952	726
W4	231	256	296	925	932	940	945	949	951	632
W5	282	400	624	944	N/A	N/A	N/A	N/A	953	266
W6	249	288	617	768	903	929	N/A	N/A	948	451
W7	496	642	873	N/A	N/A	N/A	N/A	N/A	941	194
W8		520	534	552	567	741	N/A	N/A	744	418
W9	561	682	911	N/A	N/A	N/A	N/A	N/A	953	123
W10	441	575	643	732	N/A	N/A	N/A	N/A	845	261
Engine Compartment Hood (Fig. B-4-1)										
H1		175	258	285	303	315	495	543	912	929
H2		223	264	285	295	367	447	592	820	773
H3			247	658	673	686	708	759	959	697
H4			247	283	293	317	440	568	954	774
H5		172	205	210	214	264	269	272	814	885

Table B-4-4. Time-Temperatures Relationships at Various Locations near the Engine Compartment in the 1997 Chevrolet Camaro Burn Test

Location	Time-to-Reach (s)								T_{max}	
	30 °C	50 °C	100 °C	200 °C	300 °C	400 °C	500 °C	600 °C	Time s	Temp °C
HVAC Module (#2, Fig. B-4-2)										
I2	446	553	576	791	882	898	906	922	951	667
I3	627	768	825	N/A	N/A	N/A	N/A	N/A	901	194
I4	604	659	775	817	870	939	942	944	956	777
HVAC Distribution Duct Assembly (#3, Fig. B-4-2)										
I5	622	730	874	921	N/A	N/A	N/A	N/A	961	252
I6	510	537	561	714	715	716	718	744	902	825
I7	617	759	870	938	N/A	N/A	N/A	N/A	945	226
I8	862	892	902	913	N/A	N/A	N/A	N/A	957	251
I9	842	885	897	906	908	910	N/A	N/A	914	468
I10	533	571	580	609	617	628	636	908	915	713
Instrument Panel and its Top Cover (#4, Fig. B-4-2)										
I11	661	876	N/A	N/A	N/A	N/A	N/A	N/A	956	83
I12	392	529	681	746	766	778	780	781	931	728
I13	518	741	927	N/A	N/A	N/A	N/A	N/A	959	119
I14	360	445	603	692	743	794	873	N/A	901	515
I15	415	512	778	980	N/A	N/A	N/A	N/A	995	201
I16	102	138	201	406	470	476	616	718	953	788
I17	335	397	492	606	647	663	693	767	951	719
I18	39	90	140	164	202	259	260	261	954	916
I19	456	493	650	880	937	946	N/A	NA	954	461
I20	399	416	419	425	433	435	438	442	727	897
I21	916	956	N/A	N/A	N/A	N/A	N/A	N/A	962	65
I22	644	810	931	N/A	N/A	N/A	N/A	N/A	1042	111
I23	447	662	862	N/A	N/A	N/A	N/A	N/A	946	193
I24	833	944	N/A	N/A	N/A	N/A	N/A	N/A	955	56
I25	659	799	908	N/A	N/A	N/A	N/A	NA	956	170

Time-temperature profiles for locations in the engine compartment (E locations) and on the hood of the engine (H locations), where flames were present early in the test (temperature reached 600

^oC) are plotted in Fig. B-4-3. Flames were not present at the windshield (W locations), except at locations W3 and W4, until the end of the test.

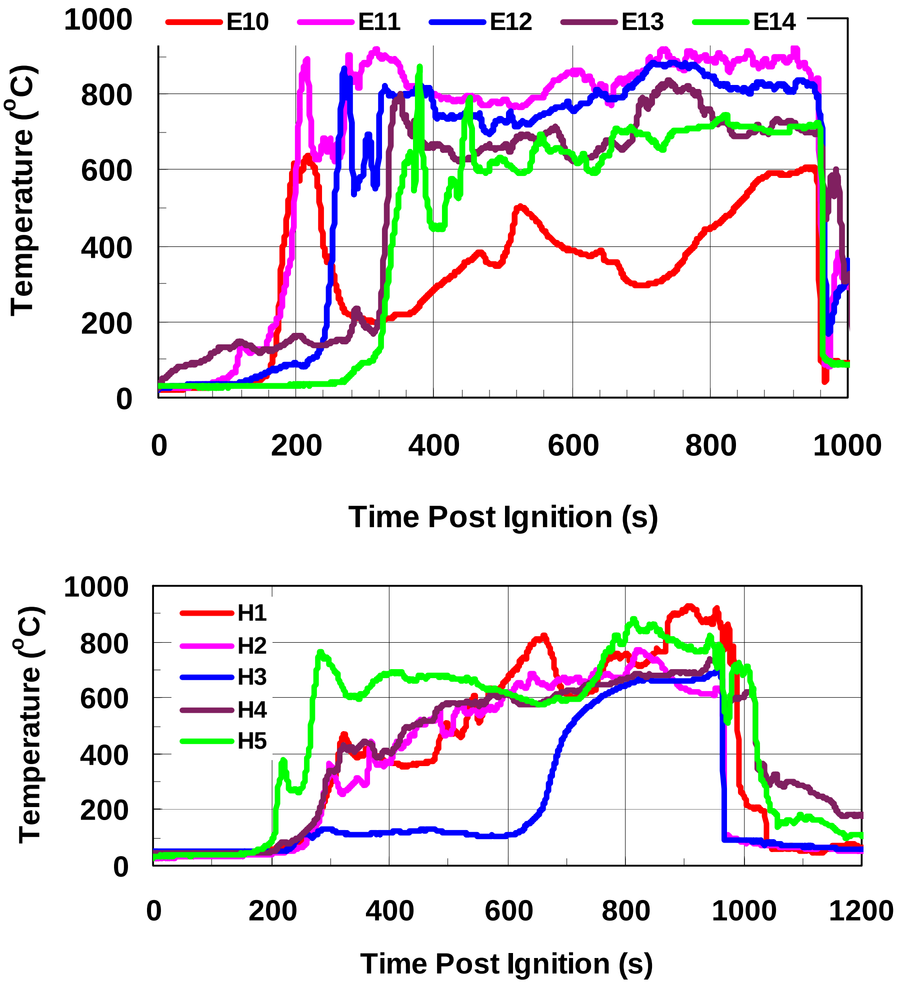


Figure B-4-3. Locations in the engine compartment and on the hood of the engine of the crashed 1997 Chevrolet Camaro, where temperatures exceeded 600 ^OC assumed to be indicative of the presence of the flame.

B-4-2. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

Flame spread into the passenger compartment progressed along two pathways simultaneously: 1) through the windshield and 2) through the HVAC module in the dash panel, both of which were broken in the crash test. Flame spread was observed for the fluids under the vehicle, into the passenger compartment through the windshield and the dash panel.

Flames began to contact the windshield between 180 and 240 seconds post ignition, when flames emerged from the engine compartment along the rear edge of the deformed hood. Increase in the temperature of the exterior surface of the windshield caused softening and stretching of the inner layer of the windshield. As a result, the lower portion of the windshield sagged onto the instrument panel top cover between 665 and 670 seconds post ignition.

Pieces of broken windshield continued to fall into the passenger compartment until the test was ended at about 960 seconds post ignition. The instrument panel, the deployed passenger airbag and the front passenger seat cushion were charred, where pieces of the windshield fell onto these objects.

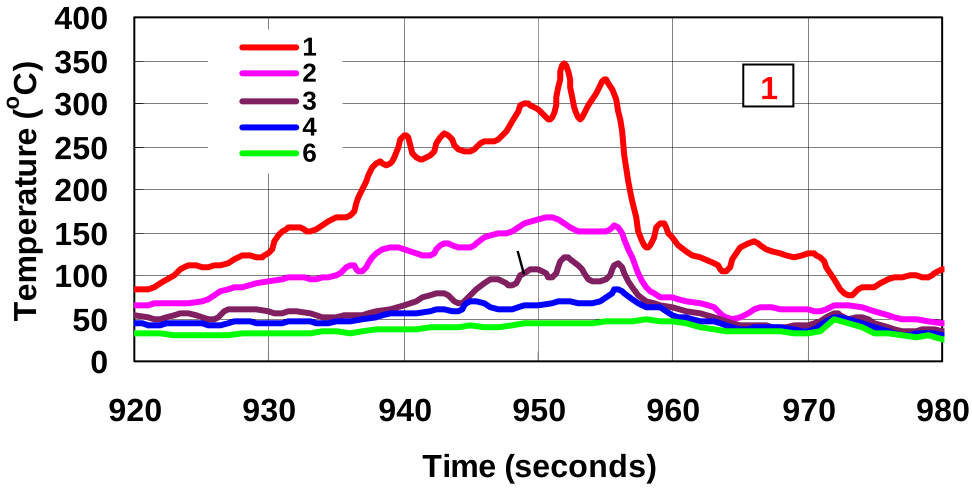
Two areas of the windshield were exposed to flames from 240 through 720 seconds post ignition (locations W3 and W4), which were located along the lower (forward) edge of the windshield below the air inlet screen. The temperature data indicated that between 720 and 780 seconds post ignition, flames spread rearward on the top of the right side of the instrument panel (locations I, #4 in Fig. B-4-2).

B-4-3 CONCENTRATIONS OF PRODUCTS AND RELEASE RATES OF HEAT AND PRODUCTS

The gas temperatures in the passenger compartment were measured by six aspirated thermocouples, arranged inside two 16-in (406-mm) long vertical probes, located over the center of the driver seat and the front passenger seat. Each thermocouple was equidistant, separated by 3-in (76-mm) inside the probes. The top thermocouple (1) in each probe was 0.5-in (13-mm) below the lower surface of the headliner. The measured temperatures are shown in Fig. B-4-4.

The maximum temperature was recorded by the first thermocouple located at 0.5-in (13-mm) below the lower surface of the headliner. The maximum average temperatures over the driver and front passenger seats are 304 and 240 ^{o}C between 949 and 956 seconds post ignition and 255 ^{o}C respectively. The vertical temperature gradients over the driver and front passenger seats are 20 ^{o}C/in and 14 ^{o}C/in respectively.

The concentrations of products in the passenger compartment were measured at a location that was in the middle of the driver's seat and the front passenger seat, 10-in (254-mm) below the headliner. The instruments used for the measurements were FTIR, GC/MS, smoke particulate sampling apparatus, and ion chromatograph (IC). FTIR was used to measure concentrations of CO, CO_2, CH_4, C_2H_4, C_2H_2, HCN, NO, and HCl. GC/MS was used to measure



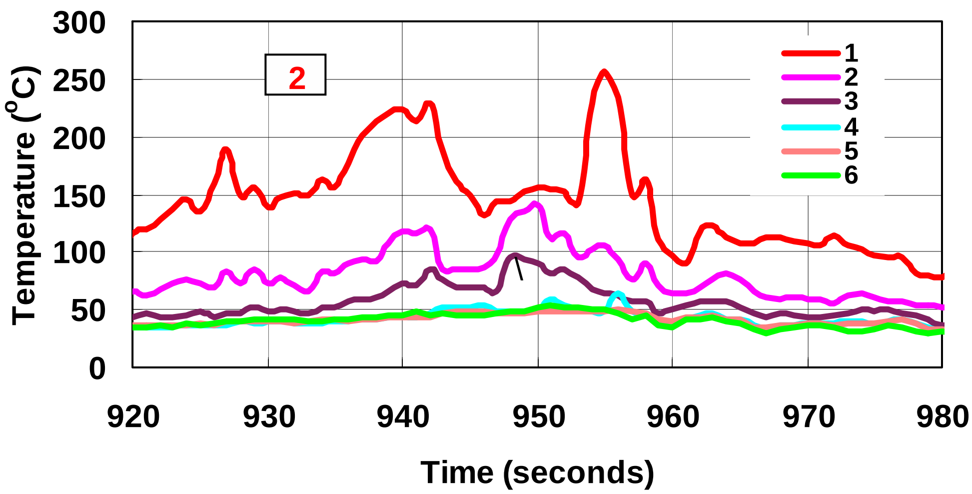
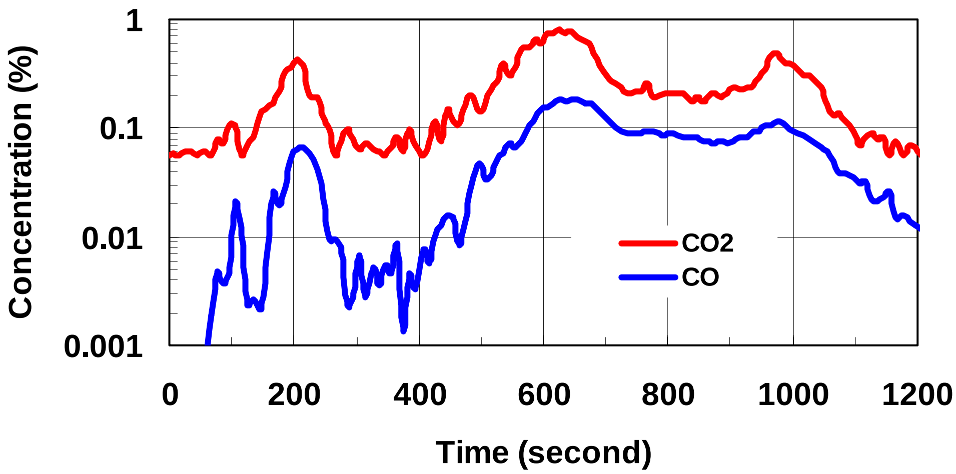


Figure B-4-4. Vertical temperature distribution inside the passenger compartment in burn test for the 1997 Chevrolet Camaro. 1) over the driver seat; 2) over the front passenger seat. Data are taken from Ref. 4.

the relative abundance of higher molecular weight aliphatic and aromatic hydrocarbons (up to C_{15}). Smoke concentration was measured by the smoke particulate sampling apparatus and the inorganic anion concentrations by IC [fluoride (F^-), bicarbonate (HCO_3^-), chloride (Cl^-), nitrite (NO_2^-), bromide (Br^-), hypochlorite ($HClO_3^-$), nitrate (NO_3^-), phosphate (HPO_4^-), sulfate (SO_4^-), and oxalate ($C_2O_4^-$)].

The concentration data are shown in Figs. B-4-5 and B-4-6. Figure B-4-5 show the concentration data for CO_2, CO, methane, ethylene, acetylene, and HCN. Smoke concentration data are listed in Table B-4-5 and plotted in Fig. B-4-6.



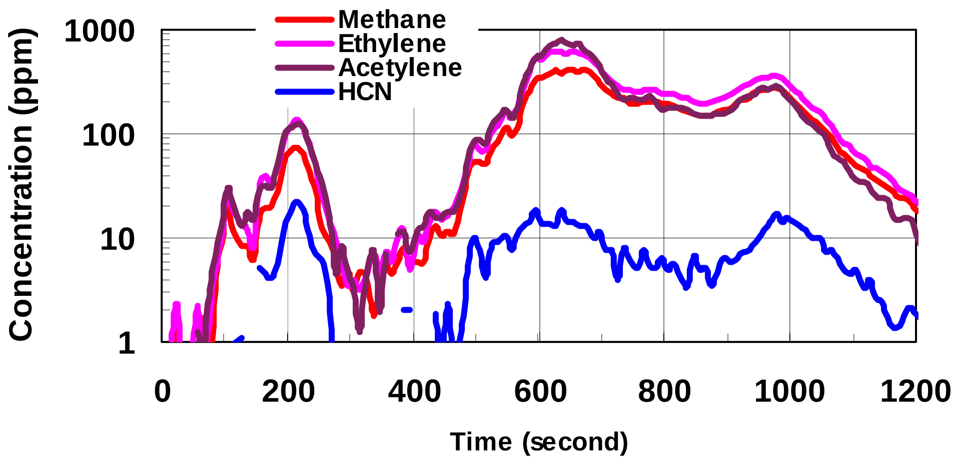


Figure B-4-5. Concentrations of products versus time between the driver and front passenger seats, 10-in below the headliner inside the passenger compartment in the burn test for the 1997 Chevrolet Camaro. Data are taken from Ref. 4.

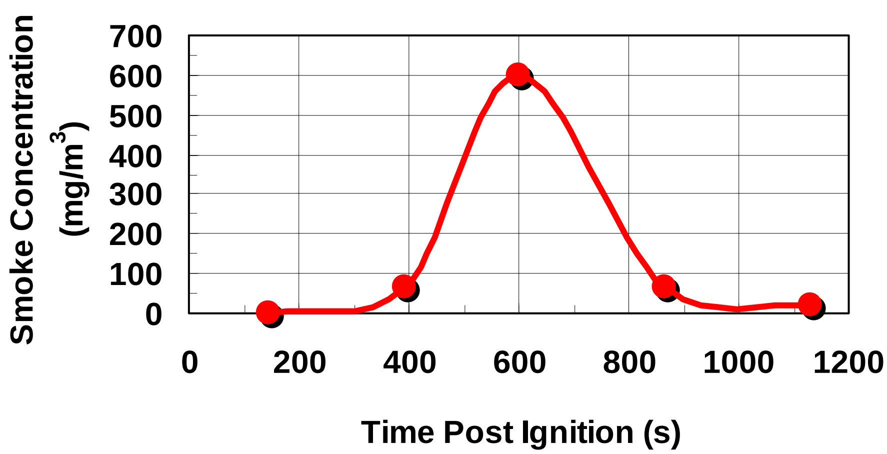


Figure B-4-6. Smoke concentration measured in the passenger compartment, 10-in below the headliner between the driver seat and the front passenger seat. Data are taken from Ref. 4.

Table B-4-5 Smoke Concentration and Composition [4]

Sampling Time (s)	Smoke Concentration (mg/m^3)	% of Smoke Concentration	
		Organic	Inorganic (Cl^-)
0 to 288	0	na	na
288 to 498	67	92.7	7.3
498 to 702	601	97.4	2.6
702 to 1032	67	96.3	3.7
1032 to 1230	22	91.8	8.2

Organic and inorganic components of smoke are also listed in Table B-4-5. The concentrations of the products reach maximum between about 600 and 1000 seconds post ignition.

The inorganic part of smoke consisted of only Cl^- as other anions were not detected. Data for the inorganic part of smoke are included in Table B-4-5. The organic part of smoke included in the table is calculated from the difference between the mass of smoke collected on the filter paper and the mass of Cl^- measured by IC.

The organic part of smoke consists of soot and organic compounds varying in the molecular weight and the boiling points. Only higher molecular weight and boiling point compounds would be collected on the filter paper. The GC/MS data indicate that these compounds are aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure.

The release rates of heat, CO, CO_2 and smoke measured in the fire plume over the burning 1997 Chevrolet Camaro model are shown in Fig. B-4-7. Release rates of chemical heat, CO, CO_2 and smoke increase rapidly from 600 to 950 seconds. Fire suppression was started at 960 seconds post ignition.

Smoke concentration and ratio of CO to CO_2 concentrations in the plume over the burning 1997 Chevrolet Camaro are plotted in Fig. B-4-8. CO to CO_2 concentration ratio versus time measured in the passenger compartment is also included in the figure. The ratio of the CO to CO_2 concentration reached a peak average value of 0.45 between about 700 and 900 seconds post ignition, indicating presence of ventilation controlled combustion conditions in the passenger compartment

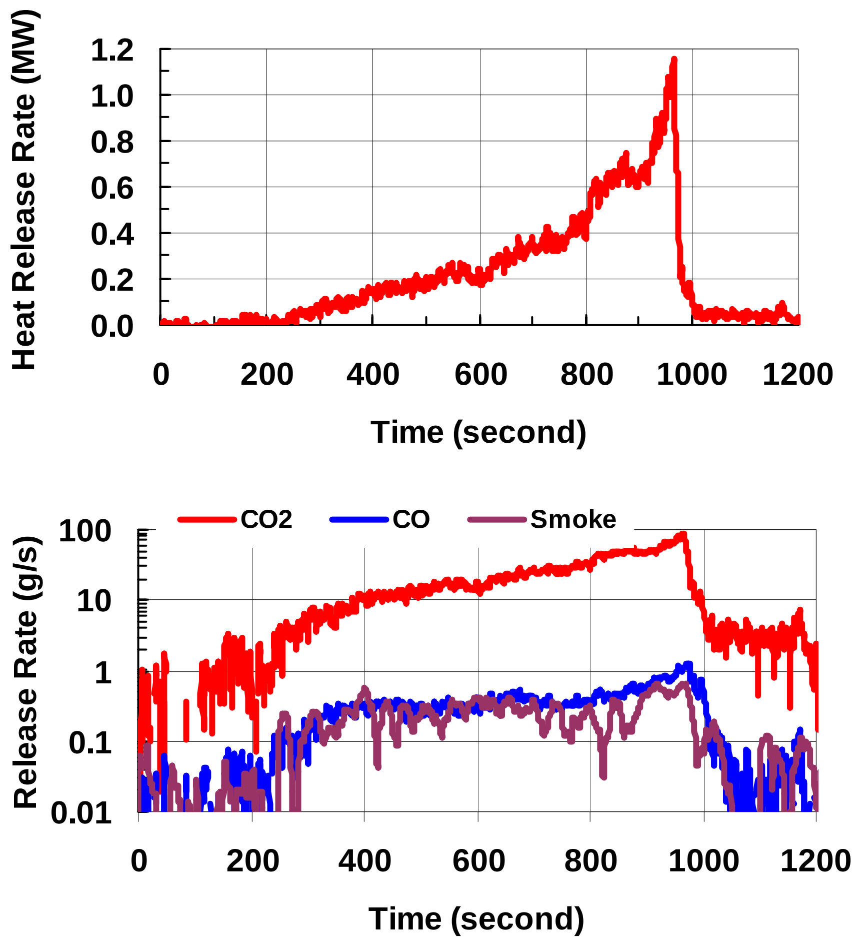
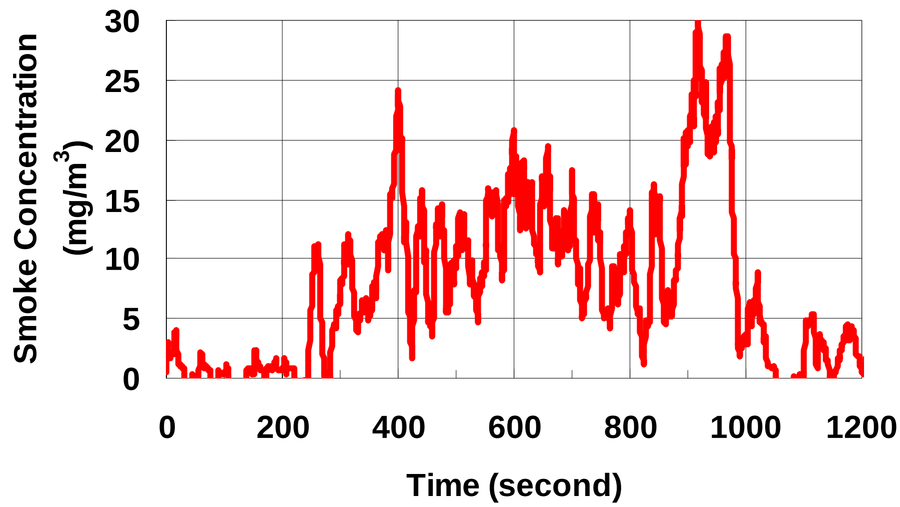


Figure B-4-7. Release rates of heat, CO, CO_2 and smoke in the burn test for the 1997 Chevrolet Camaro. Data are taken from Ref. 4.

The average smoke concentration in the plume, measured optically, is 14 mg/m^3 between 400 to 700 seconds post ignition, reaching a maximum value of about 25 m/m^3 at about 900 seconds post ignition. In the period where smoke concentration is 14 mg/m^3 in the plume, it reached a value of 601 mg/m^3 in the passenger compartment (between 498 and 702 seconds post ignition). The optically measured smoke concentration (Fig. B-4-8) is primarily the soot concentration in smoke, whereas the smoke collected on the quartz fiber filter in the smoke particulate sampling apparatus from the passenger compartment consists of both soot and higher molecular weight organic and inorganic compounds. The GC/MS and IC data for smoke collected on the quartz fiber filter paper from the passenger compartment indicates that a large fraction of smoke in the passenger compartment consists of higher molecular weight aliphatic and aromatic hydrocarbons



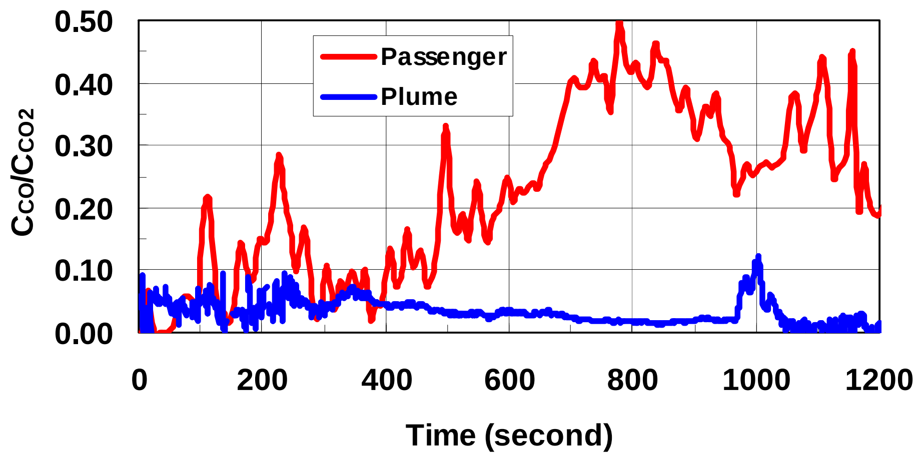


Figure B-4-8. Smoke concentration and CO to CO_2 concentration ratio versus time in the plume of the burning 1997 Chevrolet Camaro. CO to CO_2 concentration ratio versus time measured in the passenger compartment is also included in the figure. Data are taken from Ref. 4.

up to 15 carbon atoms in the chemical structure. Thus, smoke generated in the vehicle burn test consisted of 2.3 % soot (measured optically), 2.6 % Cl^- (measured by IC, Table B-4-5) and 95.1 % of higher molecular and higher boiling point organic compounds.

Figure B-4-8 shows that there are significant differences in the concentration ratios of CO to CO_2 in the fire plume and in the passenger compartment. The ratio in the passenger compartment remained high relative to the ratio in the plume throughout the burning period. The ratio was high in the passenger compartment between 700 and 900 seconds post ignition, indicating that highly under ventilated conditions were present. The ratio in the plume remained low below the limit for the ventilation-controlled condition, except in the beginning of the fire and in the fire suppression stage.

B.5 PROPAGATION OF A REAR-UNDERBODY GASOLINE POOL FIRE IN A 1998 FORD EXPLORER MODEL: TEST #5

The information included in this appendix is taken from the report entitled “Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 9: Propagation of a Rear-Underbody Gasoline Pool Fire in a 1998 Sport Utility Vehicle”, by Jeffrey Santrock, NHTSA Docket Number: 3588; Document Number: NHTSA-1998-3588-188, www.nhtsa.dot.gov [5].

The fire propagation test was performed on June 9, 1998 at FM Global using a 1998 Ford Explorer that was crashed at the GM Proving Ground on December 17, 1997. In the crash test, the vehicle was stationary and was struck in the left rear (driver’s side) by a moving barrier. The fuel system of the vehicle did not leak at any time during the crash, but leaked during the static roll test performed after the crash test. Following damages to the vehicle were noted:

- Left and right sides were crushed;
- Left and right rear quarter glass panes and rear lift gate were broken;
- The left and right quarter interior trim finishing panels were broken. The left panel was dislodged;
- The rear compartment floor pan panel and rear section of the roof were displaced upward relative to the front of the vehicle;

Potential fire paths into the occupant compartment observed during inspection of the crashed test vehicle included: 1) the window-openings in the left and right quarter panels, 2) the window opening in the rear liftgate, gaps around the left rear door and door frame due to vehicle structure deformation in the crash test, and 3) four seam openings around the rear compartment floor panel.

For the fire propagation test, all the doors and windows of the crashed vehicle were closed, except those that were damaged or broken in the crash test. An artificial method of creating an underbody gasoline pool was used in the test to start the fire. Gasoline was pumped continuously from an external reservoir at a rate of about 750 ml/min onto the ground under the rear of the test vehicle during the test (test duration about 175 seconds). The gasoline was ignited with a propane torch and allowed to burn until flames were observed spreading across the headlining panel in the test vehicle. The location of the gasoline outlet is shown in Fig. B-5-1 along with crash induced seam openings, floor pan plugs, fuel tank, the spare tire/wheel, rear axel and rear tires and rear tires/wheels, and exhaust system components. Locations of various thermocouples used to monitor temperatures and flame spread during the fire test are shown in Figs. B-5-2 and B-5-3, where sketches are taken from Ref. 5.

In the fire propagation test, flames entered the passenger compartment: 1) through the window opening in the left quarter panel, 2) through the seam openings between the rear compartment floor panel and the quarter panel behind the left rear wheelhouse and the quarter panel in the right rear corner of the vehicle and 3) through a gap between the bottom of the rear lift gate and the lift gate sill on the right side of the vehicle. Fire suppression was started at about 170 seconds after the gasoline was ignited. Summary of fire development during the vehicle burn test with is listed in Table B-5-1.

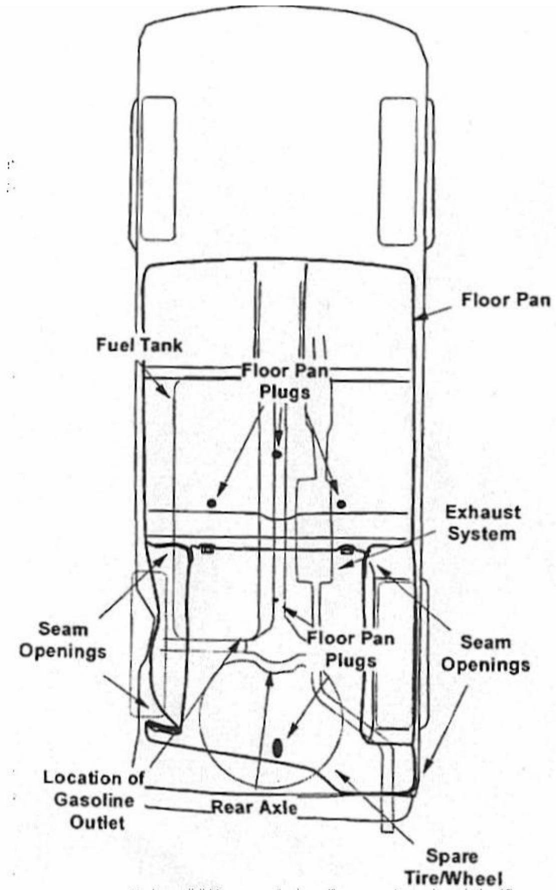


Figure B-5-1. Top view of the floor pan of the vehicle. Figure is taken from Ref. 5.

Table B-5-1. Summary of Fire Development in the Test [5]

Time (sec)	Event
0	Ignition of the gasoline pool under the vehicle by a propane torch
10-15	Flames entered the left rear wheelhouse
10-20	Flames entered the right rear wheelhouse
30-60	Right rear tire started to burn
90-100	Edge of the left interior quarter trim panel started to burn
120	Spare tire blew out
120-125	Flames entered rear compartment through the seam opening in the rear left corner of the vehicle
150-160	Fire plume started to spread along rear section of the headlining panel
157	Rear left tire blew-out
170	Fire suppression began

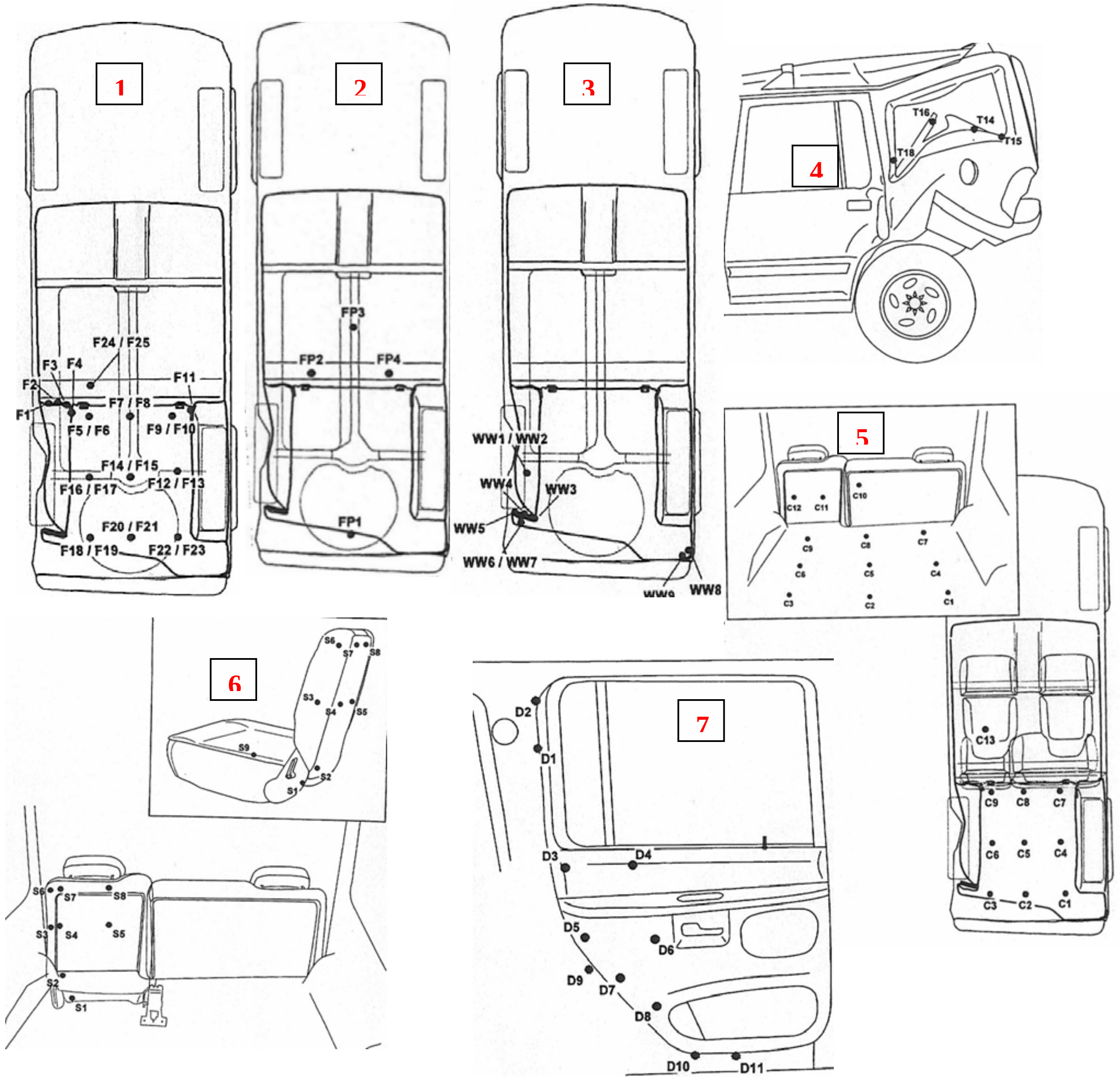


Figure B-5-2. Thermocouple locations. 1) **F**: in seam openings, 1-cm blow and on the upper surface of the floor pan; 2) **FP**: on the floor pan drain hole plugs; 3) **W**: seam and 1-cm below and on the surface of the wheelhouse; 4) **T**: on the left quarter trim panel; 5) **C**: on the upper surface of the carpet; 6) **S**: on the left rear seat; 7) **D**: on the left rear door. Sketches are taken from Ref. 5.

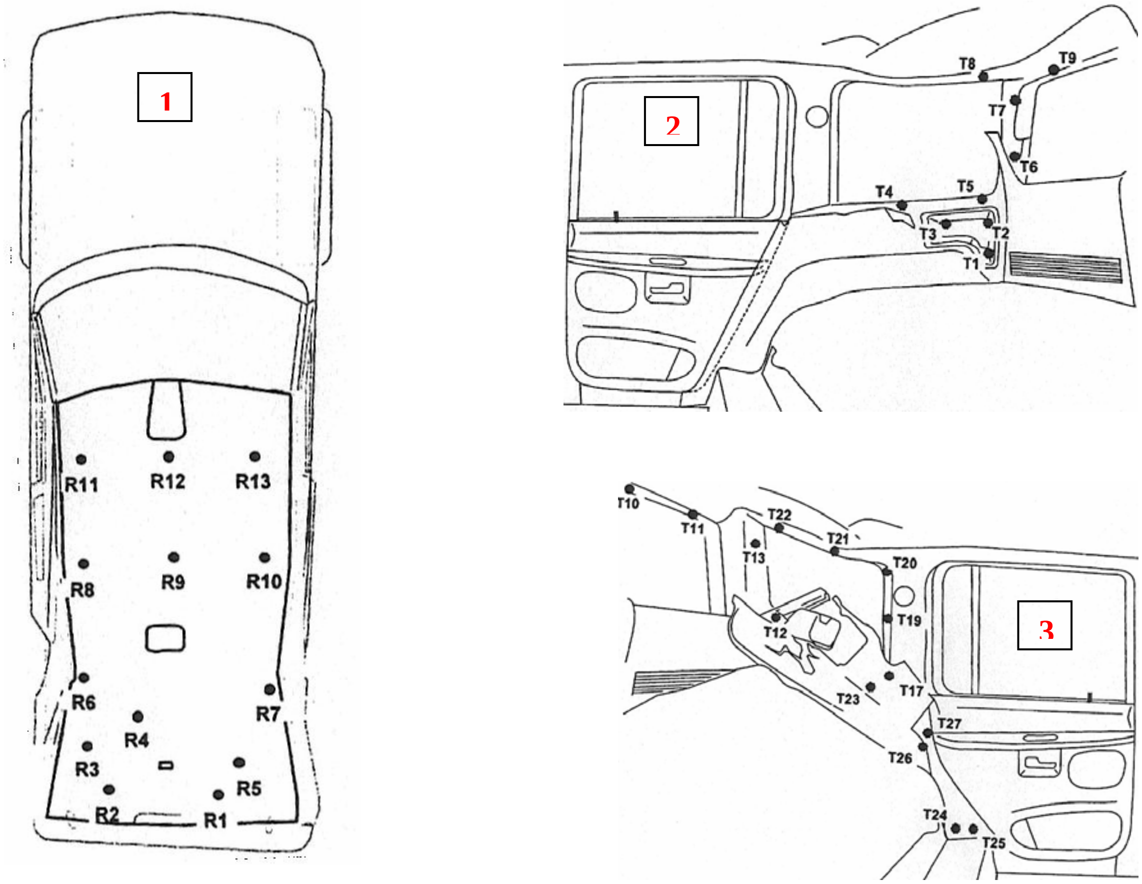


Figure B-5-3. Thermocouple locations. 1) **R**: 1-cm below the headlining panel; 2) **T1 to 9**: on the right quarter trim panel and rear garnish molding panel; 3) **T10 to 27**: on the left quarter trim and rear garnish moldings panel. Sketches are taken from Ref. 5.

B-5-1. IGNITION AND UNDERBODY GASOLINE POOL FIRE

In the test, gasoline was allowed to flow at a rate of about 750 ml/min onto the cement board surface under the vehicle (Fig. B-5-1) for about 30 seconds. The dripping gasoline spread out radially in an unsymmetrical fashion. A stream of the liquid gasoline flowed toward the right rear wheel forming an elongated pool under the rear axle of the vehicle. A propane torch was used to ignite the gasoline vapors at about 30 seconds after the start of the gasoline flow. Ignition occurred near the rear axle differential housing (Fig. B-5-1). Blue flames spread concentrically from the point of ignition through gasoline vapor retained in the bottom of the fluid containment pan.

Flames from the gasoline pool were about 70 to 90 cm high during the first few seconds after ignition. These flames contacted rear axle, spare tire, exhaust pipe, floor pan to the right and left of the spare tire and the vapor recover canister to the left of the spare tire. Flames spread laterally outward as they encountered these objects and flame height increased over the next 120 seconds. Temperatures were monitored at the following locations on the floor pan, drain hole plugs and wheelhouse (Fig. B-5-2):

1) *Floor Pan (#1)*: thermocouples F1 through F4 were located in a seam opening at the front of the left rear wheelhouse. Thermocouple F11 was located in a seam opening at the front of the right rear wheelhouse. Thermocouples F5, F7, F9, F12, F14, F16, F18, F20, F22 and F24 were located about 1-cm below the lower surface of the floor pan. Thermocouples F6, F8, F10, F13, F15, F17, F19, F21, F23, and F25 were attached to the upper surface of the floor pan with thermally conducting ceramic cement.
2) *Floor Pan Drain Hole Plugs* (*#2*): thermocouples FP1 through FP4;
3) *Wheelhouse (#3)*: thermocouples WW1 and WW6 were located about 1-cm below the lower surface of the left rear wheelhouse panel. Thermocouples WW2 and WW7 were attached to the upper surface of the left rear wheelhouse with thermally conducting ceramic cement. Thermocouples WW3, WW4, and WW5 were located in a seam opening at the rear of the left rear wheelhouse. Thermocouples WW8 and WW9 were located in a seam opening at the rear of the right rear wheelhouse.

The following information was derived from the thermocouple data measured during the test:

- *Seam Opening at the Front of the Left and Right Rear Wheelhouse (locations F1 through F4 and F11)*: temperatures increased immediately at ignition, but remained below 600 ^{o}C, indicating absence of a flame at these locations. Maximum temperatures between 300 to 400 ^{o}C at locations F1 to F4 and about 200 ^{o}C at location F11 in about 150 seconds post ignition were recorded;
- *1-cm Below the Lower Surface of the Floor Pan (locations F5, F7, F9, F12, F14, F16, F18, F20, F22 and F24*): temperatures at these locations increased instantaneously at ignition, but remained below 600 ^{o}C, indicating absence of a flame at these locations;
- *Upper Surface of the Floor Pan* (*locations F6, F8, F10, F13, F15, F17, F19, F21, F23, and F25*): temperatures at these locations were lower and increased at a rate slower than locations 1-cm below the pan. The temperatures remained below 600 ^{o}C, indicating absence of a flame at these locations;

- *Drain Hole Plugs (locations FP1 to FP4)*: temperatures at these locations increased slowly after ignition, but remained significantly lower than 600 ^oC (< 400 ^oC at FP1 and < 50 ^oC at FP2 to FP4);
- *1-cm Below the Lower Surface of the Wheelhouse (locations WW1 and WW6*): temperature at location WW1 increased instantaneously at ignition, exceeded 600 ^oC (maximum 820 ^oC), and remained at that level until about 175 seconds post ignition, indicating sustained combustion and presence of the flame. Temperature at location WW6 also increased instantaneously at ignition but did not exceed 600 ^oC until about 150 seconds indicative of the presence of the flame;
- *Upper Surface of the Left Rear Wheelhouse (locations WW2 and WW7*): temperatures at these locations were lower and increased at a slower rate than then locations 1-cm below the lower surface of the wheelhouse. The maximum temperature at location WW2 was about 380 ^oC reaching at about 175 seconds post ignition. The maximum temperature at location WW7 was about 575 ^oC reaching at about 175 seconds post ignition
- *Seam Opening at the Rear of the Left and Right Rear Wheelhouse (locations WW3, WW4, WW5 and WW9)*: temperature at location WW3 increased instantaneously at ignition, exceeded 600 ^oC (maximum 790 ^oC at 160 s), and remained at that level until about 225 seconds post ignition, indicating sustained combustion and presence of the flame. Temperature at location WW4 and WW5 also increased instantaneously at ignition but did not exceed 600 ^oC (maximum about 650 and 715 ^oC) until about 165 s indicative of the presence of the flame.

B-5-2. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

Figures B-5-2 and B-5-3 show the locations where temperatures were measured for the flame spread into the passenger compartment along with the use of the video recording. Flame spread into the passenger compartment progressed along a number of pathways simultaneously:

1. In the left side of the forward vertical and lower horizontal edges of the quarter trim panel around the quarter glass opening by their ignition by the fire plume rising along the exterior of the quarter panel;
2. Into rear compartment through a crash induced seam opening of the left wheelhouse;

3. To the right quarter trim panel through a crash induced seam opening at the rear right corner of the floor pan;
4. In the rear right side through the ignition of the lower edge of the quarter trim panel at the base of the wheelhouse by heat conducted across the floor pan;
5. Into the rear compartment through the bottom of the right lift gate.

1. Flame Spread through a Seam Opening in the Wheelhouse, Quarter Glass Opening, and Ignition of Quarter Trim Panel on Left Side of the Vehicle

The test data indicate that flames spread into the rear compartment through a crash induced seam opening between the rear-compartment floor panel and left wheelhouse panel (#3, Fig. B-5-2) between about 140 and 160 seconds (at locations WW3, WW4, and WW5). Heated gases started to enter the seam opening within a few seconds after ignition. The maximum temperatures reached at these locations were 790, 650, and 715 ^{o}C respectively between 160 and 165 seconds. Flames were observed above the left rear wheelhouse at this time.

Temperatures recorded at various locations on the left quarter trim panel around the quarter glass opening (#4, Fig. B-5-2) indicate that sections of the trim panel had ignited before flames entered the rear compartment through the seam opening in the left rear wheelhouse. Thermocouples T16 and T18 increased to ≥ 650 ^{o}C within 130 to 155 seconds post ignition. Temperatures at T14 and T15 remained below 450 ^{o}C throughout the test. Thermocouples T21 and T22 (#3, Fig. B-5-3) increased slowly to > 600 ^{o}C between 160 and 170 seconds post ignition.

2. Flame Spread into the Passenger Compartment through a Seam Opening in the Right Rear Wheelhouse

Thermocouple WW9 (#3, Fig. B-5-2) data indicated that the temperature increased from ambient at the time of ignition to a maximum of 597 ^{o}C at 147 seconds post ignition and decreased to 225 ^{o}C at 200 seconds post ignition. This data indicate that heated gases started to flow into this steam opening during the first few seconds after ignition and continued to flow into the seam opening until the test was ended and the fire was extinguished.

The estimated temperature on the lower inner surface of the storage bin increased to > 700 ^{o}C by 140 seconds post ignition, decreased to < 600 ^{o}C by 160 seconds and < 400 ^{o}C by 180 seconds post ignition. Thus, presence of flame is indicated at this location (space between the trim panel and the right quarter panel for a 20 to 30 second period between 120 and 150 seconds post ignition).

3. Flame Spread into the Passenger Compartment through the Liftgate

A fire path under the liftgate was discovered during the inspection of the test vehicle after the test. Video stills from cameras showed that at 170 seconds post ignition there was a fire plume on the exterior surface of the right side of the liftgate in the area where the scuff plate and rear compartment floor carpet had burned.

4. Flame Spread Through the Rear Compartment Floor Drain Hole Plugs and Through Heat conduction

The floor panel in the rear compartment of the test vehicle contained two drain holes located along the longitudinal centerline of the vehicle and a clearance hole drilled in the floor panel for a heat flux transducer (Fig. B-5-1). The holes were covered with ethylene-propylene-butadiene rubber plugs. Inspection of the vehicle after the test showed that sections of the floor carpet and pad in the rear and forward sections of the compartment had burned and charred during the test, temperature reached a maximum of > 500 ^{o}C, and the flames had burned through both the drain hole plugs.

The floor carpet on the left side of the rear compartment had burned and melted, where it was adjacent to the left rear wheelhouse. A section of the carpet that was under the right side of the scuff plate, where flames spread under the liftgate, had also burned and melted.

5. Flame Spread on the Headliner

Thermocouple data (R in #1 in Fig. B-5-3) started to increase within 5 seconds post ignition. The data analysis indicated that the heated gases started to accumulate along the roof trim panel in the rear compartment by 25 seconds post ignition. Temperatures above the broken left quarter trim panel were > 150 ^{o}C by 100 seconds and > 200 ^{o}C by 120 seconds post ignition.

Flames were first observed in the space above the left rear quarter wheelhouse starting at about 125 seconds post ignition (about the time the spare tire blew out). Data analysis indicated that flames first contacted the headliner in the rear left corner between 150 and 157 seconds post ignition. The flames spread along the headliner to the right side of the rear compartment and forward to above the rear seats between 157 and 170 seconds post ignition.

The fabrics covering the lower surface of the headliner had burned and charred in the areas where the maximum temperature was greater than about 500 ^{o}C.

B-5-3. CONCENTRATION OF PRODUCTS AND RELEASE RATES OF HEAT AND PRODUCTS

Due to malfunction of the aspirated thermocouples, temperature in the passenger compartment was not measured. The concentrations of the products in the passenger compartment were measured at a location that was in the middle of the driver's seat and the front passenger seat, 10-in below the headliner. The instruments used for the measurements were FTIR, GC/MS, smoke particulate sampling apparatus and ion chromatograph (IC). FTIR was used to measure concentrations of CO, CO_2, CH_4, C_2H_4, C_2H_2, HCN, NO, and HCl. GC/MS was used to measure the relative abundance of higher molecular weight aliphatic and aromatic hydrocarbons (up to C_{15}). Smoke concentration was derived from the measured smoke mass by the particulate sampling apparatus. The concentrations of the inorganic anions measured by IC included fluoride (F^-), bicarbonate (HCO_3^-), chloride (Cl^-), nitrite (NO_2^-), bromide (Br^-), hypochlorite ($HClO_3^-$), nitrate (NO_3^-), phosphate (HPO_4^-), sulfate (SO_4^-), and oxalate ($C_2O_4^-$).

The smoke concentration and composition are listed in Table B-5-2 and plotted in Fig. B-5-4. Smoke is a mixture of soot and organic and inorganic compounds. In Table B-5-2, data for the inorganic part of smoke are from the IC analysis. The organic part is the difference between the mass of smoke on the filter and the mass of inorganic anions from IC.

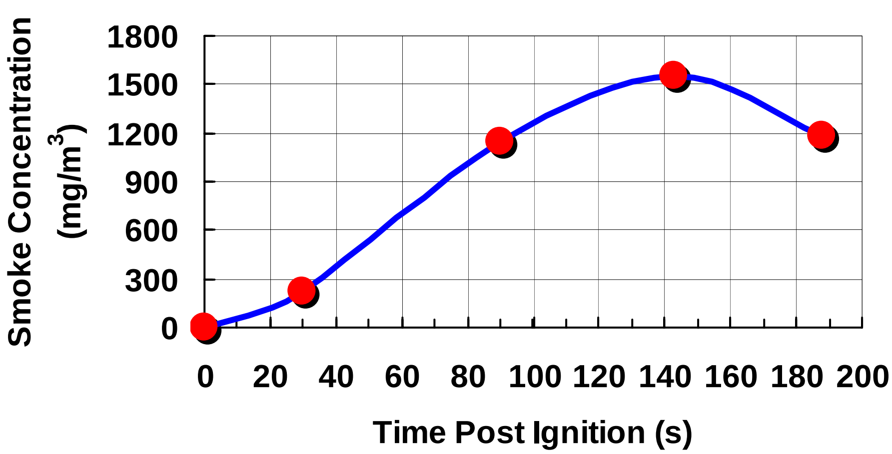


Figure B-5-4. Smoke concentration measured in the passenger compartment, 10-in below the headliner between the driver seat and the front passenger seat. Data are taken from Ref. 5.

The GC/MS analysis indicates that the organic part of smoke consists of aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure.

Table B-5-2 Smoke Concentration and Composition [5]

Sampling Time (s)	Smoke Concentration (mg/m^3)	% of Smoke Concentration			
		Organic	Inorganic		
			Cl^-	HPO_4^-	SO_4^-
0	0	0	0	0	0
0 to 60	220	91.5	4.4	1.8	2.3
60 to 120	1141	96.4	3.4	0.1	0.2
120 to 165	1548	95.0	4.6	0.2	0.2
165 to 210	1182	90.6	8.1	0.6	0.7

Data in Table B-5-2 show that organic compounds are the dominant part of the smoke in the passenger compartment. The smoke concentration reaches a peak value of 1548 mg/m^3 between 120 to 165 seconds post ignition, a period of rapid-fire growth in the passenger compartment, just before the start of fire suppression at 170 seconds post ignition.

The peak concentration data of the compounds measured in the passenger compartment are listed in Table B-5-3. Concentrations of products measured after the fire suppression was started are not taken into consideration. The ratio of CO to CO_2 concentration ratio (0.063) indicates that ventilation-controlled combustion conditions were present in the passenger compartment during the vehicle burn test.

Table B-5-3. Peak Concentrations of Products in the Passenger Compartment just before Untenable/Flashover Conditions

Product	Maximum Concentration
CO	0.25 %
CO_2	4.0 %
CH_4	400 ppm
C_2H_4	800 ppm
C_2H_2	500 ppm
HCN	None
NO	10 ppm
Smoke	1548 mg/m^3

Release rates of heat, CO, CO_2 and smoke measured in the fire plume over the burning 1997 Ford Explorer are shown in Fig. B-5-5. The data show that fire growth started to become faster after about 120 seconds. Convective and radiative components of the heat release rates were comparable.

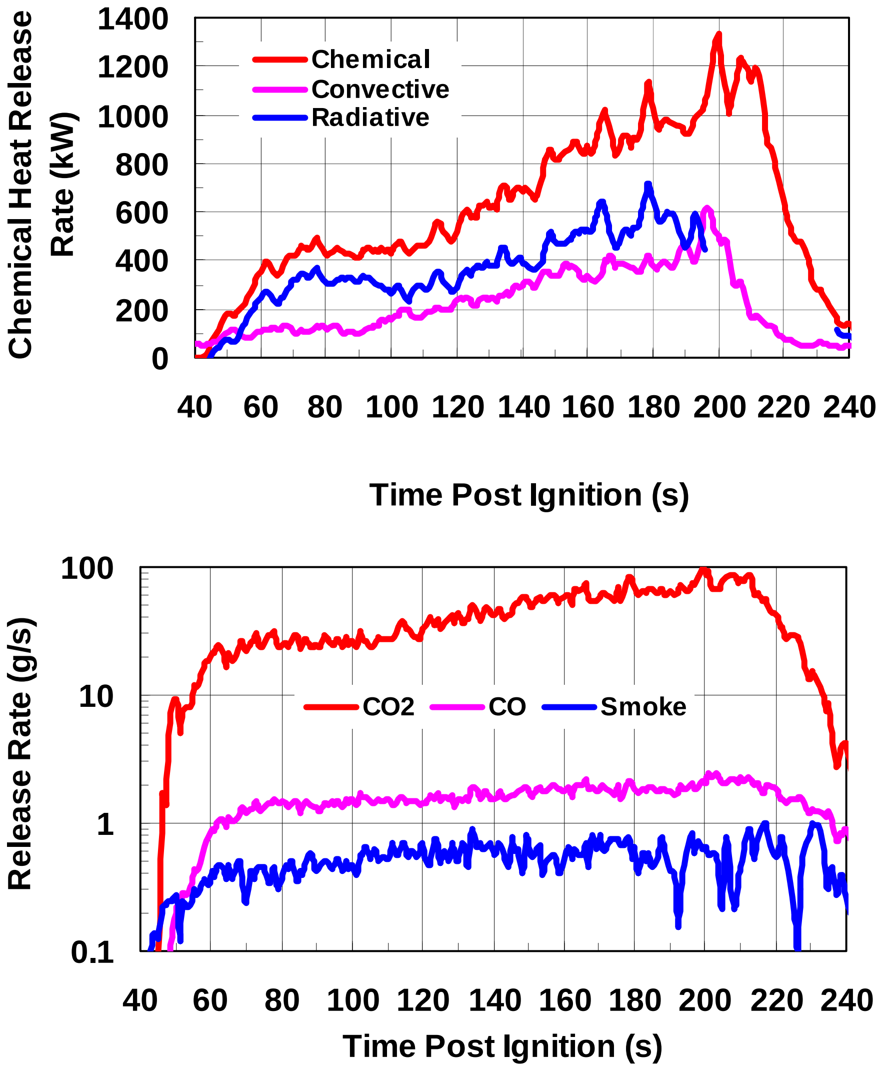


Figure B-5-5. Release rates of heat, CO, CO_2 and smoke in the burn test for the 1997 Ford Explorer. Data are taken from Ref. 5.

The smoke concentration and ratio of the CO to CO_2 concentrations are plotted in Fig. B-5-6. The average smoke concentration in the plume, measured optically, is 20 mg/m^3, whereas in the passenger compartment it reached a maximum of 1548 mg/m^3 (Table B-5-2 and Fig. B-5-4).

The optically measured smoke concentration is primarily due to soot, whereas the smoke collected on the quartz fiber filter consists of both soot and higher molecular weight organic and inorganic compounds as listed in Table B-5-2. It thus appears that smoke in the passenger compartment is significantly different than smoke in the plume of burning 1997 Ford Explorer. It appears that most of the higher molecular weight organic compounds in smoke in the passenger compartment are burned in the plume. However, the inorganic components of smoke, consisting of 3.4 to 8.1 % of Cl^- , 0.2 to 1.8 % HPO_4^- and 0.2 to 2.3 % SO_4^- would not be different in the passenger compartment and in the plume, except if external components of the vehicle became significant contributors.

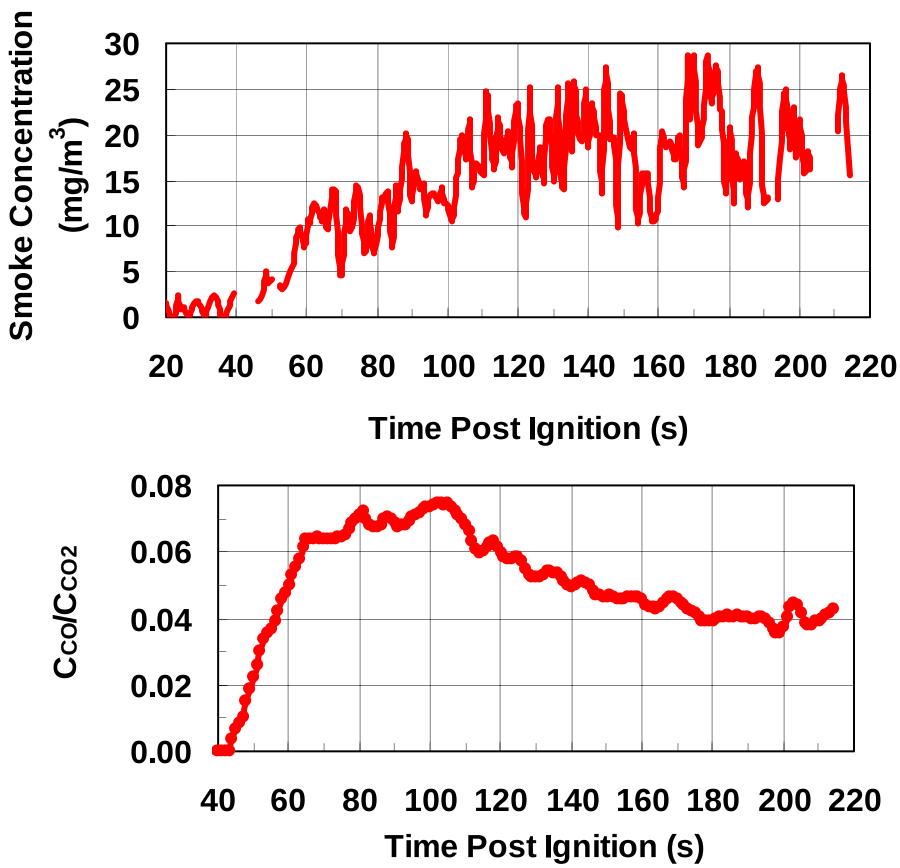


Figure B-5-6. Smoke concentration and CO to CO_2 concentration ratio versus time in the plume of the burning 1997 Ford Explorer. Data are taken from Ref. 5.

Figure B-5-6 shows that CO to CO_2 concentration ratio in the fire plume reached a maximum value of 0.036 between 80 and 100 seconds post ignition, which is slightly lower than the ratio of 0.063 measured in the passenger compartment. The ratio is indicative of ventilation-controlled combustion, i.e., presence of flames in the neighborhood of the sampling probes in the passenger compartment and partial quenching of combustion in the sampling duct of the Fire Products Collector.

B.6 PROPAGATION OF A MID-UNDERBODY GASOLINE POOL FIRE IN A 1998 MODEL OF FORD EXPLORER: TEST #6

The information included in this appendix is taken from the report entitled “Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 10: Propagation of a Mid-Underbody Gasoline Pool Fire in a 1998 Sport Utility Vehicle”, by Jeffrey Santrock, NHTSA Docket Number: 3588, Document Number: NHTSA-1998-3588-189, www.nhtsa.dot.gov [6].

The fire propagation test was performed on June 11, 1998 at FM Global using a 1998 Ford Explorer model that was crashed at the GM Proving Ground on July 30, 1997. In the crash test, the vehicle was stationary and was struck in the left front (driver’s side) by a moving barrier. The fuel tank in the vehicle was punctured by the drive shaft during the crash test. Fluid was observed leaking from the fuel tank onto the ground under the vehicle after impact. No fire was observed during the crash test nor was evidence of fire present in the test vehicle detected during the inspection of the vehicle after the test. Following damages to the vehicle were noted:

- Left and right sides were crushed;
- Both glass outer layers of the windshield were broken, but windshield remained attached to the vehicle;
- The driver’s side door window remained opened because of the crash-induced deformation of the door;
- The hood outer panel separated from the hood inner panel;
- The front compartment floor pan and forward section of the roof were displaced and deformed;
- The fuel tank was punctured by the universal joint connecting the rear propulsion shaft to the transfer case

Potential fire paths into the passenger compartment for an underbody gasoline fire with gasoline leaking from the hole in the front inboard corner of the fuel tank, identified during inspection of the crashed vehicle included:

- Electrical pass-through under the left front seat;
- Crashed induced openings around the deformed shift lever pass–through cover plate;
- Drain hole plugs in the floor panel;
- Crashed induced gaps between the bottoms of the left doors and doorsills.

For the fire propagation test, all the doors and windows of the crashed vehicle were closed, except those that were damaged or broken in the crash test. In the test, gasoline was allowed to flow at a rate of about 350 ml/min into the fuel tank skid plate and onto the cement board surface under the vehicle for about 30 seconds. A propane torch was used to ignite the gasoline vapors at about 28 seconds after the start of the gasoline flow. The diameter of the gasoline pool fire on the cement board was estimated to be about 15 inches from the time of ignition through 30 seconds post ignition. The flames from the gasoline pool fire were observed to contact and spread along the lower surface of the fuel tank skid plate. The diameter of the gasoline pool fire and the flame height decreased between 30 and 243 seconds post ignition. Thus, the rate of consumption of gasoline in the fuel tank skid plate was higher than the flow rate of liquid gasoline onto the skid plate. By 210 seconds post ignition, the size of the gasoline pool fire decreased substantially.

Smoke and heated gases from the gasoline pool fire under the vehicle flowed into and out of the engine compartment along the rear and left edges of the deformed hood. Flames were not visible in the engine compartment at any time during the test. The maximum temperature in the upper part of the engine compartment of the vehicle during the test was between about 200 and 250 ^{o}C.

In the test, flames entered the passenger compartment through drain holes and electrical pass-through openings in the floor panel. Fire suppression began at about 250 seconds after the gasoline was ignited. Summary of fire development during the vehicle burn test with is listed in Table B-6-1.

Table B-6-1. Summary of Fire Development in the Test [6]

Time (sec)	Event
0	Ignition of gasoline under the vehicle by a propane torch
10	Flames enter the passenger compartment through the electrical pass-through opening in the floor panel under the left front seat
75	Flames burn through grommet in the second electrical pass-through opening in the floor panel under the left front seat
130	Flames burn through floor carpet above the electrical-through opening in the floor panel under the left front seat
205	Flames burn through floor carpet above the second electrical pass-through opening in the floor panel under the left front seat
235-250	Flames burn through the top of the left front seat cushion
250-260	End of the test and beginning of fire suppression

B-6-1. TEMPERATURES MEASURED AT VARIOUS LOCATIONS

Thermocouple locations used to monitor temperatures and flame spread behavior are shown in Figs. B-6-1 and B-6-2. In Fig.B-6-1 thermocouples locations are:

1) Carpet in the Front Seat (#1)

a) C1 and C2 on the upper surface of the carpet above the electrical pass-through in the floor pan under the driver's seat. Temperature exceeded 600 ^{o}C at these locations, indicating the presence of flame;

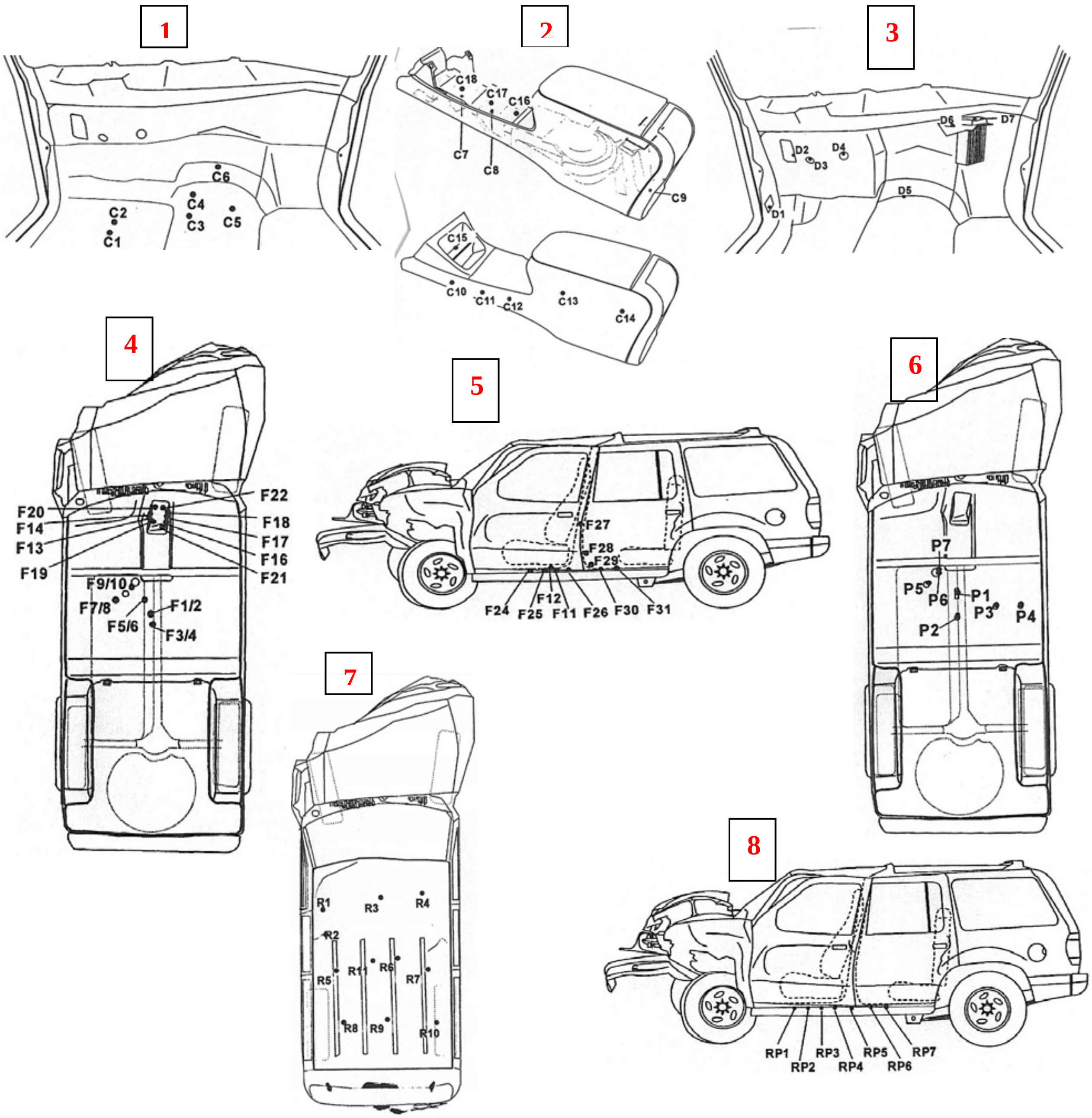


Figure B-6-1. Thermocouple locations. 1) **C1 to C6**: on the carpet in the front; 2) **C7 to C18**: on the center console; 3) **D**: front dash panel; 4) **F1 to F10 and F13 to F22**: on the floor panel; 5) **F11, F12, and F24 to F31**: near driver's door; 6) **P**: on the drain hole plugs and electrical pass-through openings in the floor panel; 7) **R**: on the roof; 8) on the rocker panel. Sketches are taken from Ref. 6.

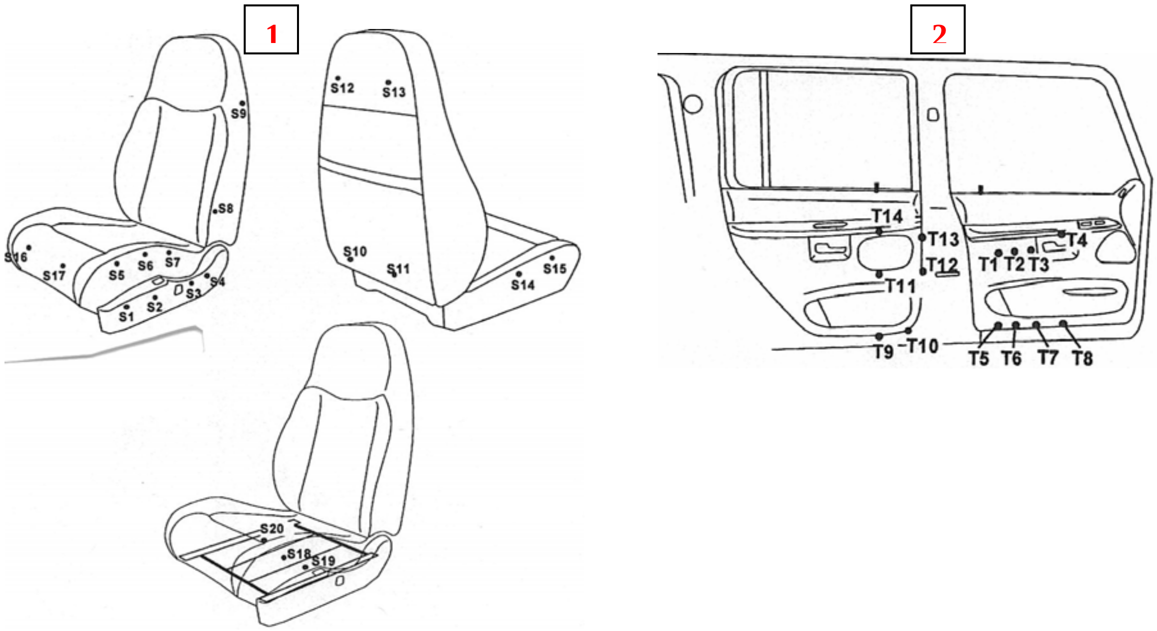


Figure B-6-2. Thermocouple locations. 1) **S**: on the left front seat; 2) **T**: on a section of the left front and rear door. Sketches are taken from Ref. 6.

b) C3, C4, C5 and C6 on the upper surface of the carpet over the front of drive line tunnel. During the active burning period, temperatures were low at these locations, indicating absence of flame but presence of hot gases;

2) Center Console (#2)

a) C7, C8 and C9: on the bottom surface of the heater duct and about 1-cm from the top surface of the heater duct for rear seat. During the active burning period, temperatures were low at these locations, indicating absence of flame but presence of hot gases;

b) C16, C17, and C18: inside and about 1 cm from the top surface heater duct for rear seat. During the active burning period, temperatures were low at these locations, indicating absence of flame but presence of hot gases;

c) C10, C11, C12, C13, and C14: on the exterior surface of the left side of the center console. During the active burning period, temperatures were low at these locations, indicating absence of flame but presence of hot gases;

d) C15: inside the center console centered laterally above the rear heater duct and behind the accessory tray. During the active burning period, temperatures were low at these locations, indicating absence of flame but presence of hot gases;

3) Front Dash Panel (#3)

a) D1: adjacent to an electrical pass-through inside the driver's side hinge pillar. Temperature was close to ambient at this location;

b) D3: at the transmission shift cable pass-through. Temperature was low at this location, indicating absence of a flame;

c) D4: at the steering column pass-through. Temperature was low at this location, indicating absence of a flame;

d) D5: at a seam opening on top of the driveline tunnel. Maximum temperature reached was about 200 ^{o}C, indicating absence of a flame but presence of hot gases;

e) D6: behind the heater core inside the HVAC module. Maximum temperature reached was about 100 ^{o}C, indicating absence of a flame but presence of hot gases;

f) D7: inside the HVAC module behind the upper right corner of the heater core. Maximum temperature reached was about 100 ^{o}C, indicating absence of a flame but presence of hot gases;

4) Floor Pan (#4)

a) F3, F5, F7, and F9: about 1-cm below the lower surface of the floor pan. Temperatures exceeded 600 ^{o}C during the active burning period, indicating that flames were present at these locations;

b) F2, F4, F6, F8, and F10: attached to the upper surface of the floor pan with thermally conducting ceramic cement. Maximum temperatures were between about 400 and 600 ^{o}C at these locations indicating presence of flames;

c) F13, F14, F16, F17, and F18: on the opening between the manual transmission shift level pas-through cover plate on top of the drive line tunnel and the floor pan. Maximum temperatures were between about 400 and 500 ^{o}C at these locations indicating absence of flames but presence of very hot gases;

d) F19, F20, F21, and F22: about 1-cm below the lower surface of the manual transmission shift level pass-through cover plate. Maximum temperatures were between about 400 and 500 ^{o}C at these locations indicating absence of flames but presence of very hot gases;

5) Near Driver's Door (#5)

a) F12: seam opening between the floor pan and rocker panel below the driver's seat. Temperature was less than about 150 ^{o}C at this location, indicating absence of flames and presence of hot gases;

b) F11, F24, F25, and F26: on the surface of the driver's side front door scuff plate. Temperatures were close to ambient at these locations;

c) F27: on the driver's side "B" pillar adjacent to an electrical pass-through: temperature was close to ambient;

d) F28, F29, and F30: on the "B" pillar underneath the rear door weather-strip extending about 1-cm into the space between the "B" pillar and the rear door. Temperatures were close to ambient at these locations;

e) F31: on the surface of the left rear door scuff plate about 1-cm outboard of the rear door weather strip. Temperature was close to ambient at this location;

6) Drain Hole Plugs and Electrical Pass-Through Openings in the Floor Panel (#6)

a) P1, P2, P3, and P4: on the upper surfaces of the floor pan drain hole plugs. Maximum temperature was about 600 ^{o}C at P1 indicating presence of flame. Peak temperatures at P2, P3, and P4 decreased from about 570 to 380 to 220 ^{o}C, indicating absence of flames and presence of hot gases at these locations;

b) P5: on the upper surface of the electrical pass-through closure. Temperature exceeded 600 ^{o}C indicating presence of flame at this location;

c) P6 and P7: in the opening of an electrical pass-through in the floor pan. Temperatures exceeded 600 ^{o}C indicating presence of flames at these locations;

7) Vehicle Roof (#7)
a) R1 through R11: 1-cm below the lower surface of the headlining panel. Peak temperatures at R1 through R5, R8, and R11 were between about 300 and 400 ^{o}C, indicating absence of flames and presence of hot gases at these locations. At locations R6, R7, R9, and R10, temperatures exceeded 600 ^{o}C indicating presence of flames at these locations;
8**) Rocker Panel (#8)**
a) RP1 through RP7: on the surface of the rocker panel and in the gap between the door and the rocker panel. Temperatures were close to ambient at these locations;

In Fig. B-6-2, thermocouple locations are:

1) Left Front Seat (#1)
a) S1 through S4: on the outer surface of the front seat cushion side cover. Temperatures were close to ambient at these locations;
b) S5 through S7: on the exterior surface of the cover on the left side of the seat bottom. Temperatures were close to ambient at these locations;
c) S8 and S9: on the exterior surface of the cover on the left side of the seat back. Temperatures were close to ambient at these locations;
d) S10 through S13: on the exterior surface of the cover on the rear of the seat back. Peak temperatures were between about 300 and 500 ^{o}C, indicating absence of flames and presence of hot gases at these locations;
e) S14 and S15: on the exterior surface of the cover on the right side of the seat bottom. Peak temperature at S14 was about 400 ^{o}C indicating absence of flame and presence of hot gases. Temperature at S15 was close to ambient.
e) S16 and S17: on the exterior surface of the cover on the front of the seat bottom. Temperatures were close to ambient;
f) S18, S19, and S20: on the lower surface of the seat frame. Peak Temperature at S18 was less than about 150 ^{o}C. Peak temperatures at S19 and S20 exceeded 600 ^{o}C indicating presence of flames at these locations;
2) Left Front and Rear Door (#2)
a) T1 through T8: on the exposed surface of the left front door interior trim panel. Temperatures were close to ambient at these locations;
b) T9 through T14: on the exposed surface of the left rear door interior trim panel. Peak temperatures were less than about 200 ^{o}C at these locations, indicating absence of flames and presence of hot gases.

B-6-2. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

Flame spread into the passenger compartment occurred through a number of openings in the floor panel: a) through the electrical pass-through openings in the floor panel under the left front seat and 2) through the drain holes in the floor panel and heat conduction through the floor panel.

1. Flame Spread Through the Electrical Pass-Through Openings in the Floor Panel under the Left Front Seat

The area under the floor carpet under the left front seat was burned, charred, and consumed by the fire. Temperatures measured at these locations indicated the presence of flames. Temperature recorded at F9 indicated flame exposure of the locations from about 10 to 185 seconds post ignition. The maximum temperature of the floor panel was 582 ^{o} C between 250 and 255 seconds post ignition. Temperatures at P6 and P7 indicated that flames entered the electrical pass-through opening where the grommet had dislodged during the crash test at about 10 seconds post ignition. Temperatures at P5 and C1 indicated that flames burned through the grommet that was not dislodged from the electrical pass-through under the left front seat at about 75 seconds post ignition and burned through the carpet above this pass-through opening at about 205 seconds post ignition.

Video cameras showed that: a) flames burned through the left front seat cushion between 235 and 250 seconds post ignition, b) a fire plume was observed between the inboard side of the left seat cushion and the center console between about 190 and 195 seconds post ignition.

2. Flame Spread into the Passenger Compartment Through the Drain Holes in the Floor Panel and Heat Conduction Through the Floor Panel

The floor carpet over the drive train tunnel under the center console was burned, charred, and consumed by the fire. The section near F1, indicated by the temperature, was exposed to flames from 10 to 350 seconds post ignition. The maximum temperature of the floor panel was between 530 and 535 ^{o}C between 280 and 310 seconds post ignition.

3. Flame Spread on the Roof Trim Panel

Infrared thermograms indicated the presence of smoke and heated gases with temperature greater than 350 ^{o}C in the area above the right rear seat between 240 and 245 seconds post ignition. Visual inspection after the test indicated that flames had burned through two area of the right rear seat by the time flames inside the passenger compartment were extinguished.

By 253 seconds post ignition, estimated temperatures were greater than 600 ^{o}C indicating that the fire plume above the right rear seat had reached the lower surface of the room trim panel above the right rear seat before the test was ended and fire extinguished.

B-6-3. CONCENTRATION OF PRODUCTS AND RELEASE RATES OF HEAT AND PRODUCTS

The gas temperature in the passenger compartment was measured by six aspirated thermocouples, arranged inside a 16-in long vertical probe, located along the longitudinal mid-line of the vehicle about equidistant from the driver and the passenger seats. Each thermocouple was separated by a distance of 3 inches (76-mm) and the first thermocouple was 0.5-in (13-mm) below the lower surface of the headliner.

The maximum temperature of 518 ^{o}C was recorded at 252 seconds post ignition in the passenger compartment at a height of 3-in below the roof trim. The air temperature decreased about 8 ^{o}C/cm below the roof trim panel at the location of the aspirated thermocouple probe.

The concentrations of the products in the passenger compartment were measured at a location that was in the middle of the driver's seat and the front passenger seat, 10-in below the headliner. The instruments used for the measurements were FTIR, GC/MS, smoke particulate sampling apparatus, and by ion chromatograph (IC). FTIR was used to measure concentrations of CO, CO_2, CH_4, C_2H_4, C_2H_2, HCN, NO, and HCl. GC/MS was used to measure the relative abundance of higher molecular weight aliphatic and aromatic hydrocarbons (up to C_{15}). Smoke concentration was measured by the smoke particulate sampling apparatus and the inorganic anion concentrations by IC [fluoride (F^-), bicarbonate (HCO_3^-), chloride (Cl^-), nitrite (NO_2^-), bromide (Br^-), hypochlorite ($HClO_3^-$), nitrate (NO_3^-), phosphate (HPO_4^-), sulfate (SO_4^-), and oxalate ($C_2O_4^-$)].

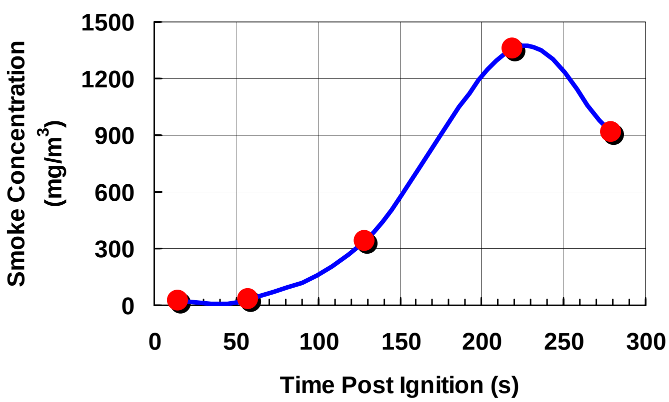


Figure B-6-3. Smoke concentration measured in the passenger compartment, 10-in below the headliner between the driver seat and the front passenger seat. Data are taken from Ref. 6.

Smoke data are plotted in Fig. B-6-3 and listed in Table B-6-2. Smoke consists of organic and inorganic compounds. The organic part of smoke consists of soot and lower and higher molecular weight organic compounds with low and high boiling points. The GC/MS data indicated that these organic compounds were aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure.

The inorganic part of smoke consists of anions, which were measured by IC in the study. The organic part of smoke was calculated from the difference in mass of the filter paper and the anions measured by IC.

In Fig. B-6-3, smoke concentration increases rapidly, reach a peak and then decreases as fire is extinguished starting at 250 seconds. Data in Table D-6-2 indicate that the organic part of smoke is dominant (90 to 91%) and decreases to 79.3 % when fire is at the flashover condition and is being extinguished. In the inorganic part of smoke, Cl^- is dominant and increases to 18.7 % when fire is at the flashover condition and is being extinguished.

Table B-6-2 Smoke Concentration and Composition [6]

Sampling Time (s)	Smoke Concentration (mg/m^3)	% of Smoke Concentration			
		Organic	Inorganic		
			Cl^-	Br^-	HPO_4^-
0 to 30	22				
30 to 84	31	90.5	5.3	0.0	4.2
84-174	337	90.0	9.2	0.5	0.3
174-264	1354	91.0	8.6	0.4	0.0
264-294	915	79.3	18.7	1.0	1.0

Maximum concentrations of compounds measured in the passenger compartment are listed in Table B-6-3. Between 174 to 264 seconds post ignition, smoke concentration reached its maximum value, just before the beginning of the fire extinguishment at 250 seconds post ignition.

Table B-6-3. Product Concentrations in the Passenger Compartment just before Time to Untenable/Flashover Conditions

Product	Maximum Concentration
CO	0.16 %
CO_2	3.8 %
CH_4	300 ppm
C_2H_4	470 ppm
C_2H_2	450 ppm
HCN	40 ppm
NO	30 ppm
Smoke	1,350 mg/m^3

The concentrations of other compounds reached their maximum values between about 30 and 370 seconds post ignition. It appears that there is an error of 350 seconds in the time shift in the FTIR data in Ref. 6 based on the data measured in the fire plume, which are presented in the following section.

The maximum CO to CO_2 concentration ratio is 0.042 in the passenger compartment indicating presence of ventilation-controlled conditions, i.e., presence of flames in the neighborhood of the measurement probes.

Release rates of heat, CO, CO_2 and smoke measured in the fire plume are shown in Fig. B-6-4.

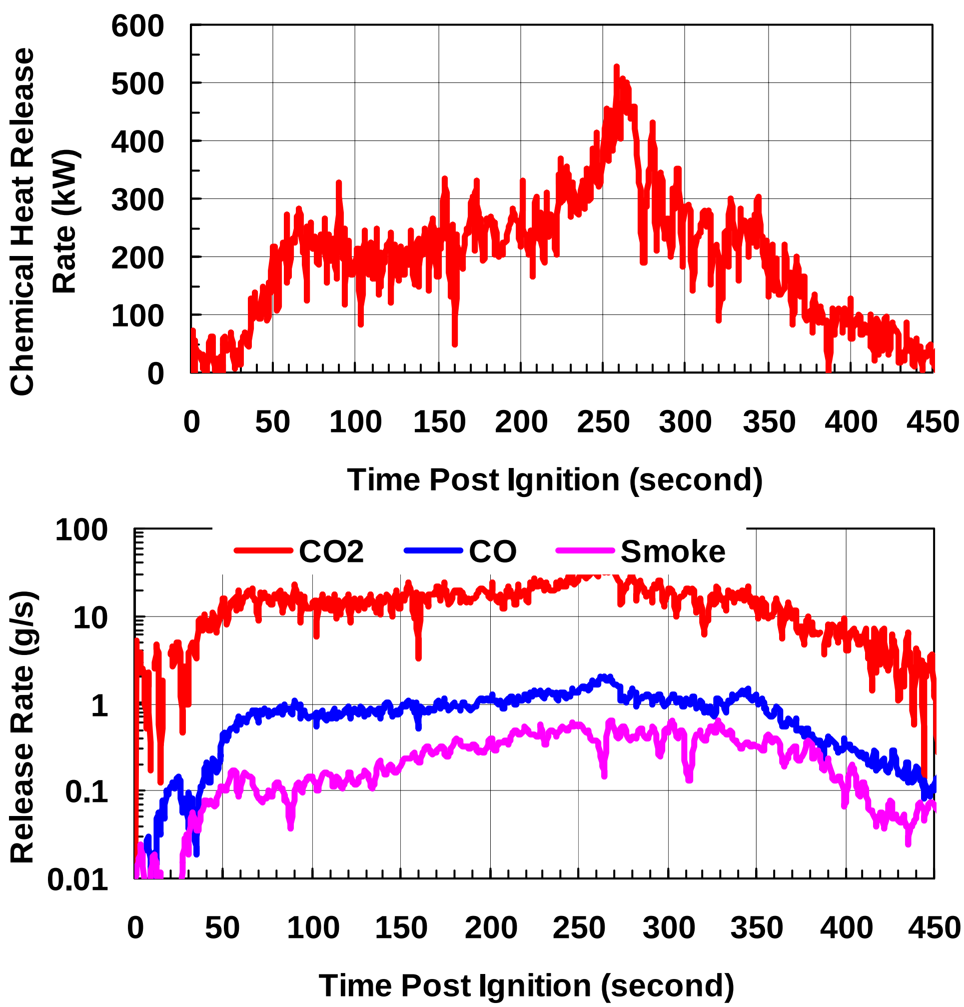


Figure B-6-4. Release rates of heat, CO, CO_2 and smoke in the burn test for the 1998 Ford Explorer. Data are taken from Ref. 6.

Release rates of chemical heat, CO, CO_2 and smoke increased rapidly from 30 to 60 seconds, remained steady until about 200 seconds, again started increasing rapidly until 260 seconds, and then decreased as fire was being extinguished.

Smoke concentration and the ratio of CO to CO_2 concentrations are plotted in Fig. B-6-5. The maximum average smoke concentration in the plume, measured optically, is 22 mg/m^3, whereas in the passenger compartment it reached a maximum of 1354 mg/m^3 (Table B-6-3 and Fig. B-6-3).

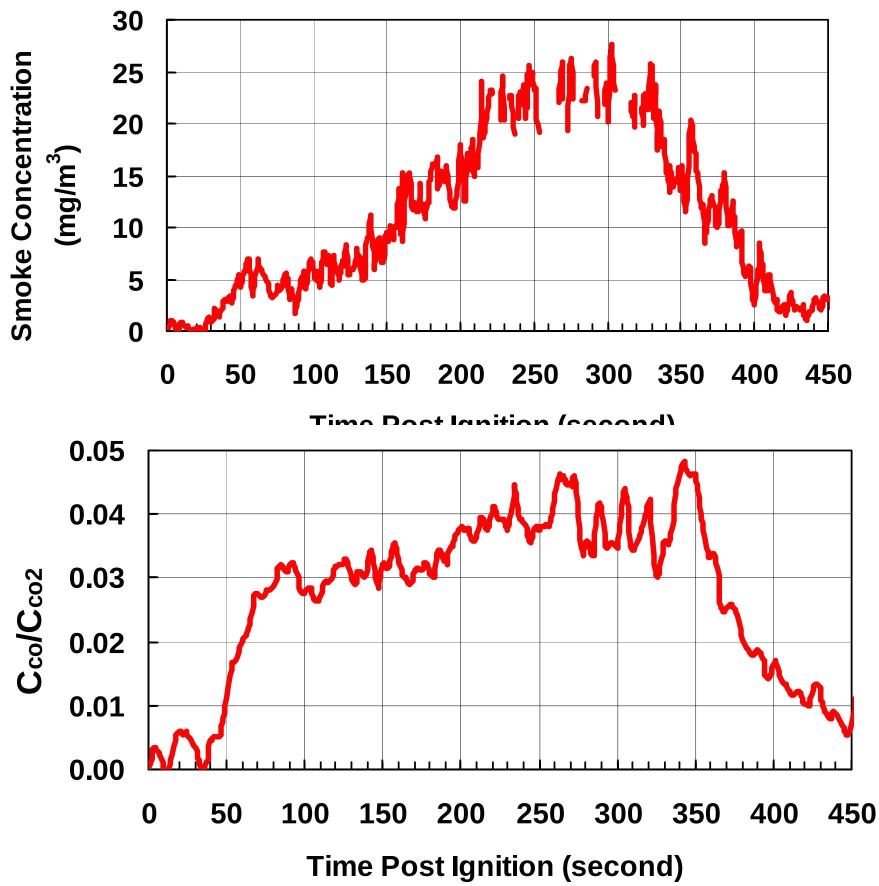


Figure B-6-5. Smoke concentration and CO to CO_2 concentration ratio versus time in the plume of the burning 1998 Ford Explorer. Data are taken from Ref. 6.

The optically measured smoke concentration (Fig. B-6-5) is primarily the soot concentration in smoke, whereas the smoke collected on the quartz fiber filter consists of both soot and higher molecular weight organic and inorganic compounds. The GC/MS and IC data for smoke collected on the quartz fiber filter paper from the passenger compartment indicated that a large fraction of smoke in the passenger compartment consisted of higher molecular weight aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure. It thus appears that smoke in the passenger compartment is significantly different than smoke in the plume of burning 1998 Ford Explorer. It appears that most of the higher molecular weight organic compounds in smoke in the passenger compartment are burned in the plume. However, the inorganic components of smoke, consisting of 5.3 to 8.6 % of Cl^-, 0 to 4.2 % HPO_4^- and 0 to 1.4 % Br^- would not be different in the passenger compartment and in the plume, except if external components of the vehicle become significant contributors.

The concentration ratio for CO to CO_2 in the fire plume reached a maximum average value of 0.036, very close the ratio of 0.042 (Table B-6-3) found in the passenger compartment, again suggesting ventilation controlled combustion, i.e., partial quenching of combustion in the sampling duct of the Fire Products Collector.

B.7 PROPAGATION OF AN ENGINE COMPARTMENT FIRE IN A 1998 HONDA ACCORD: TEST #7

The information included in this section is taken from the report entitled “Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 12: Propagation of an Engine Compartment Fire in a 1998 Front Wheel Drive Passenger Vehicle”, by Jeffrey Santrock, NHTSA Docket Number: 3588, Document Number: NHTSA-1998-3588-203, www.nhtsa.dot.gov [7].

The fire propagation test was performed on February 23, 1999 at FM Global using a 1998 Honda Accord model that was crashed at the GM Proving Ground on August 12, 1998. In the crash test, the vehicle was stationary and was struck in the left front (driver’s side) by a moving barrier. A fire was observed in the windshield fluid reservoir of the vehicle after the crash test. The sequence of events leading to fire was determined to be:

1) The reservoirs for the power steering fluid and windshield washing fluid, located in the left side of the engine compartment, were crushed. The windshield washing fluid reservoir was split into several pieces during the impact. The filler neck for the windshield washing fluid reservoir was severed;

2) The power steering fluid expelled from the reservoir and ignited on contact with the exhaust manifold. Some of the windshield washing fluid was at the bottom of the broken reservoir;

3) Burning power steering fluid aerosol entered the windshield washing fluid reservoir as the vehicle rebounded and ignited the methanol vapors in the reservoir.

For the fire propagation test, all the doors were closed. The windshield and the glass in the left front door were broken in the crash test and were not replaced. Fire was started by using about 2 liters of a 1:1 mixture of antifreeze and water heated to about 100 ^{o}C, sprayed onto the hood insulator, and allowed to drip into the engine compartment. The windshield washing fluid was heated to 50 ^{o}C and was added to the replaced windshield washing fluid reservoir, as the original reservoir had shattered in the crash test. Power steering fluid, heated to 85 ^{o}C, was sprayed by a hand held pump towards the windshield washing fluid reservoir from an insulated oiling can fitted with a misting nozzle. A propane torch was used to ignite the power steering fluid such that the burning fluid aerosol impinged on and entered the windshield washing fluid reservoir. A space heater was used around the windshield washing fluid reservoir to compensate for the low ambient temperature at the Test Center in the month of February. The ambient temperature in the windshield washing fluid reservoir was 40 ^{o}C at the start of the test. The ignition of the methanol vapors in the windshield washing fluid reservoir was taken as the ignition time.

Burning vapors of methanol ignited the windshield washing fluid reservoir between 240 and 360 seconds post ignition. Flames spread from the windshield washing fluid reservoir to the left front inner fender panel, the left headlamp assembly and the left front tire. Flames entered the passenger compartment through the gap between the deformed hood and the left front fender. Summary of the fire development during the vehicle burn test is listed in Table B-7-1.

Table B-7-1. Summary of Fire Development in the Test

Time (sec)	Event
0	Ignition of methanol vapors in the windshield washing fluid reservoir
240 to 360	The windshield washing fluid reservoir started to burn
660 to 720	Flames spread from the windshield washing fluid reservoir to the left front inner fender panel
900 to 960	Flames spread from the windshield washing fluid reservoir and the left front inner fender panel to the left front tire
1260-1320	Flames spread across the hood insulator into the engine compartment
1320 to 1440	Flames started to vent from the engine compartment along the rear edge of the hood and impinge onto the windshield
1500 to 1560	Pieces of burning windshield started to fall inward into the passenger compartment
1560 to 1620	The left front seat cushion, center console and the steering wheel were ignited by pieces of burning windshield
1620	Fire suppression began

B-7-1. TEMPERATURES MEASURED AT VARIOUS LOCATIONS

Thermocouple locations used to monitor temperatures and flame spread behavior are shown in Figs. B-7-1 and B-7-2. Locations where temperatures were measured by thermocouples are:

1) **Windshield Washing Fluid Reservoir, Right Front Wheelhouse Panel, Right Headlamp Assembly, Right Front Door (#1 in Fig. B-7-1)**

a) A1 to A4: inside the windshield washing fluid reservoir. Maximum temperature at A1 was low (230 ^{o}C from about 840 seconds post ignition to the end of the test). Maximum temperatures at A2, A3 and A4 were in the range of 750 to 800 between 1380 and 1440 seconds post ignition. At location A4, temperature reached a maximum of 600 ^{o}C at 420 seconds post ignition and decreased reaching a constant value of 200 ^{o}C and then increasing from 1290 seconds post ignition.

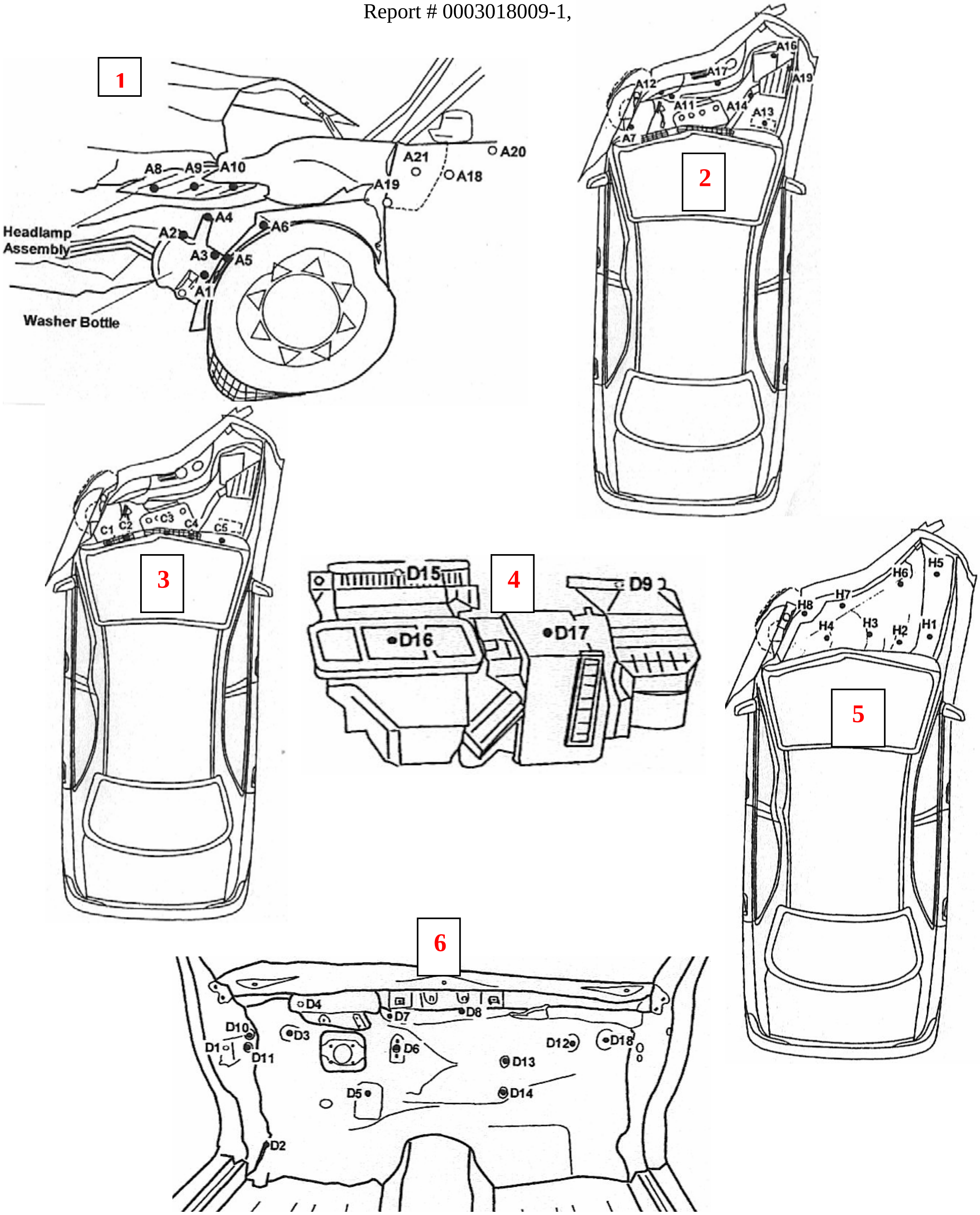


Figure B-7-1. Thermocouple locations: 1) windshield washing fluid reservoir, right front wheelhouse panel, right headlamp assembly, right front door; 2) engine compartment; 3) HVAC air intake cowl; 4) HVAC module and ducts; 5) engine hood; 6) dash panel. Sketches are taken from Ref. 7.

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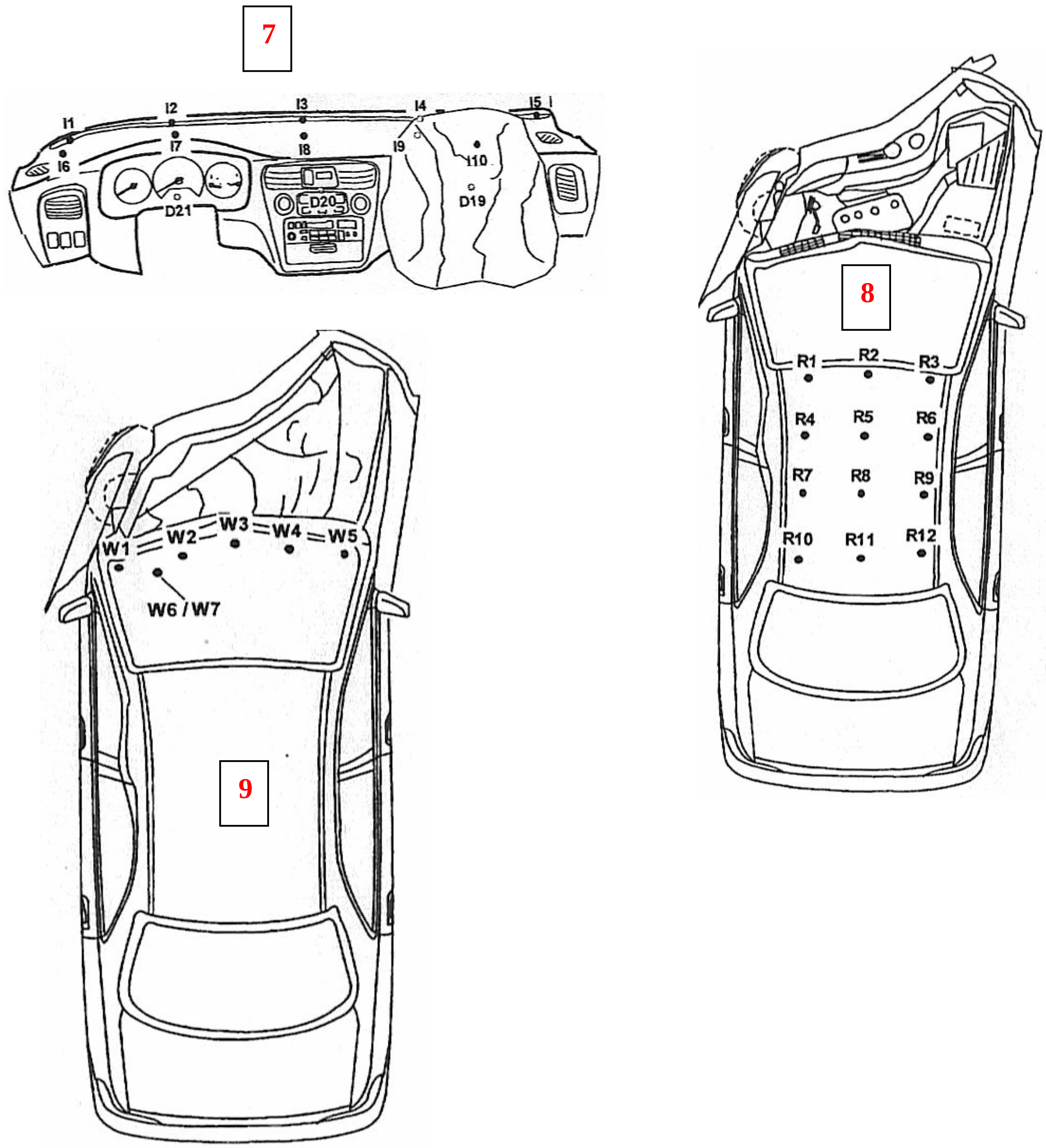

Figure B-7-2. Thermocouple locations: 7) instrument panel; 8) roof; 9) windshield. Sketches are taken from Ref. 7.

b) A5 and A6: on the right front wheelhouse panel. Maximum temperatures at these locations were in the range of about 650 and 820 ^{o}C between about 1260 and 1560 seconds post ignition.
c) A8, A9, and A10: on the right headlamp lens. Maximum temperatures at these locations were in the range of about 720 to 870 between about 1380 and 1560 post ignition;
d) A18, A19, A20, and A21: inside the right front door. Maximum temperatures at these locations were less than 50 ^{o}C, except at location A19, where it reached a value of about 270 ^{o}C at about 1620 seconds post ignition

2) **Engine Compartment (#2 in Fig. B-7-1)**

a) A7: on the right front wheelhouse panel. Maximum temperature at this location was about 870 ^{o}C between about 1380 and 1560 seconds post ignition;

b) A11 and A12: adjacent to the power steering fluid pump. Maximum temperature at location A11 was about 450 ^{o}C between about 1500 and 1620 seconds post ignition. Maximum temperature at location A12 was 800 ^{o}C at about 1560 seconds post ignition;

c) A13: on the upper surface of the under hood fuse/rely box cover. Maximum temperature at this location was about 800 ^{o}C between about 1440 and 1620 seconds post ignition;

d) A14: on the intake air tube. Maximum temperature at this location was about 900 ^{o}C between about 1500 and 1620 seconds post ignition;

e) A16: on the battery. Maximum temperature at this location was about 800 ^{o}C at about 1560 seconds post ignition

f) A17: on the radiator fan shroud. Maximum temperature at this location was about 700 ^{o}C at about 1560 seconds post ignition

g) A19: on a piece of air cleaner housing cover. Maximum temperature at this location was about 280 ^{o}C at about 1620 seconds post ignition.

3) HVAC Air Intake Cowl (#3 in Fig. B-7-1)

a) C1 through C5: about 1-cm below the lower surface of the HVAC air intake cowl. Maximum temperatures at C1 to C4 locations were in the range of about 850 to 900 ^{o}C and about 700 ^{o}C at location C5 between about 1500 and 1620 seconds post ignition.

4) HVAC Module and Ducts (#4 in Fig.B-7-1)

a) D9: in the HVAC air intake. Maximum temperature at this location was about 300 ^{o}C at about 1620 seconds post ignition.

b) D15: in the defroster duct. Maximum temperature at this location was less than about 50 ^{o}C.

c) D16: in the air-mixing duct. Maximum temperature at this location was close to the ambient temperature;

d) D17: on the upper evaporator housing. Maximum temperature at this location was close to the ambient temperature.

5) Engine Hood (#5 in Fig. B-7-1)

a) H1 through H8: about 1-cm the lower surface of the hood insulator. Maximum temperatures at all locations were in the range of 800 and 920 ^{o}C between 1320 and 1560 seconds post ignition.

6) **Dash Panel (#6 in Fig. B-7-1)**

a) D1: inside the left A-pillar. Maximum temperature at this location is 250 at about 1620 seconds post ignition;

b) D2: on the crash induced seam opening between the floor panel and the inner rocker panel. Maximum temperature at this location is close to ambient;

c) D3, D12, and D18: on the interior surface of an electrical pass-through closure in the dash panel. Maximum temperatures at these locations are less 50 ^{o}C;

d) D4, D7 and D8: in a crash-induced seam opening between the lower and upper dash panels. Maximum temperatures at these locations were about 200 ^{o}C at about 1620 seconds post ignition;

e) D5: on the steering column pass-through. Maximum temperature at this location was less than 50 ^{o}C;
f) D6: on the interior surface of the throttle linkage pass-through closure. Maximum temperature at this location was less than 50 ^{o}C;
g) D10 and D11: on closures in the left A-pillar. Maximum temperature at D10 was about 800 ^{o}C and at D11 it was about 630 ^{o}C between about 1500 and 1620 seconds post ignition;
i) D13 and D14: in the heater hose pass-through. The maximum temperature at this location was less than 50 ^{o}C.

7) Instrument Panel (#7 in Fig. B-7-2)
a) I1 through I5: along the forward edge of the instrument panel. Maximum temperatures at I1 to I4 were in the range of 820 and 920 ^{o}C and at I5, it was 650 ^{o}C between about 1500 and 1560 seconds post ignition;
b) I6 through I10: lateral centerline of the upper surface of the instrument panel. Maximum temperatures at I6 and I7 locations were in the range of 400 to 450 ^{o}C between about 1590 and 1620 seconds post ignition. The maximum temperatures at I8, I9 and I10 were 890 ^{o}C, 650 ^{o}C and 780 ^{o}C respectively between about 1560 and 1590 seconds post ignition.
c) D19, D20 and D21: on the instrument panel cross member. Maximum temperatures at these locations were less than about 100 ^{o}C.

8) Roof (#8 in Fig. B-7-2)
a) R1 through R12: about 1-cm below the lower surface of the roof trim panel. A maximum temperature of 650 ^{o}C was recorded at locations R1 and R2 at about 1560 seconds post ignition. Maximum temperatures at other locations (R3 to R12) were in the range of about 200 and 250 ^{o}C recorded at 1560 seconds post ignition.

9) Windshield (#9 in Fig. B-7-2)
a) W1 through W5: about 1-cm forward of the exterior glass outer layer in the windshield. Maximum temperatures recorded at these locations were between 800 and 930 ^{o}C at about 1500 seconds post ignition;
b) W6: attached to the exterior glass outer layer. A maximum temperature recorded at this location was 900 ^{o}C at about 1500 seconds post ignition;
c) W7: attached to the interior glass outer layer. A maximum temperature recorded at this location was 680 ^{o}C at about 1500 seconds post ignition;

B-7-2. FLAME SPREAD IN THE ENGINE COMPARTMENT

Video cameras showed that flames first entered the engine compartment between 1260 and 1320 seconds post ignition. By 1440 seconds post ignition, flames had spread toward the right on the hood-lining panel and to the combustible materials in the left side of the engine compartment, covering the entire width of the hood insulator. Hot gases entered the left side of the engine compartment and flowed from left to right along the lower surface of the deformed hood between 1080 and 1260 seconds post ignition. At 1320 seconds post ignition, temperatures along the left side of the hood were between 500 and 600 ^{o}C, while temperatures on the right side of the hood insulator were < 200 ^{o}C. By 1500 seconds post ignition, flames were observed venting from the engine compartment along the right side of the deformed hood and temperatures on the hood insulator were greater than 600 ^{o}C on the entire lower surface of the hood insulator. From temperature measurements, it was estimated only components in the rear of the engine compartment had ignited, while temperatures in the front of the engine compartment were less than 200 ^{o}C. Between 1500 and 1620 ^{o}C post ignition, flames spread forward in the engine compartment.

B-7-3. FLAME SPREAD IN THE PASSENGER COMPARTMENT

Flames spread into the passenger compartment through the windshield and the pass-through openings in the left side of the dash panel. Flames entering the passenger compartment via pass-through openings in the dash panel ignited components in the left side of the instrument panel. Flame spread through the windshield progressed by: 1) flame spread rearward along the top of the instrument panel and 2) ignition of the interior components by pieces of windshield with the inner layer burning and falling into the passenger compartment.

1. Flame Spread into the Passenger Compartment through the Windshield

Video recordings showed the following, supported by temperatures measured at various locations:

1) *About 420 seconds post ignition*: left corner of the windshield exposed to heated gases from the fire;
2) *About 1320 seconds post ignition*: A section of the windshield in front of the left front seat was exposed to flames from the burning HVAC air intake cowl;
3) *Between about 1320 and 1440 seconds post ignition*: a hole developed in the lower left side of the windshield in front of the steering wheel. Flames from the engine compartment entered the passenger compartment through this hole and spread upward along the interior surface of the windshield, igniting the windshield inner-layer around the hole and in an area where pieces of glass were dislodged from the windshield and the inner-layer was exposed.
4) *Between about 1380 and 1410 seconds post ignition*: pieces of windshield with the inner layer burning started to fall into the passenger compartment;
5) *Between 1470 and 1500 seconds post ignition*: a section of windshield sagged onto the left side of the instrument panel.

2. Flame Spread Rearward Along the Top of the Instrument Panel

Video recordings showed the following, supported by temperatures measured at various locations:

6) *Between about 1380 and 1410 seconds post ignition*: forward edge of the left side of the instrument panel ignited. This occurred in the same area where holes developed along the lower edge of the windshield between about 1320 and 1440 seconds post ignition. This suggests that flames venting from the engine compartment along the rear edge of the left side of the deformed hood ignited the top of the instrument panel as sections of the windshield fell onto the instrument panel;
7) *Between about 1410 and 1500 seconds post ignition*: flames spread to the right across the front of the instrument panel;
8) *Between about 1410 and 1620 seconds post ignition*: flames spread rearward on the center of the instrument panel, coincident with the timing of holes developing in the center of the windshield;
9) *Between about 1530 and 1560 seconds post ignition*: flames spread to the right on the forward section of the instrument panel and ignited the deployed passenger side air bag.

3. Ignition of the Front Seats, Center Console and Steering Wheel

At about 1620 seconds post ignition, pieces of burning windshield inner-layer fell onto the passenger compartment and ignited the deployed passenger side air bag, the floor carpet in the front of the right front seat, the front seat cushions, the steering wheel cover, and the center console.

4. Flame Spread into the Passenger Compartment through the Left Inner Hinge Pillar

The upper left corner of the insulation on the interior of the dash panel was burned and charred. The dash panel and hinge pillar panels contained a number of pass-through and other openings with elastomer and polymer closures. Two of the pass-through closures in the upper part of the left hinge pillar had burned through and an electrical pass-through closure in the upper left of the dash panel was charred. Maximum temperatures recorded at these locations supported the burning of closures (about 800 ^{o}C at D10 and 630 ^{o}C at D11 between about 1500 and 1620 seconds post ignition).

5. Heat and Fire Damage to the Headlining Panel and Front Seats

The pattern of heat and fire damage to the roof trim panel, temperature profiles along the lower surface of the headlining panel and the data recorded by the aspirated thermocouple assembly located in the passenger compartment, indicate that a burning upper layer did not develop in the passenger compartment during the test. Except for a section of the fabric covering on the roof trim panel and a section of the fabric covering on the left sun visor, the roof trim panel showed no evidence of being exposed to hat and flames during the test.

Between about 1350 and 1380 seconds post ignition, hot gases started to accumulate along the roof of the vehicle.

B-7-4. CONCENTRATION OF PRODUCTS AND RELEASE RATES OF HEAT AND PRODUCTS

The gas temperature in the passenger compartment was measured by six aspirated thermocouples, arranged inside a 16-in (406-mm) long vertical probe, located along the longitudinal mid-line of the vehicle about equidistant from the driver and the passenger seats. Each thermocouple was separated by a distance of 3-in (76-mm) and the first thermocouple was 0.5-in (13-mm) below the lower surface of the headliner.

The aspirated thermocouples indicated that between about 1320 and 1380 seconds post ignition, hot gases started to flow into the passenger compartment along the roof trim panel. At about 1620 seconds post ignition, the vertical temperature gradient was about 0.37 ^{o}C/mm at the location of the aspirated thermocouple assembly and linear from about 13-mm to 400-mm below the lower surface of the roof trim panel.

The concentrations of the products in the passenger compartment were measured at a location that was in the middle of the driver's seat and the front passenger seat, 10-in (250-mm) below the headliner. The instruments used for the measurements were FTIR, GC/MS, smoke particulate sampling apparatus and ion chromatograph (IC). FTIR was used to measure concentrations of CO, CO_2, CH_4, C_2H_4, C_2H_2, HCN, NO, and HCl. GC/MS were used to measure the relative abundance of higher molecular weight aliphatic and aromatic hydrocarbons (up to C_{15}). Smoke concentration was measured by the smoke particulate sampling apparatus and the inorganic anion concentrations by IC [fluoride (F^-), bicarbonate (HCO_3^-), chloride (Cl^-), nitrite (NO_2^-), bromide (Br^-), hypochlorite ($HClO_3^-$), nitrate (NO_3^-), phosphate (HPO_4^-), sulfate (SO_4^-), and oxalate ($C_2O_4^-$)].

Data for the smoke concentration is plotted in Fig. B-7-3 and the smoke composition is listed in Table B-7-2. Smoke consists of organic and inorganic compounds. The organic part of smoke consists of soot and lower and higher molecular weight organic compounds with low and high boiling points. The GC/MS data indicates that the organic part of smoke collected on the filter paper consists of aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure. The GC/MS data also indicated that chlorinated aliphatic hydrocarbons were present in the organic part of smoke.

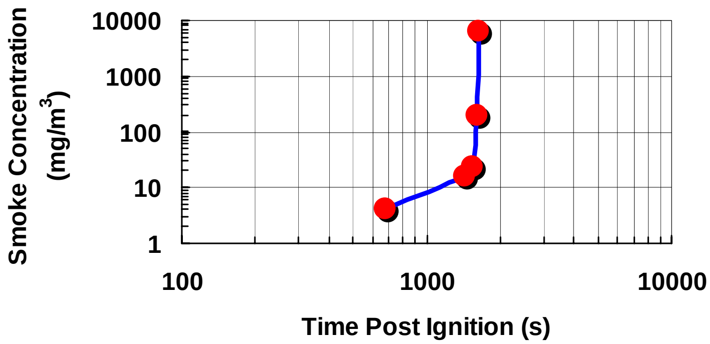

Figure B-7-3. Smoke concentration measured in the passenger compartment, 10-in below the headliner between the driver seat and the front passenger seat. Data are taken from Ref. 7.

Table B-7-2 Smoke Concentration and Composition [26]

Sampling Time (s)	Smoke Concentration (mg/m^3)	% of Smoke Concentration			
		Organic	Cl^-	Br^-	SO_4^-
0 to 1350	4	100.0	0.0	0.0	0.0
1350 to 1522	16	76.5	10.1	0.0	13.4
1522 to 1574	24	50.6	24.2	0.0	25.2
1574 to 1622	191	81.0	2.5	16.5	0.0
1622 to 1625	6224	86.5	5.2	8.3	0.0

The inorganic part of the smoke consists of anions, which were measured by IC in the study. The organic part of smoke was calculated from the difference in the mass of the filter paper and the anions measured by IC.

Figure B-7-3 shows the smoke concentration increased very rapidly after 1574 seconds post ignition, reaching a very high value of 6224 mg/m^3 between 1622 and 1625 seconds post ignition, a period where flames entered the passenger compartment. The test was ended at 1620 seconds post ignition. Data in Table B-7-2 indicate that after 1350 seconds post ignition, the organic part of smoke was only between 51 and 87 % by mass. Significant amounts of Cl^- and SO_4^- were present in smoke between 1350 and 1574 seconds post ignition, whereas amounts of Br^- were present in smoke between 1574 and 1625 seconds post ignition. In addition, chlorinated hydrocarbons were also present in the organic part of smoke. It thus appears that burning upper layer did not develop in the passenger compartment during the test because fire retardants were effective, as indicated by the significant amounts of the anions.

Maximum concentrations of various products measured in the passenger compartment are listed in Table B-7-3. Concentrations of CO, CO_2, methane, ethylene, acetylene and nitric oxide increased at about 1500 seconds and reached peak values at about 1590 seconds and starting decreasing immediately, reaching negligible concentrations at about 1740 seconds post ignition.

Data in Table B-7-3 show that the ratio of CO to CO_2 concentration is 0.035, indicating that slightly under-ventilated conditions were present around the location in the passenger compartment where concentration measurements were made.

Table B-7-3. Maximum Product Concentrations in the Passenger Compartment Just Before Untenable/Flashover Conditions

Product	Maximum Concentration
CO	0.044 %
CO_2	1.25 %
CH_4	30 ppm
C_2H_4	45 ppm
C_2H_2	28 ppm
HCl	Close to 0 ppm
HCN	Close to 0 ppm
NO	18 ppm
Smoke	6224 mg/m^3

Release rates of heat, CO_2 and smoke and smoke concentration measured in the fire plume over the burning 1998 Honda Accord model are shown in Fig. B-7-4. CO concentration was not measured as the instrument malfunctioned during the test. In addition, data for the convective heat release rate are not reported due to errors found during fire suppression**.** Release rates started to increase from about 1300 second post ignition, reaching maximum values between about 1600 and 1650 post ignition. Fire suppression was started at 1620 seconds post ignition. The chemical heat release rate reached a peak average value of 900 kW.

The maximum average smoke concentration in the plume, measured optically, reached a value of 43 mg/m^3 between 1600 and 1650 seconds post ignition and then decreased during fire suppression. In the passenger compartment, the maximum smoke concentration measured on the filter was 6224 mg/m^3 between 1622 to 1625 seconds post ignition (Table B-7-3).

The smoke concentration measured optically (Fig. B-7-4) is primarily the soot concentration in smoke, whereas the smoke collected on the quartz fiber filter in the smoke particulate sampling apparatus from the passenger compartment consists of both soot and higher

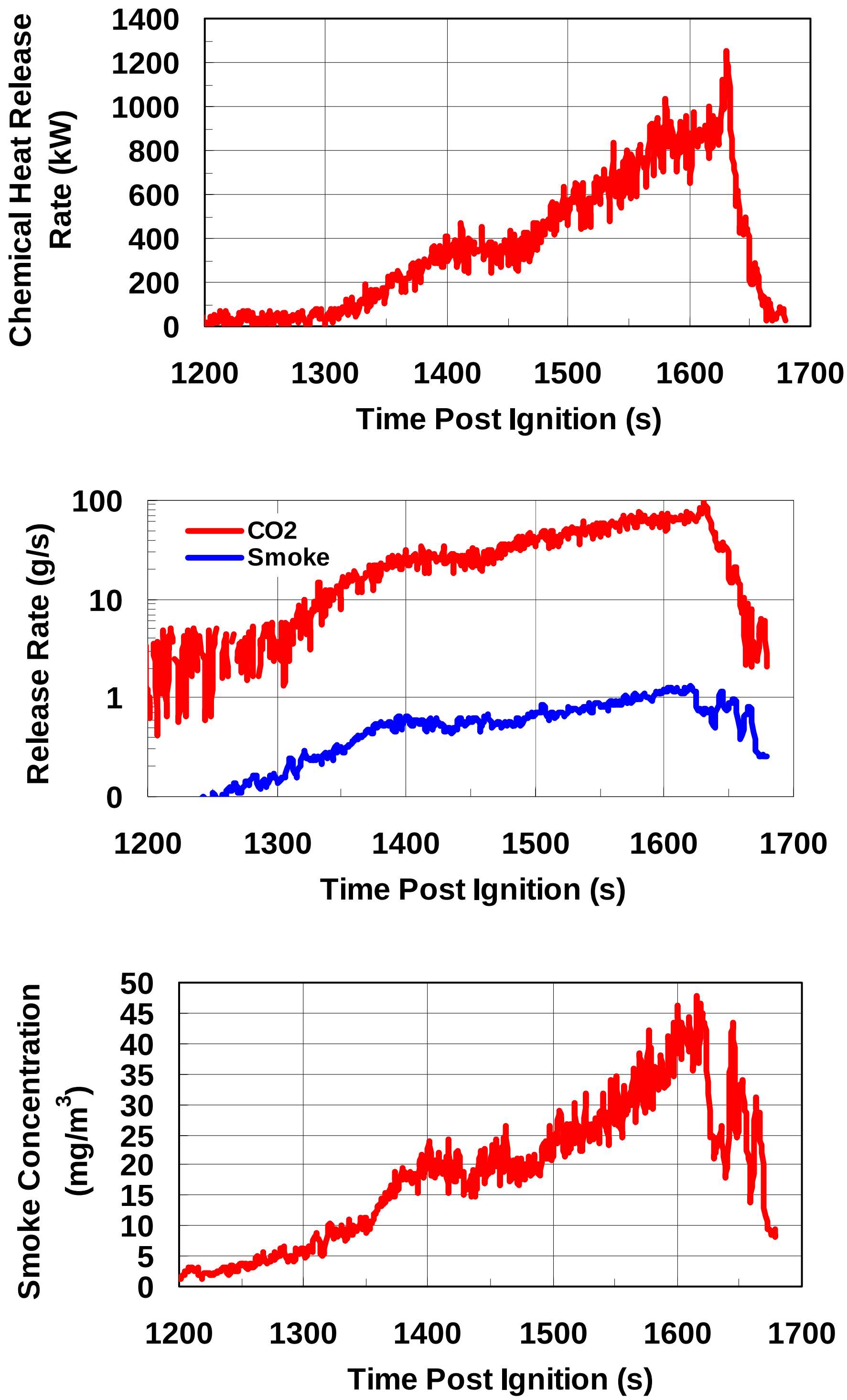

Figure B-7-4. Release rates of chemical heat, CO_2 and smoke and smoke concentration in the burn test for the 1998 Honda Accord. Data are taken from Ref. 7.

molecular weight organic and inorganic compounds. The GC/MS and IC data for smoke collected on the quartz fiber filter paper from the passenger compartment indicated that a large fraction of smoke in the passenger compartment consisted of higher molecular weight aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure, as well as chlorinated aliphatic hydrocarbons. Thus major fractions of the hydrocarbons appeared to have been consumed in the fire plume.

B.8 PROPAGATION OF AN UNDERBODY GASOLINE POOL FIRE IN A 1998 MODEL OF HONDA ACCORD: TEST #8

The information included in this appendix is taken from the report entitled "Evaluation of Motor Vehicle Fire Initiation and Propagation, Part 12: Propagation of an Underbody Gasoline Pool Fire in a 1998 Front Wheel Drive Passenger Vehicle", by Jeffrey Santrock, NHTSA Docket Number: 3588, Document Number: NHTSA-1998-3588-201, www.nhtsa.dot.gov [8].

The fire propagation test was performed on February 25, 1999 at FM Global using a 1998 Honda Accord that was crashed at the GM Proving Ground on May 13, 1998. In the crash test, the vehicle was stationary and was struck in the left front (driver's side) by a moving barrier. The fuel system of the vehicle leaked during the crash. Inspection after the crash test revealed a crack in the pump assembly and a tear in the fuel tank. No fire was observed during the crash test nor was evidence of fire present in the test vehicle during the inspection of the vehicle after the test. Following damages to the vehicle were noted:

- Left and right sides were displaced;
- The rear window glass and the glass in the right and left rear doors was broken;
- The left rear was bent and was displaced outward from the doorframe, creating gaps between the rear and lower edges of the door and the doorframe. The door remained latched;
- The roof was displaced upward;
- The rear seat back was folded down;
- The trim on he rear package shelf was dislodged and was laying on top of the folded down seat back;
- Seams had opened between the left and right wheelhouse panels and the inner quarter panels and the floor panel;
- The left rocker panel detached partially from the door. The door remained latched;
- Deformation of the quarter panel, rocker panel and the door resulted in a gap between the lower and rear edges of the door and the doorsill and the latch pillar.

Based on the inspection of the crashed vehicle, following potential fire paths into the passenger compartment from the underbody gasoline fire were identified:

- Rear window opening;
- Window openings in the left and right rear doors;
- Seam openings between the floor panel and the left and right wheelhouse panels;
- Gaps around the left rear door and door f ram e that were the result of deformation to the structure of the vehicle;

For the fire propagation test, all the doors were closed and the window glasses in both the front doors were raised to their fully closed position. The glass in the rear window and the left and right rear doors, which were broken in the crash test, were not replaced.

An artificial method of creating an underbody gasoline pool was used. Gasoline was pumped continuously from an external reservoir onto the top of the fuel tank. In the test, gasoline was allowed to flow at a rate of about 400 ml/min. Liquid gasoline was flowing from several points on the rear cross-member of the rear suspension sub-frame onto the cement board surface under the floor panel in the trunk of the vehicle within 5 seconds after starting the gasoline flow. Gasoline was allowed to flow for about 30 seconds onto the cement board surface. A propane torch was then used to ignite the vapors. The gasoline-wetted area under the vehicle was circular.

The diameter of the gasoline pool fire on the cement board was estimated to be about 82-cm at 1 sec post ignition and decreased to 35 cm by 60 seconds post ignition. The estimated flame diameter was between 30 and 40 cm from 60 to 140 seconds post ignition. At the time of ignition, flames extended laterally from about the rear cross-member of the rear suspension sub-frame rearward to the spare tire well in the trunk. Gasoline vapors that had accumulated under the rear of the test vehicle were consumed within a few seconds after ignition.

Flames entered the passenger compartment through the crash-induced seam openings around the left and right wheelhouses. The test was stopped when the flames were observed on the headlining panel. Fire suppression began at about 155 seconds after the gasoline was ignited.

Summary of fire development during the vehicle burn test with is listed in Table B-8-1.

Table B-8-1. Summary of Fire Development in the Test [8]

Time (sec)	Event
0	Ignition of gasoline under the vehicle by a propane torch
15	Flames in the area between the left side of the floor panel in the trunk and the rear tire
75	Flames started to vent from the right rear wheelhouse
75-90	Flames began to contact the rear surface of the left side of the rear seat back and ignited the foam pads in the rear seat back and rear seat bolsters
120	Flames were observed on the lower surface of the roof trim panel in the rear left quadrant of the passenger compartment
155	Fire suppression was started

B-8-1. TEMPERATURES MEASURED AT VARIOUS LOCATIONS

Thermocouple locations used to monitor temperatures and flame spread behavior are shown in Figs. B-8-1. Locations where temperatures were measured by thermocouples are:

1) Rear of the Vehicle (#1)

a) A0, A1, A2, A3, A28 and A29: on the left rear inner door trim panel. Temperatures at all these locations were close to ambient;

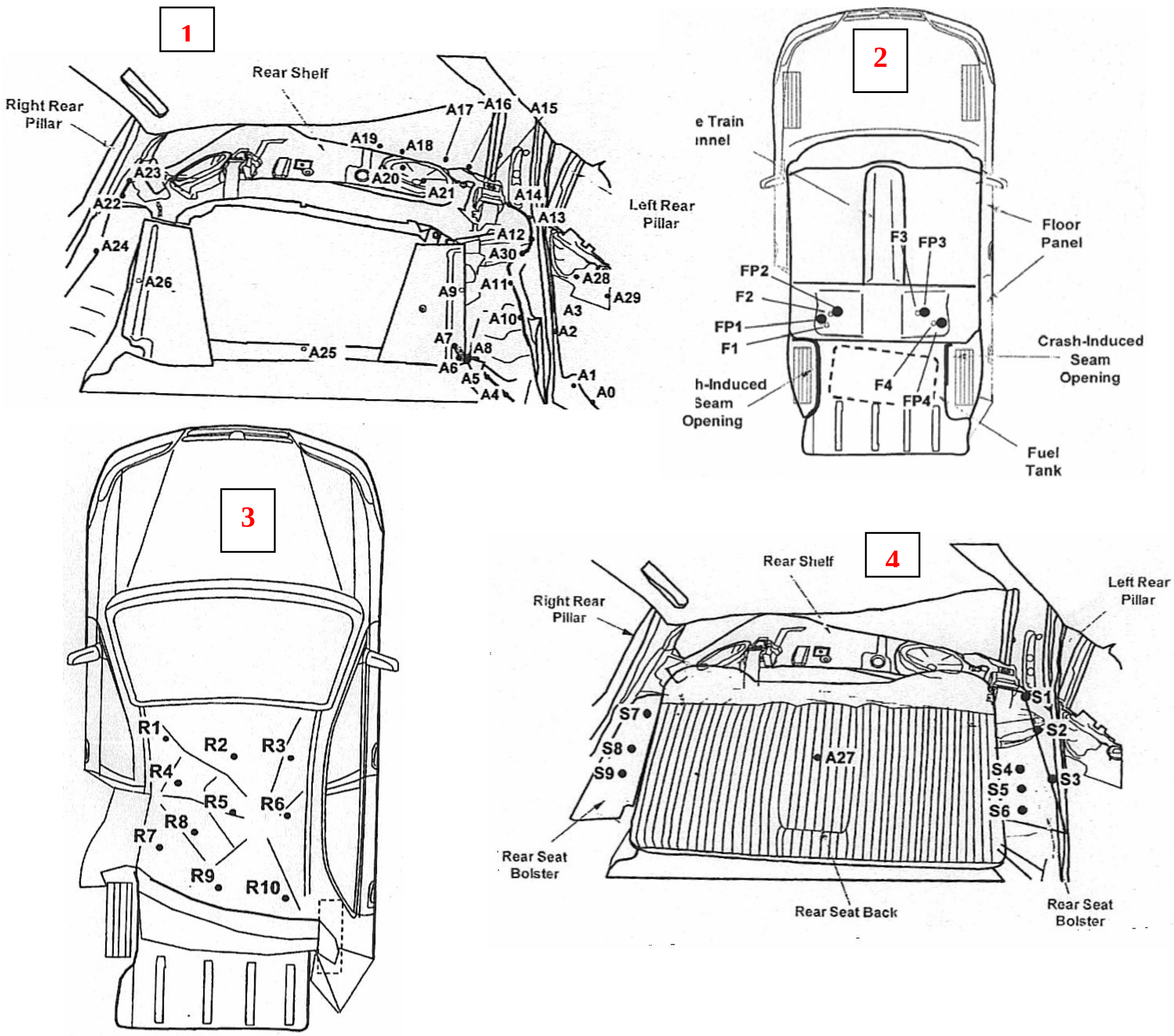

Figure B-8-1. Thermocouple locations: 1) **A0 to A29**: rear of the vehicle; 2) **F1** to **F4** and **FP1** to **FP4**: on and below the floor panel; 3) **R1** to **R10**: below the head lining panel; 4) **A27** and **S1** to **S9**: on and around the rear seat. Sketches are taken from Ref. 8.

b) A4, A5, A6, A7 and A8: in a crash induced seam opening between the left rear wheelhouse panel and the floor panel. Temperatures at all these locations exceeded 600 ^{o}C, except at A4, where maximum temperature was 250 ^oC. Thus, flames were present at these locations, except at location A4;

c) A9: behind the left rear seat back support panel above a crash-induced seam opening between the left wheelhouse and the floor panel. Temperature at this location exceeded 600 ^oC, indicating presence of flame;

d) A10, A11, A12, A13, A14, A15, and A30: in a crash induced seam opening between the left rear wheelhouse panel and the left inner quarter panel. Temperatures exceeded 600 ^oC at A10, A11, and A12, indicating presence of flames at these locations. Temperatures were close to 600 ^oC at A13, and A14, indicating proximity to flames. Temperature at A15 was less than 300 ^oC and was close to ambient at A30.

e) A16, A17, A18, and A19: along the rear edge of the rear package shelf. Temperatures either exceed 600 ^oC or are close to 500 to 600 ^oC indicating that flames are present at these locations or they are in proximity to flames;

f) A20 and A21: above the speaker cone in the speaker on the left side of the rear package shelf. Temperatures exceed 600 ^oC indicating presence of flame at these locations;

g) A22, A23, and A24: in a crash-induced seam opening between the right rear wheelhouse and the right inner quarter panel. Temperature exceeds 600 ^oC at A 23, is close to 600 ^oC at A24 and to 500 ^oC at A24, indicating that these locations are in proximity to flames;

h) A25: under the caret in a crash-induced gap between the floor panel and the fuel pump assembly access cover plate in the trunk. Temperature is less than 350 ^oC indicating presence of hot gases only at this location;

i) A26: in a gap between the right rear wheelhouse and the right seat back support panel. Temperature exceeds 600 ^oC indicating presence of flame at this location;

j) A28 and A29: on the inner surface of the interior trim panel on the left rear door. Temperatures at these two locations are close to ambient;

2) Floor Panel (#2)

a) F1, F2, F3, and F4: about 1-cm below the lower surface of the floor panel. Temperatures at these locations were less than 200 ^oC indicating that they were far from flames or hot combustion zone;

b) FP1: on the upper surface of an electrical pass-through in the floor panel under the let side of the rear seat cushion. Temperature was close to ambient at this location;

c) FP2, FP3, and FP4: on the upper surfaces of the drain hole plugs in the floor panel under the rear seat cushion. Temperatures were close to ambient at these locations.

3) Headlining Panel (#3)

a) R1 through R10: about 1-cm below the lower surface of the headlining panel. Temperatures were equal to greater than 600 ^oC at R4, R5, R7, R8, and R9 indicating presence of flames. Temperatures were below 400 at R1, R2, R3, R6, and R10, indicating presence of hot gases.

4) Rear Seat (#4)

a) A27: on the rear surface of an access panel in the rear seat back;

b) S1, S2, and S3: on the rear surface of the outer edge of the rear seat back left side panel;

c) S4, S5, and S6: on the rear surface of the outer edge of the rear seat back left side panel;

d) S7, S8, and S9: on the rear surface of the outer edge of the rear seat back right bolster.

B-8-2. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

Flame spread into the passenger compartment occurred through the crashed induced seam openings around the left and right wheelhouses simultaneously in the rear of the vehicle. These flames entering the passenger compartment ignited several items in the rear: 1) left side of the seat back, 2) left seat belt, 3) left side of the shelf trim panel, 4) right seat back bolster, and 5) interior trim panel on the right rear pillar. Video recordings showed the following:

1) *By 10 seconds post ignition*: smoke and hot gases started to vent from both wheelhouses and were observed behind the rear seat back.
2) *By 15 seconds post ignition*: flames were visible in the area between the left side of the floor panel in the trunk and the inboard side of the left rear tire.
3) *By 75 to 90 seconds post ignition*: flames had begun to vent from the right rear wheelhouse and from the left rear wheelhouse. Flames began to contact the back surface of the left side of the rear seat back;
4) *By 120 seconds post ignition*: flames were visible on the lower surface of the roof trim panel through the upper left corner of the rear window opening;
5) *By 155 seconds post ignition*: flames started to vent from the passenger compartment along the rear edge of the roof. The height of the fire plumes venting from the rear wheelhouses increased until the fire was extinguished starting at about 155 seconds post ignition.

1. Flame Spread through Crash Induced Seam Openings around the Left Rear Wheelhouse

Between 20 and 30 seconds post ignition, flames started to spread into the passenger compartment through crash induced seam opening between the left rear wheelhouse panel and the left inner quarter panel. This flame spread behavior was indicated by the temperatures recorded at A5 to A8, A10 to A14, and A16 to A21, which were close to or greater than 600 ^{o}C.

2. Flame Spread through Crash Induced Seam Openings around the Right Rear Wheelhouse

The flames entered the right side of the trunk through a crash induced seam opening between the right wheelhouse panel and the floor panel in the areas of the shock tower. This behavior was indicated by the temperature recorded at A26, which exceeded 600 ^{o}C between 17 and 21 second post ignition and from 87 seconds to the end of the test. Flames were present behind the right side of the rear seat back sporadically starting at 15 to 20 seconds post ignition. Temperatures recorded at A22, A23 and A24 did not exceed 600 ^{o}C at any time before the start of fire suppression.

3. Flame Spread on the Roof Trim Panel

Temperature data indicated that by 10 seconds post ignition, hot gases had started to flow into the left rear section of the roof trim panel and flames were present by 90 seconds post ignition. The area where the fabric on the lower surface of the roof trim panel was charred corresponded to the area where temperatures below the roof trim panel exceeded about 500 ^oC.

B-8-3. CONCENTRATION OF PRODUCTS AND RELEASE RATES OF HEAT AND PRODUCTS

The gas temperature in the passenger compartment was measured by six aspirated thermocouples, arranged inside a 16-in (406-mm) long vertical probe, located along the longitudinal mid-line of the vehicle about equidistant from the driver and the passenger seats. Each thermocouple was separated by a distance of 3-in (76-mm) and the first thermocouple was 0.5-in (13-mm) below the lower surface of the headliner.

Temperatures started to increase starting at about 80 seconds post ignition as flames started to spread into the passenger compartment and the space in the deformed roof. At 150 seconds post ignition, the temperature just below the roof trim panel was 546 ^oC. The burning upper layer extended 3- in (80-mm) to 6-in (150 mm) below the roof trim panel at the location of the aspirated thermocouples with a temperature gradient of 1.1 $^oC/mm$. The temperatures at 12-in (300-mm) to 15-in (380-mm) were 32 ^oC at 150 seconds post ignition.

Concentrations of the products in the passenger compartment were measured at a location that was in the middle of the driver's seat and the front passenger seat, 10-in (250-mm) below the headliner. The instruments used for the measurements were FTIR, GC/MS, smoke particulate sampling apparatus and ion chromatograph (IC). FTIR was used to measure concentrations of CO, CO_2, CH_4, C_2H_4, C_2H_2, HCN, NO, and HCl. GC/MS were used to measure the relative abundance of higher molecular weight aliphatic and aromatic hydrocarbons (up to C_{15}). Smoke concentration was measured by the smoke particulate sampling apparatus and the inorganic anion concentrations by IC [fluoride (F^-), bicarbonate (HCO_3^-), chloride (Cl^-), nitrite (NO_2^-), bromide (Br^-), hypochlorite ($HClO_3^-$), nitrate (NO_3^-), phosphate (HPO_4^-), sulfate (SO_4^-), and oxalate ($C_2O_4^-$)].

Data for the smoke concentration is plotted in Fig. B-8-2 and the smoke composition is listed in Table B-8-2. Smoke consists of organic and inorganic compounds. The organic part of smoke consists of soot and lower and higher molecular weight organic compounds with low and high boiling points. The GC/MS data indicate that the organic part of smoke collected on the filter paper consists of aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure

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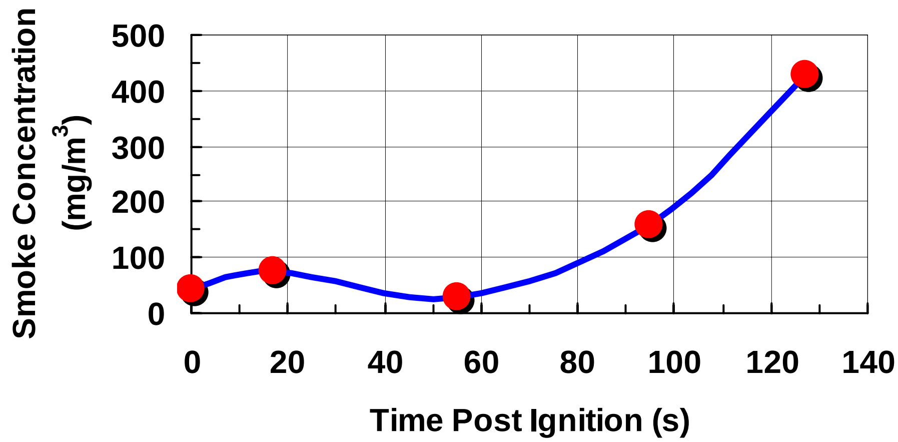

Figure B-8-2. Smoke concentration measured in the passenger compartment, 10-in below the headliner between the driver seat and the front passenger seat. Data are taken from Ref. 8.

Table B-8-2 Smoke Concentration and Composition

Sampling Time (s)	Smoke Concentration (mg/m^3)	% of Smoke Concentration		
		Organic	Cl^-	HPO_4^-
-45 to 0	44	99.1	0.0	0.9
0 to 33	76	96.7	0.0	3.3
33 to 77	27	94.6	3.1	2.3
77 to 112	157	93.7	5.6	0.7
112 to 142	428	91.4	6.5	2.1

The inorganic part of the smoke consists of anions, which were measured by IC in the study. The organic part of smoke was calculated from the difference in the mass of the filter paper and the anions measured by IC.

Figure B-8-2 shows the smoke concentration increases after about 50 seconds post ignition and reaches a peak value of 428 mg/m^3 between 112 and 142 seconds post ignition. Fire suppression was started at about 155 seconds post ignition

Data in Table B-8-2 indicate that the organic part of smoke was dominant (91 to 99%). The inorganic part of smoke consisted of Cl^- in the range of 0 to 6.5 % and HPO_4^- in the range of 0.7 to 3.3 %.

The measured concentration data listed in Table B-8-3 in the passenger compartment show that CO, CO_2, methane, ethylene, acetylene, HCN, and NO started to be released at about 50 seconds post ignition and their concentrations increased until about 155 seconds, a time at which fire suppression was started as fire started to grow rapidly and/or flashover was imminent. In this period of rapid fire growth or imminent flashover, between about 155 to 180 seconds post ignition, the concentrations increased very rapidly and reached their maximum values at about 180 seconds and then decreased, indicating the fire was being suppressed. Data for these periods are listed in Table B-8-3.

Table B-8-3. Maximum Product Concentrations in the Passenger Compartment just before Untenable/Flashover Conditions

Product	Maximum Concentration
CO	0.16 %
CO_2	1.0 %
CH_4	230 ppm
C_2H_4	350 ppm
C_2H_2	240 ppm
HCl	0 ppm
HCN	15 ppm
NO	5 ppm
Smoke	428 mg/m^3

The maximum CO to CO_2 concentration ratio, in the passenger compartment, during the fire growth period, was 0.18 and during the rapid-fire growth period it was 0.16, indicating that ventilation-controlled conditions were present in the vehicle burn test, i.e., measuring probe was near the flame. HCl was not present in the gas phase, although smoke collected on the filter paper contained up to a maximum of 6.5 % by weight of Cl^-, suggesting that the ions were removed from the gas phase by adsorption on the smoke particulates.

Release rates of heat, CO_2 and smoke measured in the fire plume over the burning 1998 Honda Accord are shown in Fig. B-8-3. Smoke concentration data are shown in Fig. B-8-4. CO concentration was not measured as the instrument malfunctioned during the test. In addition, data for the convective heat release rate are not reported due to errors found during fire suppression.

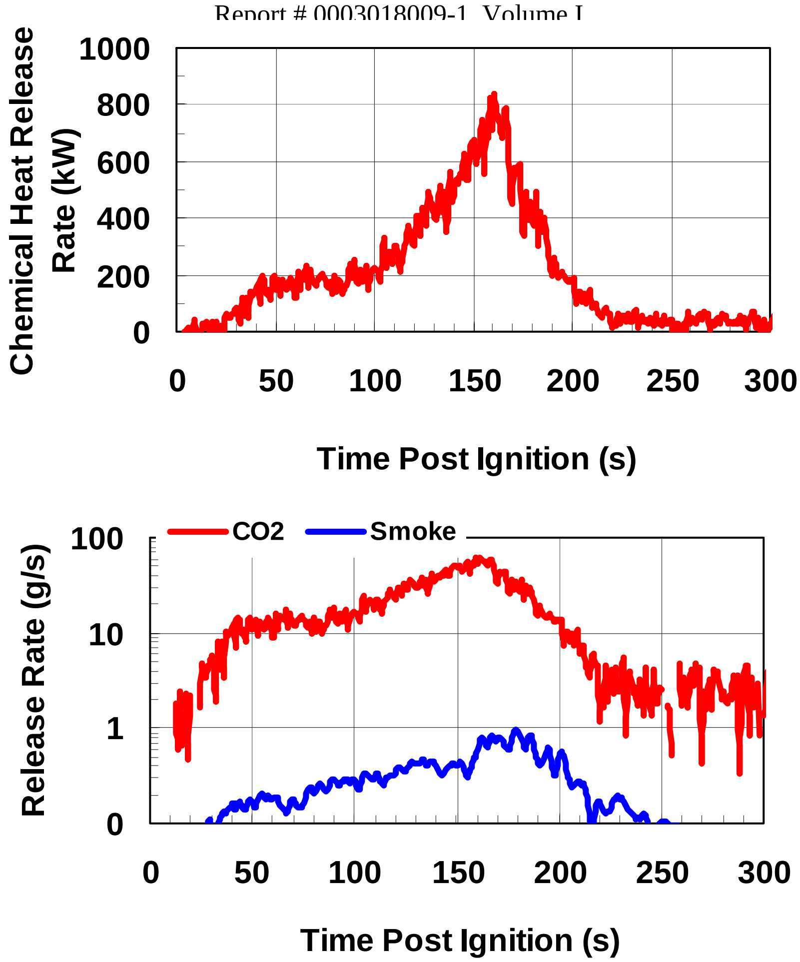

Figure B-8-3. Release rates of chemical heat, CO_2 and smoke in the burn test for the 1998 Honda Accord. Data are taken from Ref. 8.

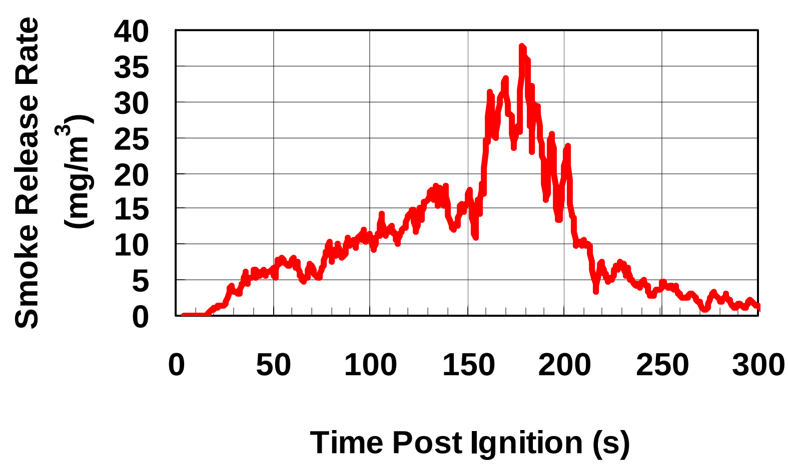

Figure B-8-4. Smoke concentration versus time in the plume of the burning 1998 Honda Accord. Data are taken from Ref. 8.

Release rates of heat, CO_2 and smoke reach their maximum values at about 155 seconds post ignition, a time when fire suppression agent was applied to a rapidly growing fire.

The maximum average smoke concentration in the plume, measured optically, reached a value of 15 mg/m^3 between 125 and 155 seconds post ignition and 35 mg/m^3 at 180 seconds post ignition and then decreased during fire suppression. In the passenger compartment, the maximum smoke concentration measured on the filter was 428 mg/m^3 between 112 to 142 seconds post ignition (Table B-8-2).

The smoke concentration measured optically is primarily the soot concentration in smoke, whereas the smoke collected on the quartz fiber filter in the smoke particulate sampling apparatus from the passenger compartment consists of both soot and higher molecular weight organic and inorganic compounds. The GC/MS and IC data for smoke collected on the quartz fiber filter paper from the passenger compartment indicated that a large fraction of smoke in the passenger compartment consisted of higher molecular weight aliphatic and aromatic hydrocarbons up to 15 carbon atoms in the chemical structure.

These data show that the organic part of smoke in the passenger compartment consists of 91 to 99 % of higher molecular weight aliphatic and aromatic hydrocarbons and some soot. The inorganic part of smoke in the passenger compartment consists of 0 to 6.5 % of Cl^- and 0.7 to 3.3 % of HPO_4^-. The smoke composition changes significantly in the plume, where large amounts of the organic part of smoke are consumed, whereas the composition of the inorganic part is not expected to change much.

B.9.10. FULL SCALE VEHICLE FIRE TESTS OF A CONTROL VEHICLE AND A TEST VEHICLE CONTAINING A HVAC MODULE MADE FROM PLASTICS CONTAINING FLAME RETARDANT CHEMICALS: TESTS #9 AND #10

The information included in this appendix is taken from the report entitled "Part 1: Full Scale Fire Tests of a Control Vehicle and a Test Vehicle Containing a HVAC Module made from Polymers Containing Flame Retardant Chemicals", by Jeffrey Santrock, NHTSA Docket Number: 3588; Document Number: NHTSA-1998-3588-190, www.nhtsa.dot.gov [9]. Tests were performed using two vehicles of the same model (1999 Chevrolet Camaro) with an objective to evaluate the effectiveness of fire retardants in reducing the burning intensity of vehicle fire initiated in the engine compartment. The control vehicle had standard plastic parts; whereas the HVAC module from the other vehicle was removed and replaced with an HVAC module containing fire retarded polypropylene and polyester components. The vehicle was identified as the FR vehicle. The control and FR vehicles were crashed using identical crash test protocols.

The fire propagation tests with the control and FR vehicles were performed on February 17 and 21, 2000 respectively at FM Global using identical fire test protocols, where fires were started in the engine compartment. The crash tests with the FR and control vehicles were performed on October 13 and 27, 1999 respectively at the GM Proving Ground. In the crash tests, the vehicles were towed onto a steel pole at a speed of 55 kmh (34.3 mph) with point of contact to the right of the vehicle centerline. The lateral offset between the vehicle longitudinal centerline and the pole center was 300 mm. The vehicles contained factory fills of motor oil (4.3 liters), transmission fluid (4.7 liters), engine coolant (10.8 liters), brake fluid (0.78 liter), power steering fluid (0.72 liter) and windshield washing fluid. The fuel tanks in each of the vehicle contained 60.4 liters of Stoddard solvent. Gasoline for the engine was supplied from a secondary fuel tank. Before impact, engines in the control and FR vehicles were run for about 3 and 1 hour respectively and were left running in the crash tests.

For the fire propagation test, all the doors were closed and the door window glasses were raised to the fully close position in each door. The glass outer-layers in the windshields of both the control and FR vehicles broke in the crash tests. The windshields remained attached to the frames of the vehicles, with the windshield inner-layer supporting the glass fragments. The right window glasses (passenger door) in both the control and FR vehicles were broken during the crash tests and were not replaced for the fire tests.

The fire was started in each test by an electrical igniter installed in the air cleaner housing in the engine compartment. The electrical igniter consisted of nichrome heating wire wrapped around several pieces of polypropylene sheet, producing about 1.2 kW of energy. On ignition, flames were observed in the areas around the air cleaner housing in the engine compartment of each vehicle.

B.9.10-1. TEMPERATURES MEASURED AT VARIOUS LOCATIONS

Thermocouple locations used to monitor temperatures and flame spread behavior are shown in Fig. B.9.10-1. Locations where temperatures were measured by thermocouples are:

1) **HVAC Air Intake Cowl in the Front of the Vehicle (#1 in Fig. B.9.10-1)**
a) C1 to C5: on the upper surface of the HVAC air intake cowl cover extending into the HVAC air intake;
2) Engine Compartment (# 2 in Fig. B.9.10-1)
a) E1: on the upper surface of the battery;
b) E2 to E6: in the air cleaner assembly;
c) E7: on the upper surface of the power distribution center;
d) E8: on the upper surface of the left front headlight;
e) E9: on the upper surface of the brake fluid reservoir;
f) E10: on the right side of exterior surface of HVAC;
g) E11: on the left side of exterior surface of HVAC;
h) E12: inside the air cleaner assembly above the igniter.
3) Windshield (#3 in Fig. B.9.10-1)
a) W1 to W10: on the outer surface of the windshield.
4) HVAC Evaporator-Left (#4 in Fig. B.9.10-1)
a) H1, H3, H5, H7, H9, H11, H13, H15 and H17: extended about 2.5-cm outward from the left side surface of the evaporator;
5) HVAC Evaporator-Right (#5 in Fig. B.9.10-1)
b) H2, H4, H6, H8, H10, H12, H14, H16 and H18: extended about 2.5-cm outward from the right side surface of the evaporator;
5) HVAC Module (#6 in Fig. B.9.10-1)
a) H20 and H21: about 2.5-cm forward of the front surface of the heater core;
b) H22: about 1-cm below the top surface of the HVAC module distribution ducts;
c) H23: about 1-cm below the top surface of the HVAC module mixing doors;
d) H24 and H25: in the HVAC air intake opening.

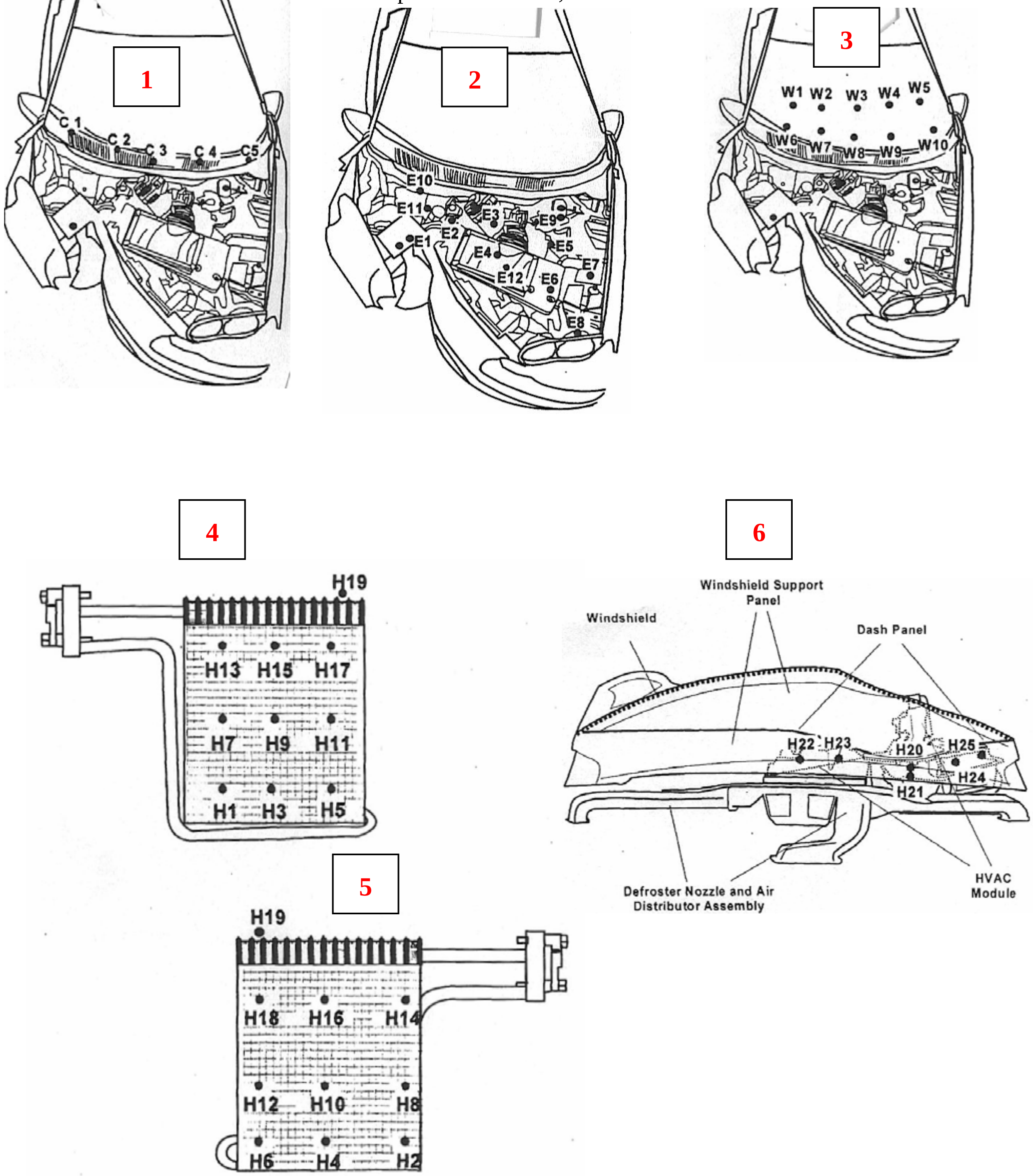

Figure B.9.10-1. Thermocouple locations: 1) HVAC air intake cowl; 2) engine compartment; 3) windshield; 4) HVAC evaporator-left; 5) HVAC evaporator-right; 6) HVAC module. Sketches are taken from Ref. 9.

Table B.9.10-1 lists the average maximum temperatures and time durations measured in the control and FR vehicle burn tests.

Table B.9.10-1. Maximum Temperatures and Time Durations Measured in the Control and FR Vehicle Burn Tests [9]

Location	Control Vehicle		FR Vehicle	
	Time Duration Post Ignition (s)	Maximum Temperature (^oC)	Time Duration Post Ignition (s)	Maximum Temperature (^oC)
HVAC air intake cowl (#1 in Fig. B.9.10-1)				
C1	360 to 570	800	300 to 720	800
C2	420 to 690	800	240 to 690	850
C3	300 to 720	750	240 to 690	870
C4	360 to 750	900	300 to 720	900
C5	540 to 720	950	450 to 780	880
Engine Compartment (#2 in Fig. B.9.10-1)				
E1	600 to 690	875	240 to 750	825
E2	480 to 600	850	270	1000
			360 to 780	700
E3	540 to 810	650	330 to 390	950
E4	300 to 750	750	90 to 300	750
E5	480 to 720	750	360 to 540	900
E6	510 to 750	875	510 to 780	650
E7	720 to 768	750	720 to 780	725
E8	780	850	690 to 780	875
E9	540 to 630	850	420 to 720	800
E10	420	350	> 600	< 75
E11	780	250	630 to 780	300
E12	420 to 720	875	300 to 450	800
Windshield (#3 in Fig. B.9.10-1)				
W1	780	350	780	400
W2	780	325	648 to 780	150
W3	420 and 780	150	420 and 780	150
W4	780	625	780	650
W5	780	250	780	150
W6	420	300	540 to 720	675
	780	400		
W7	330	650	660 to 780	675
	750	650		
W8	390 to 450	775	660 to 720	475
W9	630	675	510	825
	750	575	690 to 750	825
W10	720	500	660 to 780	750

Table B.9.10-1 continued on the next page

Table B.9.10-1 continuing from the previous page

Location	Control Vehicle		FR Vehicle	
	Time Duration Post Ignition (s)	Maximum Temperature (^oC)	Time Duration Post Ignition (s)	Maximum Temperature (^oC)
HVAC Evaporator-left (#4 in Fig. B.9.10-1)				
H1	780	250	≥ 780	70
H3	780	175	≥ 780	75
H5	810	150	≥ 780	50
H7	750	625	780	125
H9	780	700	780	125
H11	810	450	780	75
H13	780	225	750	350
H15	780	250	780	175
H17	750	725	780	100
H19	780	75	≥ 780	100
HVAC Evaporator- Right (#5 in Fig. B.9.10-1)				
H2	600 to 720	600	≥ 780	50
H4	≥ 780	100	≥ 780	75
H6	780	100	≥ 780	75
H8	750	570	780	150
H10	750	550	≥ 780	75
H12	780	150	≥ 780	75
H14	780	150	780	250
H16	780	450	≥ 780	175
H18	810	350	≥ 780	100
H20	780	250	780	100
HVAC Module (#6 in Fig. B.9.10-1)				
H21	810	125	810	50
H22	810	75	≥ 780	75
H23	≥ 780	100	≥ 780	75
H24	≥ 780	125	720	275
H25	≥ 780	150	780	325

B.9.10-2. FLAME SPREAD IN THE ENGINE COMPARTMENT

Flames spread rearward from the air cleaner housing, where igniter was located, to the air inlet screen along the lower edge of the windshield, then laterally along the air inlet screen to the right side of the engine compartment. Differences in the shapes of the deformed hoods, the geometries of the engine compartments and the arrangement of components within the engine compartments appeared to have affected the timing of the flame spread in the engine compartment. The gap between the air cleaner housing cover and the air cleaner housing was larger in the FR vehicle than in the control vehicle, allowing flames to emerge from the air cleaner about 150 seconds sooner in the FR vehicle than in the control vehicle. Ignition and flame spread observations are listed in Table B.9.10-2.

Table B.9.10-2. Ignition and Flame Spread Observations for the Burn Tests for Control and FR Vehicles [9]

Observations- Engine Compartment	Time Post Ignition (s)	
	Control Vehicle	FR Vehicle
Flames from the burning igniter and air cleaner element started to emerge from the rear of the air cleaner housing	210	60
Ignition of the air inlet screen and spread of flames laterally along the hood face seal on the air inlet screen	280	180
Ignition of the right edge of the HVAC air inlet screen, a section of wiring harness on top of the right front wheelhouse and the inner edge of the right fender	340	240
Flame spread to the right side of the air inlet screen; temperature > 800 ^{o}C. Most of the combustible materials in the upper section of the right side of the engine compartment appeared to be burning and flames started to spread to the left side of the engine compartment around the brake fluid reservoir	420	300
Ignition of the combustible materials in the front of the left side of the engine compartment	420 to 540	540 to 660
Flames spreading into the passenger compartment through the windshield opening reaching the rear of the instrument upper trim panel and pieces of burning windshield start to fall inward- end of the test	767	770
Start of fire suppression	780	780

The patterns of burn damage in and around the engine compartments of the control and FR vehicles were similar. Combustible materials in the upper sections of the engine compartments were largely consumed by the fire. Sections of glass fiber mat from the hood silencer pad had detached from the hood and were lying on top of the left side of the engine, the generator, the HVAC module and the left wheelhouse panel. The left and right outer fender panels had ignited and burned. Pieces of fender panels fell off the test vehicles and were visible on the ground near the vehicles after the tests. The front bumper fascia and energy absorber ignited and were largely consumed by the fire.

Sections of the auxiliary A/C evaporator and blower upper cases in the engine compartment, exposed to flames at about 690 seconds post ignition, had ignited during the tests for both the vehicles.

B.9.10-3. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

Flames entered the passenger compartment concurrently through: 1) the windshield onto the instrument panel top cover and 2) the HVAC module in the dash panel. During the tests, pieces of windshield fell inward igniting the deployed passenger air bags and the front seat cushions. Sections of A/C evaporator and blower, upper cases exterior to the dash panel, ignited during the tests.

The exterior surfaces of the windshield were exposed to hot gases and flames from the burning air inlet screen in both the vehicles. The following observations were made during the flame penetration into the passenger compartment through the windshield:

1) *Between about 240 and 300 seconds in the control vehicle and about 180 and 240 second in the FR vehicle post ignition*: temperatures on the air inlet screen and sections of the windshield just above it exceeded 600 ^{o}C;
2) *Between about 420 and 480 seconds post ignition*: radiation from the flames heated the windshield and caused its inner layer to soften and stretch and its lower portion to sag onto the instrument panel top cover in both the tests;
3) *By about 480 seconds post ignition*: pieces of windshield separated and fell onto the instrument panel top cover and deployed passenger air bag in the passenger compartment in both the tests;
4) *By about 750 seconds post ignition*: flames had spread rearward along the top of the instrument panel to the passenger air bag cover and the bag itself in both the tests. The lower section of the right A-pillar trim panel had ignited and was burning in both the tests;

B.9.10-4. CONCENTRATION OF PRODUCTS AND RELEASE RATES OF HEAT AND PRODUCTS

The gas temperature in the passenger compartment was measured by six aspirated thermocouples, arranged inside a 16-in (406-mm) long vertical probe, located along the longitudinal mid-line of the vehicle about equidistant from the driver and the passenger seats. Each thermocouple was separated by a distance of 3-in (76-mm) and the first thermocouple was 0.5-in (13-mm) below the lower surface of the headliner.

Air temperatures just below the headlining trim panel in the passenger compartment, recorded by the aspirated thermocouples, started to increase between about 300 and 600 seconds post ignition in both the tests. Air temperature at the location of the aspirated thermocouple assembly reached a maximum value of 160 ^{o}C at 776 seconds in the test for the control vehicle and 114 ^{o}C at 778 seconds post ignition in the test for the FR vehicle. Air temperature decreased with distance below the headlining trim panel. At about 18-in (457-mm) below the headlining trim panel, air temperature reached a value of 50 ^{o}C at 795 seconds in the control vehicle burn test and 44 ^{o}C at 799 seconds post ignition in the FR vehicle burn test. Burning upper layer did not develop in either of the tests.

During the tests, combustion products entered the passenger compartment before the flame spread. The concentrations of the products in the passenger compartment were measured by FTIR and GC/MS at a location that was in the middle of the driver's seat and the front passenger seat, 10-in (250-mm) below the headliner. Smoke particulate sampling apparatus and the ion chromatograph (IC) were not used in these tests. Concentrations of only CO, CO_2, CH_4, C_2H_4, C_2H_2, HCN, NO, and HCl were measured in the tests. The products started to be released at about 780 seconds in the control vehicle test and in about 300 seconds post ignition in the FR vehicle test. In the FR vehicle test, there were two peaks for the product concentrations occurring at about 390 seconds and close to untenable/flashover conditions, whereas in the control vehicle test, there was only one peak for the product concentrations close to untenable/flashover conditions. Maximum concentrations of products occurring at about 390 seconds for the FR vehicle and close to untenable/flashover conditions for both vehicles are listed in Table B.9.10-3.

Table B.9.10-3. Maximum Product Concentrations in the Passenger Compartment

Product	Maximum Concentration (ppm)		
	At about 390 s	Close to Untenable/Flashover Conditions	
	FR Vehicle	FR Vehicle	Control Vehicle
CO	1000	100	330
CO_2	3,200	400	2400
CH_4	350	100	70
C_2H_4	550	100	50
C_2H_2	450	80	50
HCN	27	8	10
NO	6	3	14

The release rates of heat, CO_2, CO and smoke, concentration of smoke and concentration ratios of CO to CO_2 measured in the fire plume over the burning control and FR vehicles are shown in Figs. B.9.10-2 and B.9.10-3 .

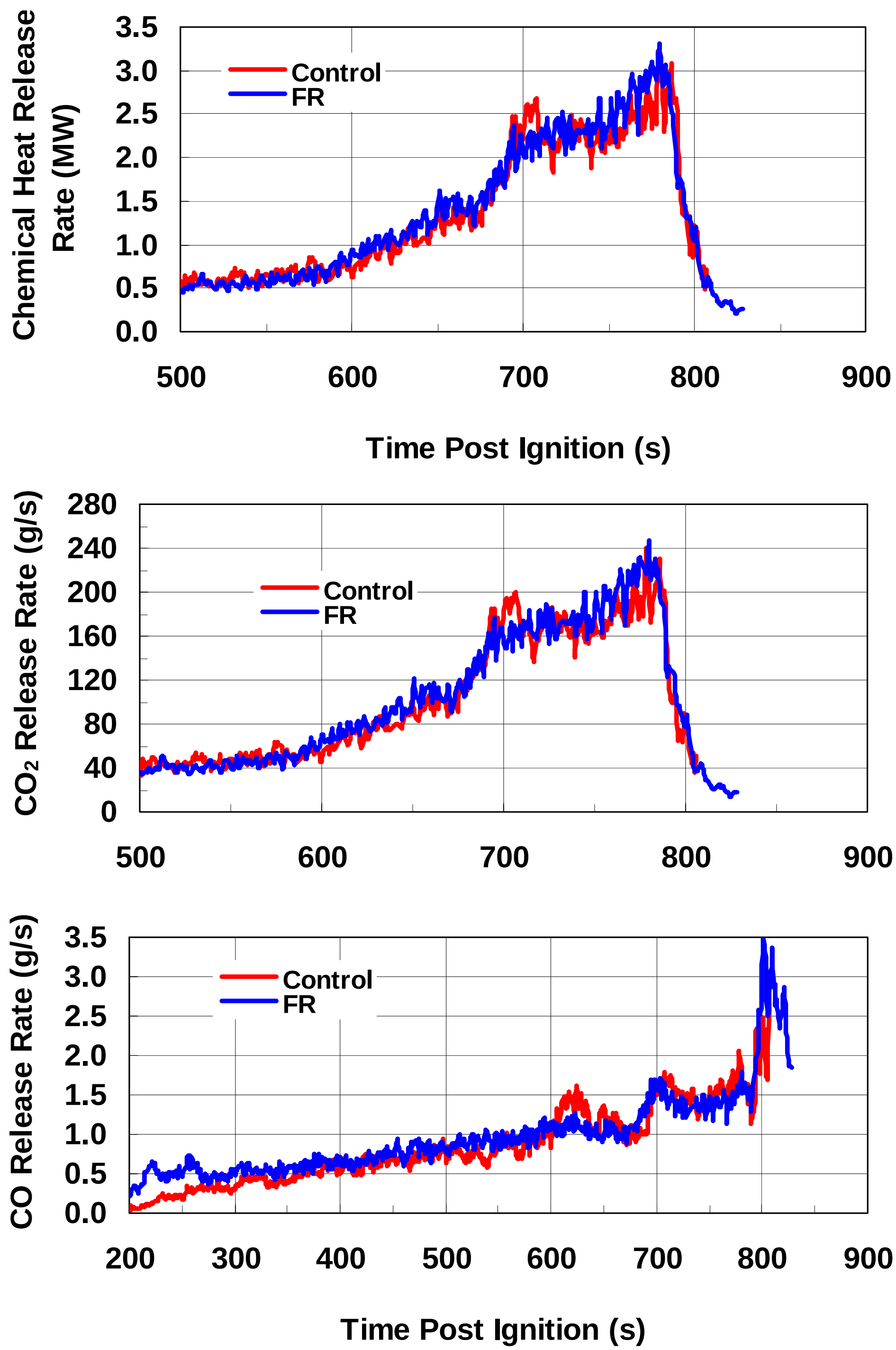

Figure B.9.10-2. Release rates of heat, CO_2 and CO in the burn tests for the control and FR vehicles. Data are taken from Ref. 9.

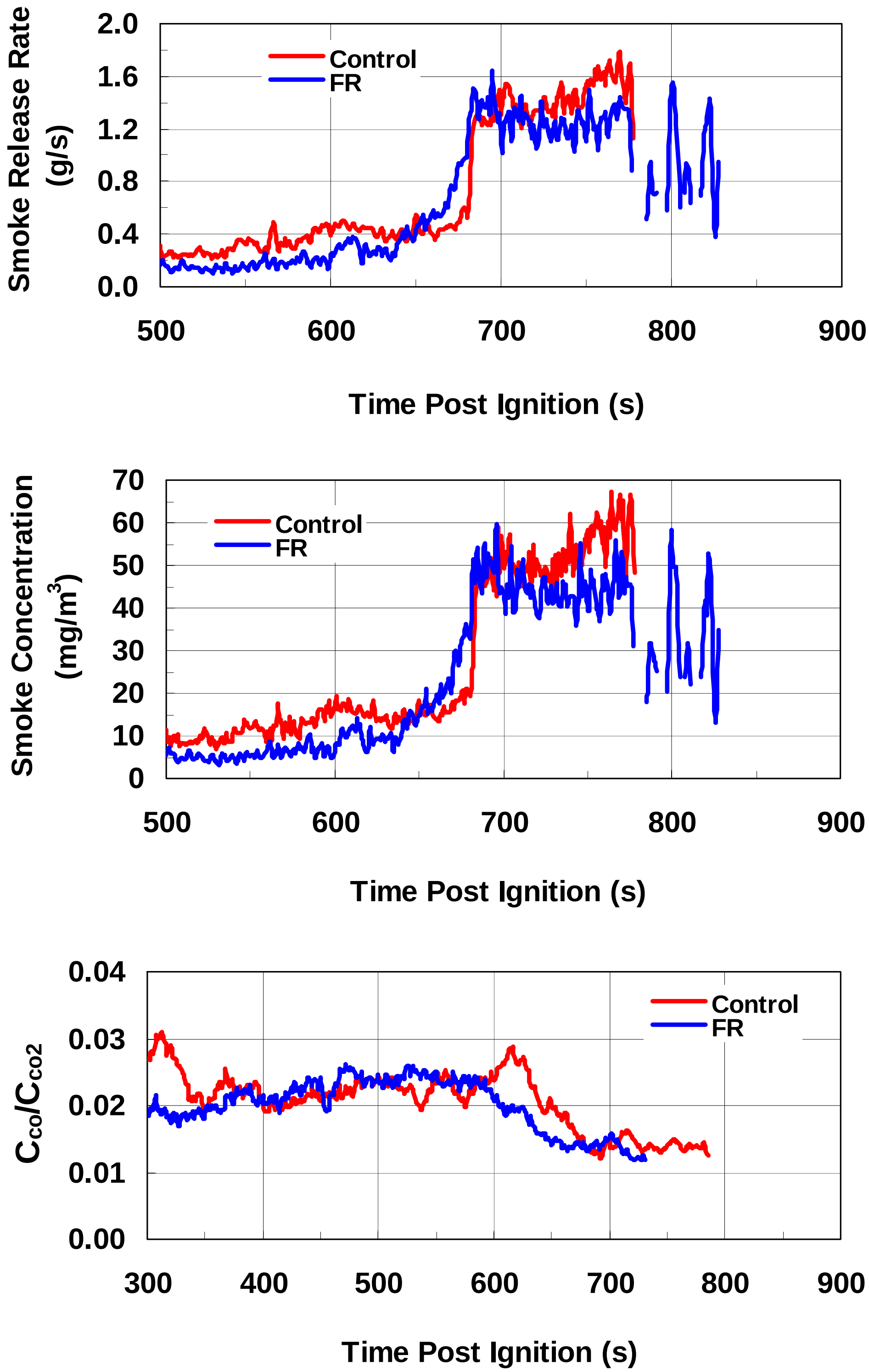

Figure B.9.10-3. Release rates of smoke and its concentration and ratio of CO to CO_2 concentrations in the burn test for the control and FR vehicles. Data are taken from Ref. 9.

Although differences in the shape and orientation of the deformed hoods of the vehicles resulted in differences in timing in the flame spread in the engine compartments for the first 300 seconds, distributions of flames in the engine compartments were essentially the same by about 360 seconds post ignition.

All the profiles in Figs. B.9.10-2 and B.9.10-3 for the release rates of heat, CO_2, CO, smoke, concentration of smoke and CO to CO_2 concentration ratio for the tests with the control and FR vehicles are also similar. The release rate profiles in Figs. B,9.10-2 and B.9.10-3 indicate that the rates start to increase rapidly (fire start to grow rapidly) at about 650 seconds post ignition, reaching maximum values close to untenable/flashover conditions. In the tests, at about 767 and 770 seconds post ignition, flames had spread rearward on the instrument panel upper trim panel and pieces of burning windshield were falling into the passenger compartment for the control vehicle and FR vehicle tests respectively. Fire suppression for both tests was started at 780 seconds post ignition.

Smoke in the passenger compartment as observed visually was greater in the FR vehicle test than in the control vehicle test. The concentrations of the products measured in the passenger compartment (Table B.9.10-3) indicate that between about 300 to 540 seconds post ignition, large amounts of CO, CO_2, methane, ethylene, and acetylene were present in the passenger compartment in the FR vehicle test, but these products were absent in the control vehicle test. However, between about 780 and 840 seconds post ignition, the concentrations of these products in both the tests were comparable (CO_2 concentration appears to be erroneous). HCN and NO were also present, but HCl was absent.

Sections of the auxiliary A/C and blower upper cases ignited and burned in both the tests. The case in the control vehicle was made from 40% talc-filled polypropylene resin. The case in the FR vehicle was made from polypropylene containing antimony trioxide, decabromodiphenyloxide and zinc based flame retardant. The cases were exposed to flames starting at about 340 seconds in the control vehicle test and at about 240 seconds post ignition in the FR vehicle test. The cases above the A/C evaporator core were burned in both the tests. The amounts of materials consumed in the fire tests were about the same and all the test data were essentially similar. Thus, the particular flame retardants used in the HVAC module did not result in an observable difference in the flammability of the HVAC module in these tests; however, there may be other retardants, which could be effective.

B.11 FULL SCALE VEHICLE FIRE TESTS OF A CONTROL VEHICLE AND A TEST VEHICLE CONTAINING AN INTUMESCENT PAINT ON ITS UNDERBODY: TEST #11

The information included in this appendix is taken from the report entitled “Part 3: Full Scale Fire Tests of a Control Vehicle and a Test Vehicle Containing an Intumescent Paint on its Underbody”, by Jeffrey Santrock and E. LaDue, NHTSA Docket Number: NHTSA-1998-3588-204, www.nhtsa.dot.gov [10]. Test was performed using a 1999 model of Ford Explorer, identified as the experimental vehicle. The results were compared with the results of the test performed previously on June 11, 1998 with a 1998 model of Ford Explorer (test #6) [6], identified as the control vehicle (Appendix B, Section B.6). The objective of the test was to evaluate the effectiveness of intumescent coating applied to the floor panel in blocking the flame penetration into the passenger compartment and in reducing the heat transfer through the floor panel by the gasoline pool fire under the vehicle.

The fire propagation test was performed on February 23, 2000 at FM Global. Prior to the fire propagation test, the experimental vehicle was crashed on November 24, 1999 at the GM Proving Ground. In the crash test, the vehicle was stationary (parked with the brakes on and positioned at a 21 ^{o} angle relative to the velocity vector of the moving barrier) and was struck in the left front corner (driver’s side) by a moving barrier. The vehicle contained factory fills similar to that of the control vehicle: motor oil (4.3 liters), transmission fluid (4.7 liters), engine coolant (10.8 liters), brake fluid (0.78 liter), power steering fluid (0.72 liter) and windshield washing fluid. Gasoline for the engine was supplied from a secondary fuel tank. Before impact, engine was warmed. The crash test did not result in a fire or a leak in the fuel system.

For the fire propagation test, all the doors were closed, except for the left front door, the window glasses were raised to the fully closed position in each door. In the test, gasoline was allowed to flow at a rate of about 300 ml/min into the fuel tank skid plate and onto the cement board surface under the vehicle for about 30 seconds, very similar to that allowed in the test for the control vehicle (test #6). A propane torch was used to ignite the gasoline vapors at about 38 seconds after the start of the gasoline flow, very similar to that used in the test #6 for the control vehicle (at 28 seconds). The diameter of the gasoline pool fire on the cement board was estimated to be between 10 and 15 inches wide from the time of ignition through 30 seconds post ignition (in test #6 for the control vehicle, the diameter was about 15-in). The flames from the gasoline pool fire were observed to contact and spread along the lower surface of the fuel tank skid plate, very similar to that observed in test #6 for the control vehicle. The rate of consumption of gasoline in the fuel tank skid plate was higher than the flow rate of liquid gasoline onto the skid plate, very similar to test #6. By 150 seconds post ignition, the size of the gasoline pool fire decreased substantially, very similar to that observed in test #6 for the control vehicle at 210 seconds post ignition.

The flames from burning gasoline on the cement board spread out along the lower surface of the fuel tank skid plate and the underbody between the fuel tank and left rocker panel in test #11 for the experimental vehicle, very similar to that observed in test #6 for the control vehicle. Temperatures measured at various locations in test #11 for the experimental vehicle indicated that the area of the floor panel above the front inboard corner of the fuel tank, that contained two electrical pass-through openings, was exposed to flames from about 30 seconds post-ignition to the end of the test. Temperatures in this area were > 500 ^{o}C between 15 and 30 seconds post ignition and increased to > 600 ^{o}C between 270 and 300 seconds post ignition. Differences in temperatures measured below the floor panel at several places indicated that there were differences in the distribution of flames on the underbodies in test #6 for the control vehicle and test #11 for the experimental vehicle.

Test #11 for the experimental vehicle was ended and fire suppression started at 300 seconds post ignition, whereas test #6 for the control vehicle was ended and fire suppression started between 250 to 260 seconds post ignition.

B-11-1. TEMPERATURES MEASURED AT VARIOUS LOCATIONS

Thermocouple locations used in the test for the experimental vehicle to monitor temperatures and flame spread behavior are shown in Fig. B-11-1. Locations where temperatures were measured by thermocouples are:

1) **Lower Surface of the Manual Transmission Shift Level Pass-Through Cover Plate (#1 in Fig. B-11-1)**

a) A1 to A5: on the gaps between the cover plate and floor panel caused by the deformation of the cover plate and floor panel;

2) Floor Panel (# 2 in Fig. B-11-1)

a) F1, F3, F5, F7, F9, F11, F13, F15, F17, F19, F21, D23, F24, F25, F26, F27 and F29: 1-cm below the lower surface of the floor panel;

b) F2, F4, F6, F8, F10, F12, F14, F18 and F30: attached to the upper surface of the floor panel;

c) F16: attached to the upper surface of the manual transmission shift lever pass-through cover plate;

3) Floor Pan Drain Hole Plugs (#3 in Fig. B-11-1)

a) P1: in an electrical pass-through opening in the floor panel where the grommet has been dislodged in the crash test;

b) P2: on the upper surface of a grommet in an electrical pass-through closure in the floor panel;

b) P3, P4, P5, P6, P7, P8, P9 and P10: on the upper surfaces of closures for drain holes in the floor panel.

4) Below the Left Front Seat (not shown in Fig. B-11-1): FS1, FS2, FS3 and FS4 just below the lower surface of the foam pad of the seat cushion;

5) Under the Right Rear Seat (not shown in Fig. B-11-1): RS1, RS2, RS3, and RS4 just below the loser surface of the foam pad of the seat cushion;

6) Under the Left Rear Seat (not shown in Fig. B-11-1): RS5, RS6, RS7, RS8, RS9 and RS10: just below the foam pad of the seat cushion;

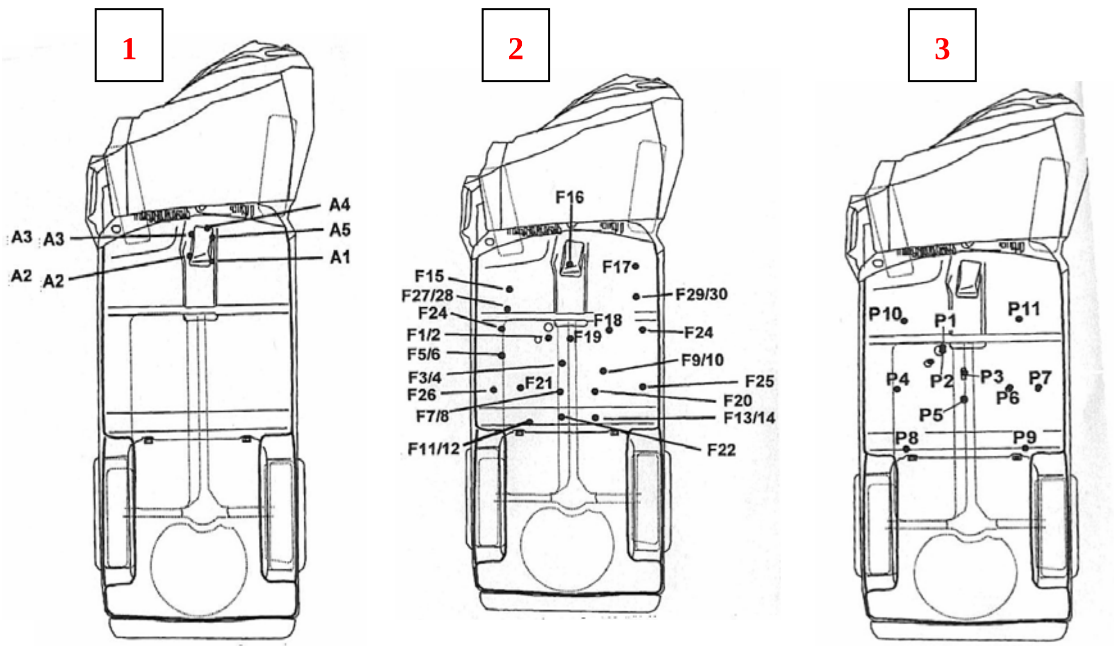

Figure B-11-1. Thermocouple locations: 1) manual transmission shift level pass-through cover plate; 2) floor panel; 3) floor pan drain hole plugs. Sketches are taken from Ref. 10.

Maximum average temperatures and time durations measured in the burn test for the experimental vehicle are listed Table B-11-1.

Table B-11-1. Maximum Average Temperatures and Time Durations [10]

Location	Time Duration Post Ignition (s)	Maximum Average Temperature (^oC)
Manual Transmission Shift Lever Pass-Through Cover Plate (#1 in Fig. B-11-1)		
A1	60 to 360	350
A2	360 t 480	300
A3	270 to 390	350
A4	270 to 390	500
A5	90 to 330	440
Floor Panel, Below the Lower Surface (#2 in Fig. B-11-1)		
F1	90 to 360	575
F3	150 to 330	425
F5	330	400
F7	300	600
F9	240 to 360	425
F11	210 and 330	475
F13	120 to 360	500
F15	240 to 360	300
F17	210 to 330	225
F19	30 to 330	500
F21	60 to 330	325
F23	30 to 300	575
F25	360	250
F27	150 to 330	350
F29	300	250
Floor Panel, Upper Surface (#2 in Fig. B-11-1)		
F2	360	500
F4	330	350
F6	300	300
F8	330	500
F10	360	375
F12	240 to 390	275
F14	360	425
F16	300 to 390	525
F18	120 to 330	425
F20	300	625
F22	30 to 300	600
F24	300	325
F26	360	350
F28	330	175
F30	300	200

Table B-11-1 continued on the next page

Location	Time Duration Post Ignition (s)	Maximum Average Temperature (^oC)
Floor Pan Drain Hole Plugs (#3 in Fig. B-11-1)		
P1	30 to 360	750
P2	330	625
P3	330	375
P4	390	250
P5	240	625
P6	300	425
P7	360	300
P8	360	350
P9	360	450
P10	330	200
P11	360	150
Below the Lower Surface of the Foam Pad in the Left Front Seat Cushion		
FS1	330	725
FS2	330	725
FS3	330	750
FS4	330	675
Below the Lower Surface of the Foam Pad in the Right Rear Seat Cushion		
RS1	≥ 300	< 50
RS2	≥ 300	< 50
RS3	≥ 300	50
RS4	≥ 300	50
Below the Lower Surface of the Foam Pad in the Left Rear Seat Cushion		
RS5	≥ 300	<50
RS6	≥ 300	<50
RS7	≥ 300	<50
RS8	≥ 300	<50
RS9	≥ 300	<50
RS10	≥ 300	<50

B-11-2. FLAME SPREAD INTO THE PASSENGER COMPARTMENT

The underbody of the experimental vehicle used in the test was coated with an intumescent paint. The drain hole and the pass-through closures in the floor panel, however, were not coated. Thus, the drain hole and the pass-through closures of the experimental vehicle used in test #11 and the control vehicle used in test #6, were physically very similar.

In both the vehicles (test #11 for the experimental vehicle and test #6 for the control vehicle), flames entered the passenger compartment through the electrical pass-through openings in the floor panel under the left front seat. Times for flame spreads into the passenger compartment in tests #6 and #11 were similar. Timings for the start of smoke flow out of the passenger compartment through the top of the left front door in tests #6 and #11 were also similar (between about 90 and 120 seconds post ignition). Hot gases started to flow onto the lower surface of the foam pad between about 50 and 60 seconds post ignition in test #11 and in about 20 seconds post ignition in test #6. Temperatures just below the lower surface of the foam pad in the left front seat cushion were greater than 600 ^{o}C between about 240 and 360 seconds post ignition in test #11 and at about 220 seconds post ignition in test #6. Flames were observed burning through the cushions in the left front seats in both the tests at about 270 seconds post ignition.

The principle of applying the intumescent coating to a surface is to reduce heat transfer to the surface as the coating bubbles or swells and chars as it is heated. The heat transfer is reduced because of the formation of an expanded insulating layer on the surface by the gas bubbles trapped in the charred residue. The intumescent coating applied to the underbody of the experimental vehicle was found to have some affect in reducing the heat transfer from the underbody gasoline fire into the vehicle floor, based on the comparisons of the heat flux and the temperature values between the experimental and control vehicle tests (tests #6 and #11). As a result, time to untenable/flashover condition was increased from 250 seconds (#6) to 300 seconds (#11).

The floor panel under the rear seat in the control vehicle test #6 ignited, an equivalent area of the floor carpet in the experimental vehicle test #11 did not ignite. These areas of floor carpets in both the vehicles had melted and showed evidence of thermal degradation because of the heat transfer from the burning gasoline under the vehicles through the floor panel. The thermally degraded carpet in test #6, for the control vehicle ignited, because flames had burned through a plug in a drain hole opening in the floor panel under the right side of the rear seat. In test #11 for the experimental vehicle, flames did not burn through the drain hole plug (there was no coating applied to the drain item). There was, however, some effect on the flame shape by the intumescent coating.

B-11-3. CONCENTRATIONS AND RELEASE RATES OF HEAT AND PRODUCTS

The gas temperature in the passenger compartment was measured by six aspirated thermocouples, arranged inside a 16-in (406-mm) long vertical probe, located along the longitudinal mid-line of the vehicle about equidistant from the driver and the passenger seats. Each thermocouple was separated by a distance of 3-in (76-mm) and the first thermocouple was 0.5-in (13-mm) below the lower surface of the headliner.

The maximum air temperatures measured by aspirated thermocouples between the driver's and front passenger seats are listed in Table B-11-2.

Table B-11-2. Vertical Gas Temperature between the Driver's and Front Passenger Seat

Distance from the Headliner (mm)	Maximum Temperature (^{o}C)	
	Control Vehicle (Test #6)	Experimental Vehicle (Test #11)
13	450	640
89	518	500
165	400	160
241	400	120
318	310	160
394	260	140

Gas temperatures closer to the roof (13 and 89-mm below the headliner) for test #11 for the experimental vehicle and test #6 for the control vehicle are comparable. However, below 165-mm from the roof, gas temperatures in test #6 for the control vehicle are significantly higher than the temperatures in test #11 for the experimental vehicle. Thus, decomposition of intumescent coating kept the temperature in the passenger compartment lower than recorded in the control vehicle.

In both the tests, concentrations of the products in the passenger compartment were measured by FTIR at a location that was in the middle of the driver's seat and the front passenger seat, 10-in (250-mm) below the headliner. Concentrations of the following products were measured in the passenger compartment: CO, CO_2, CH_4, C_2H_4, C_2H_2, HCN, NO, and HCl. Following additional instruments were used in test #6 for the control vehicle: 1) GC/MS to measure the relative abundance of higher molecular weight aliphatic and aromatic hydrocarbons (up to C_{15}) in the passenger compartment; 2) smoke particulate sampling apparatus to measure the smoke concentration in the passenger compartment; and 3) ion chromatograph (IC) to measure the concentrations of the following inorganic anions fluoride (F^-), bicarbonate (HCO_3^-), chloride (Cl^-), nitrite (NO_2^-), bromide (Br^-), hypochlorite ($HClO_3^-$), nitrate (NO_3^-), phosphate (HPO_4^-), sulfate (SO_4^-), and oxalate ($C_2O_4^-$).

The maximum concentrations of products measured in the passenger compartment close to the untenable/flashover ($\mathbf{t_{u,fl}}$) conditions for experimental vehicle (#11) and control vehicle (#6) are listed in Table B-11-3 (estimated $\mathbf{t_{u,fl}}$ = 250s for #6 and $\mathbf{t_{u,fl}}$ = 300s for test #11, see Chapters IV and V);

Data in Table B-11-3 show that the concentrations of products in the passenger compartment in test #11 for the experimental vehicle are higher than the concentrations in test #6 for the control vehicle, indicating decomposition of intumescent coating and longer time for pyrolyzate to accumulate in the passenger compartment before the untenable/flashover conditions are reached. The CO to CO2 concentration ratios in the passenger compartment in tests #6 and #11 are comparable (0.042 and 0.037 respectively), indicating similar combustion conditions (ventilation controlled condition).

Table B-11-3. Maximum Product Concentrations in the Passenger Compartment Close to Untenable/Flashover Conditions

Product	**Maximum Concentration**	
	Control Vehicle (Test #6)	**Experimental Vehicle (Test #11)**
CO (ppm)	1,600	7,500
CO_2 (ppm)	38,000	205,000
CH_4 (ppm)	300	650
C_2H_4 (ppm)	470	1,550
C_2H_2 (ppm)	450	2,600
HCN (ppm)	40	300
NO (ppm)	30	90
Smoke (mg/m^3)	1350	NR

The release rates of heat, CO_2, CO and smoke, concentration of smoke and concentration ratios of CO to CO_2 measured in the fire plume over the burning control and experimental vehicles in tests #6 and #11 respectively are shown in Figs. B-11-2 and B-11-3.

All the profiles in Figs. B-11-2 and B-11-3 are similar. Release rates of heat and CO_2, associated with the completeness of combustion in the fire plume, are somewhat higher in test #6 for the control vehicle compared to test #11 for the experimental vehicle. Release rates of CO and smoke, concentration of smoke and ratio of CO to CO_2 concentrations, associated with the incompleteness of combustion in the fire plume, are higher in test #11 for the experimental

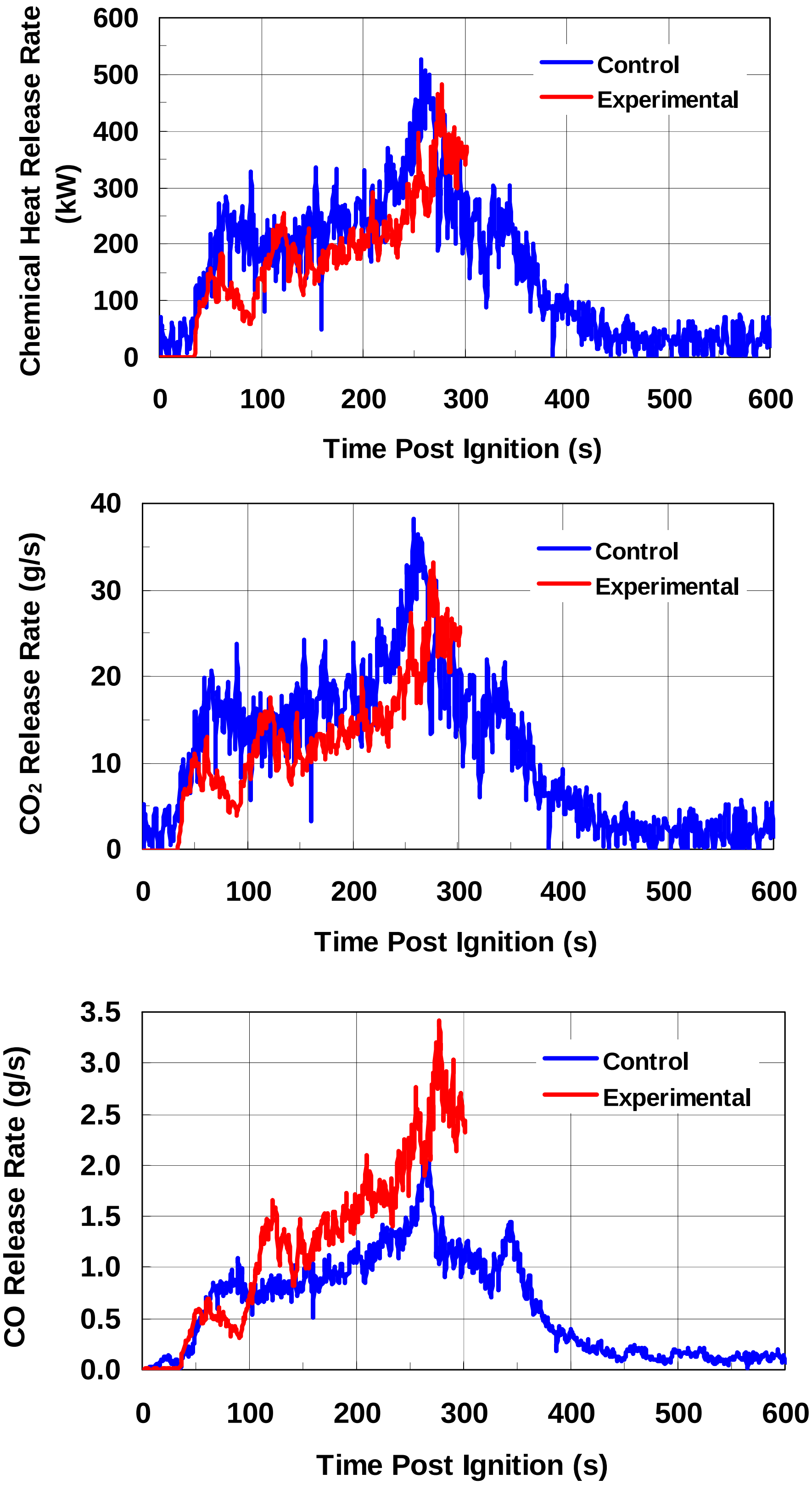

Figure B-11-2. Release rates of chemical heat, CO_2 and CO in tests #6 and #11 for the control and experimental vehicles respectively. Data are taken from Ref. 10.

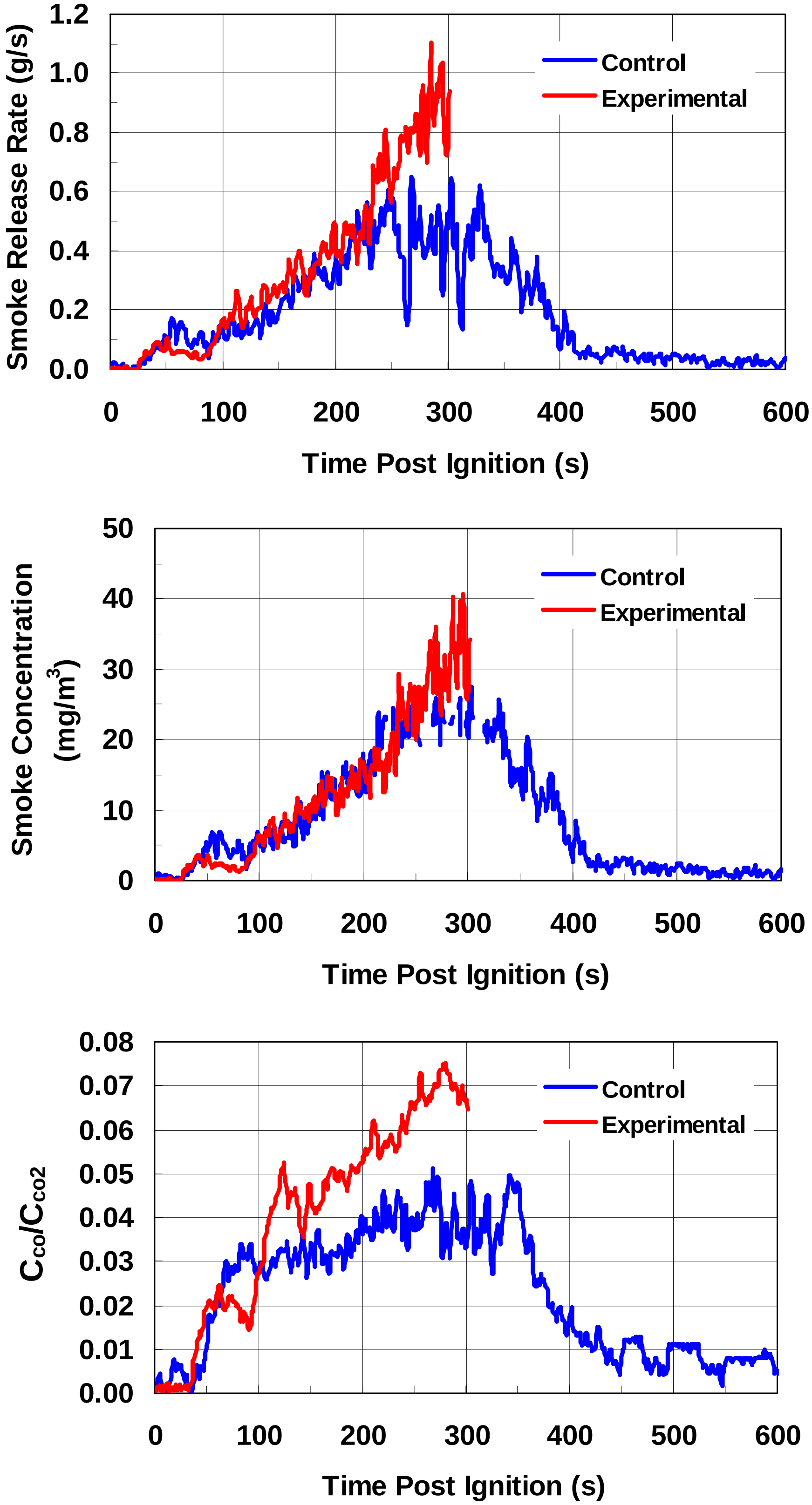

Figure B-11-3. Release rates of smoke and its concentration and ratio of CO to CO_2 concentrations in tests #6 and #11 for the control and experimental vehicles respectively. Data are taken from Ref. 10.

vehicle compared to test #6 for the control vehicle, similar to that found in the passenger compartment. These data suggest that combustion conditions in test #11 for the experimental vehicle were more fuel rich than in test #6 for the control vehicle, indicating that materials in test #11 were gasifying but were burning to a limited extent in the passenger compartment and in the plume compared to that in test #6.

B.12 FULL SCALE FIRE TESTS FOR SUPPRESSION OF VEHICLE FIRES: TEST SERIES # 12

The information included in this appendix is taken from the report entitled "Part 2A: Evaluation of Fire Suppression Systems in a Full Scale Vehicle Fire Test and Static Vehicle Fire Tests", by Jeffrey Santrock and Steven Hodges, NHTSA Docket Number: 3588; Document Number: NHTSA-1998-3588-204, www.nhtsa.dot.gov [11]. Several tests were performed to evaluate the effects of on-board fire suppression systems in controlling and suppressing fires resulting from vehicle crashes.

Prior to crash tests, the National Institute of Standards and Technology (NIST) evaluated the effectiveness of gaseous, dry chemical and solid propellant gas generator (SPGG) fire suppression systems in small and large-scale tests using engine compartment mock ups and in the engine compartment of a stationary vehicle with no crash damage [16]. The following order of effectiveness was found between the three types of the technologies: SPGG systems >dry chemical agents > gaseous agents [16].

For the suppression of fires resulting from vehicle crashes, the experimental fire suppression system based on optical fire detection and the SPGG fire suppression technology [11]. The fire suppression system used a solid propellant similar to that in the air bag inflators to produce mixture of inert gases and particulate that was propelled onto the fire in a high velocity gas discharge [11]. Fire suppression thus could occur via several paths: 1) displacement of air by inert gases and reduction in the availability of oxygen to the flame; 2) expansion of the inert gases resulting in the reduction of the total energy and the flame temperature; 3) fire suppression actions of the residue from the propellant similar to dry chemical agents; and 4) flame lift off due to high velocity discharge of gases from the SPGG unit.

The selected experimental fire suppression system based on optical fire detection and SPGG technology was installed in the engine compartment of a 1999 Honda Accord [11]. The fire suppression system included two prototype SPGG units and optical flame detectors. The SPGG units and the optical flame detectors were bolted to the lower surface of the hood. One SPGG unit with the optical flame detector was attached to the left side and the other on the right side of the hood rearward of the crush initiator in the inner hood panel. The SPGG units were preset to deliver a concentration of about 3 kg/m^3-s of dry chemical, a limit for fire suppression established by the manufacturer (this concentration has to be maintained for long enough time so that re-ignition does not occur).

The criteria for assessing the effectiveness of the fire suppression system in the event of a fire during the crash test and during the subsequent static fire tests were: 1) functionality of the fire suppression system during and after the crash test; 2) fire extinguishment in the engine compartment by the suppression system during the crash test or during manual fire initiation in the subsequent static tests.

B-12-1. Fire Suppression in a Crash Test

The 1999 Honda Accord with installed fire suppression system was subjected to a crash test on August 10, 1999 at the GM Proving Ground, using a test protocol that resulted in a fire in the engine compartment of a similar vehicle model in a previous crash test (#7 [7]). The cause of the fire in test #7 was determined to be autoignition of power steering fluid expelled from the fluid reservoir onto the exhaust manifold [7].

Before the crash test, a static warm-up procedure of the stationary vehicle was used for the 1999 Honda Accord with installed fire suppression system. The vehicle had factory fills of: motor oil (5.6 liters), transmission fluid (6.2 liters), engine coolant (6.9 liters), brake fluid (unknown), power steering fluid (1.1 liter) and windshield washing fluid. The fuel tank contained 61 liters of Stoddard Solvent (95% of the usable capacity of the fuel tank). Gasoline for the engine was supplied from a secondary fuel tank. Before impact, engine was warmed. After preparing the vehicle, it was kept stationary (positioned at a 21^{o} angle relative to the velocity vector of the moving barrier) and was struck in the left front corner (driver’s side) by a moving barrier.

The left front crash test resulted in a fire in the engine compartment of the vehicle. Flames were observed in the area of the exhaust manifold starting at about 184 ms after time zero. Flames were also observed in the area between the front of the engine and the upper radiator cross member at 220 ms after time zero. The GC/MS data showed the presence of power steering fluid vapors in the space between the exhaust manifold and heat shield. The temperature of the exhaust manifold runner was sufficiently high for the autoignition of the power steering fluid vapors.

Fire was detected by the optical flame detector on the left at 298 s, triggering the discharge of the SPGG unit on the left. Detector on the right did not detect fire at this time and thus the unit on the right did not discharge. This is consistent with the initiation of the fire on the left side of the engine compartment. The discharge of the SPGG unit on the left failed to extinguish the fire, except for a very short time in the beginning. Fire had to be extinguished manually. Table B-12-1 lists the event for flame spread in the engine compartment.

Table B-12-1. Flame Spread in the Engine Compartment [11]

Time (ms)	**Observations**
280	Flames in the front of the engine compartment in the approximate location of the exhaust manifold.
380	Effluent from the SPGG units venting from the engine compartment through the gaps between the deformed hood and the front fenders
1200	Effluent from the SPGG units venting from the engine compartment through the gaps between the deformed hood and the front fenders
2700	Flames emerging from under the front of the engine compartment. Fire suppression agent dispersed out of the engine compartment.

B-12-1. Fire Suppression in Static Vehicle Fire Tests

Four static fire tests were performed using the crashed 1999 Honda Accord model. The vehicle was stationary and other components in the engine compartment were at ambient temperature. Two new, fully charged SPGG units were installed in the vehicle before each test. The first static test involved manual activation of the SPGG unit without a fire in the engine compartment. In the subsequent three static tests, fires were ignited in the engine compartment using an electrical igniter or by spraying power steering fluid onto an electrically heated metal block. Table B-12-2 lists the observations for the static fire tests for suppression.

D-11-3. Comparison of the Fire Suppression Tests

The results from the fire suppression tests performed by GM [11] were different from the results of tests performed by NIST [12]. In the NIST tests, engine compartment mock ups and engine compartment of a stationary vehicle with no crash damage were used. In the NIST tests, 200 ml/min gasoline fire in the engine compartment of a stationary vehicle in the absence of forced ventilation was suppressed by less than 500 g of the solid propellant generator.

Table B-12-2. Observations for the Static Fire Tests for Suppression [11]

Test	Action	Observations
#1	Manual SPGG discharge without a fire in the engine compartment	Fragments of hood liner in the engine compartment and on the ground in the front of the vehicle. Ignition of materials in the engine compartment by the heated gas discharge from SPGG. Smoke rising from the hood liner fragments in the engine compartment. Glowing embers in some of the hood liner fragments
#2	Electric ignition of plastic	Flaming ignition of the plastic in 90 seconds and shortly afterwards SPGG units discharged. Power to the igniter was not turned off. Fire was extinguished, but plastic reignited in about 18 seconds. Fire was extinguished manually.
#3	Autoignition of the power steering fluid on a hot metal plate at 400 ^{o}C	The SPGG units discharged shortly after flames were detected. The flames were extinguished, but reignited after about 37 seconds after the first fire. Fire was extinguished manually
#4	Electrical ignition of top of the battery	Flaming ignition of the plastic in 90 seconds. Power to the igniter was turned off. Fire was not detected so SPGG units were discharged manually. Fire was extinguished.

The tests performed by GM, however, showed that the solid propellant generator was not effective in the suppression and extinguishment of the engine compartment fire. The differences in the test results of the studies at GM [11] and NIST [12] could be due to several factors; some of these factors have been identified by NIST:

- Rapidity of the suppressant discharge for penetration of the agent through the flow field obstacles (engine components);
- Details of the flow field geometry, fuel and suppressant associated parameters;
- Suppressant dispersion around the vehicle components;
- Extension of fuel pool in an underbody fire beyond he vehicle footprint and moderate to high winds;
- Suppression system nozzle type, orientation and placement.