

# FIRE BEHAVIOR OF AUTOMOTIVE POLYMERS

Archibald Tewarson

FM Global Research, Norwood, MA, USA (archibald.tewarson@fmglobal.com)

## ABSTRACT

Thermo-physical-chemical and fire properties of about 195 polymers from various automobile parts have been quantified in the mini- and small-scale tests. Some of these parts in their actual configurations and sizes have been burned in the intermediate-scale tests. In addition, seven latest models of automobiles from four manufacturers have been burned in the large-scale tests using two sets of crashed automobiles to simulate rear-crash and front-crash automobile fires. The properties of the polymers and fire behaviors of polymer parts and of automobiles have been used to identify fire paths into the passenger compartments and to develop principles for fire retardancy of polymers effective in automobile crash fire conditions.

In the study, it was found that untenable conditions were reached in the passenger compartment very rapidly in the rear-crash-simulated automobile fires, but took longer time to reach in the front-crash-simulated automobile fires. Certain automotive parts could not resist the flame penetration into the passenger compartment, for which effective fire retardant treatments would be needed. Penetration of thermal wave into the passenger compartment was found to be as important as the penetration of flame for untenable conditions. Polymer softening, melting, melt-flow, decomposition and vaporization indicate importance of the thermal wave penetration that needs to be investigated under vehicle crash fire conditions.

## INTRODUCTION

Polymers used in the design of automobile parts are inherently flammable and have been involved in automobile fires especially in vehicle crashes. As a result, a Fire Safety Research Program was established by the General Motors (GM) Corporation pursuant to the "Settlement Agreement" of March 7, 1995 between GM and the US Department of Transportation (DOT). The GM Fire Safety Research Program had the following objectives [1]:

- Identify fire paths into the passenger compartment with fire initiated in the engine compartment as a result of front crash, and in the rear under the vehicle by small pool fire due to leaking gasoline as a result of rear crash;
- Identify technologies to increase passenger escape or survival time from a vehicle fire in a crash. The technologies could include increased fire resistance of automotive polymers, blocking the underbody fire by highly fire resistant body plugs, and onboard fire detection, suppression, and extinguishment.

The objectives set forth in the Program were fulfilled by the performance of the following tests:

- *Mini-scale tests*: performed at GM to quantify the thermo-physical-chemical properties and nature of chemical compounds in automotive polymer vapors [2,3,4,5,6,7];
- *Small-scale tests*: performed at GM in the modified 9833P flammability apparatus [8,9] and at FM Global Research in the ASTM E 2058 apparatus [10,11,12] to quantify the fire properties of the automotive polymers;

- *Intermediate-scale tests*: performed at the National Institute of Standards and Technology (NIST) to quantify the fire behavior of automotive polymer parts, using the 100-kW and 500-kW Calorimeters [13,14,15];
- *Front and rear vehicle crash tests*: performed at GM [16,17,18,19,20];
- *Large-scale crashed vehicle burn tests*: performed at FM Global Research [21,22,23,24,25,26,27]. The large-scale tests were terminated when untenable conditions were reached in the passenger compartment. The untenable conditions were defined as [17]: 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 evident.

## BACKGROUND

As thermoplastics and elastomers are exposed to heat flux, they generally undergo softening and melting, while thermosets char followed by the release of vapors to the environment [28]. As the polymer vapor-air mixture encounters a heat source, the mixture ignites and a flame is established at the surface, defined as *ignition*. This flame transfers heat back to the surface, resulting in the continuous release and burning of polymer vapors; the process is defined as *combustion*. The flame front moves on the surface because of the heat transfer ahead of the front, defined as *fire spread*. Fire spread continues until entire surface is burning.

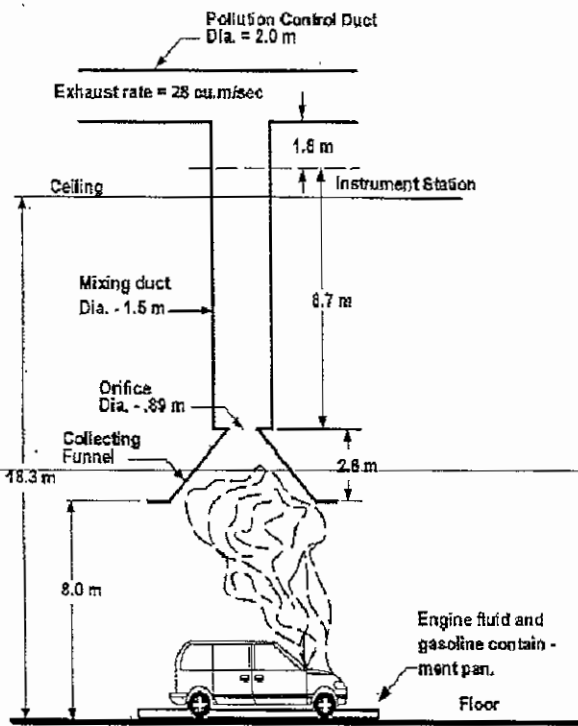


Figure 1. Schematic diagram of a large-scale vehicle burn test

In the preignition, ignition, combustion, and fire spread processes, heat, smoke, toxic and corrosive compounds are released at rates dependent on the generic nature of the polymer, its surface area, magnitude of the heat flux exposure from its own flame and from external heat sources, and ventilation. The release rates of heat, smoke, toxic, and corrosive compounds are responsible for creating both thermal and non-thermal hazards in fires. These hazards decrease with increase in the fire resistance of the polymers. Thus, for increasing fire safety, the polymers are modified by variety of techniques to increase their fire resistance, the most common being the use of fire retardants and inert fillers.

The preignition, ignition, combustion, and fire spread processes depend on the thermo-physical-chemical and fire properties of the polymers. The effectiveness of the polymer

## Preignition

The preignition process includes softening, melting, flow of polymer melt, decomposition or vaporization of the polymer.

1) *Softening, melting, and flow of polymer melt*: these polymer characteristics depend on the polymer morphology (amorphous and crystalline nature of the polymer) [28]. They are characterized by the glass transition temperature ( $T_{gl}$ ) and the melting temperature ( $T_{mi}$ ).  $T_{gl}$  and  $T_{mi}$ , heat of fusion and other melting characteristics were quantified in the mini-scale and small-scale tests for the automotive polymers with and without the fire retardants [2,3,4,8]. Significant differences were found between these properties for different automotive polymers. Data quantified for the changes in the melting characteristics for some selected automotive polymers are included in Table 1. The data indicate that the fire retardant treatment of PP is effective in preventing dripping at low heat exposure. The softening, melting, and flow of polymer melt are the first indicators for the fire path into the passenger compartment from engine compartment or from under the vehicle. Their absence is indicative of the increased fire resistance of the automotive polymers.

**Table 1.** Data for melting, decomposition or vaporization of polymers measured in the modified 9833P flammability apparatus at low heat exposure<sup>a</sup>

Temperature °C	Property	PP	PP-1 (FR)	PP-2 (FR)	Nylon 6	Nylon 66 (FR)
20	Melting (Drip %)	24.4	1.1	1.2	0.5	0.1
93		29.9	0.9	0.9	7.8	0.5
121		52.5	1.7	1.8	10.7	1.1
150		61.7	3.0	2.8	12.0	1.6
20	Decomposition or vaporization (Mass Loss %)	29.9	2.4	3.2	3.9	1.1
93		31.0	1.9	2.7	8.6	1.7
121		70.7	4.6	4.6	11.0	1.9
150		72.1	7.3	7.4	12.4	2.2

a: Data are taken from Ref. 9. In the modified 9833P flammability apparatus, sample dimensions were 300-mm x 100-mm x 4-mm thick with polymer slab slanted at an angle of 45° inside a 0.7-m<sup>3</sup> enclosure. Both sample surfaces were exposed to heat. A Meeker burner was used to ignite the sample at the bottom. PP: polypropylene, FR: fire retardant.

The effectiveness of fire retardant treatments of the polymers at low heat flux exposure, such as in Table 1, however, may not be effective under high heat flux exposure conditions such as in vehicle crashes observed in the intermediate-scale tests for automobile parts [13,14,15]. In these tests it was found that a significant aspect of the burning behavior of the automotive polymer parts was the development of a polymer melt pool fire below the part. The polymers in these parts had low  $T_{gl}$ ,  $T_{mi}$  and heat of fusion values [2].

2) *Decomposition and vaporization*: the decomposition and vaporization characteristic of a polymer is governed by its thermal stability, characterized by the decomposition temperature ( $T_d$ ) and the vaporization temperature ( $T_v$ ). The values of  $T_d$  and  $T_v$  are governed by the same factors as  $T_{gl}$  and  $T_{mi}$ , namely the chain rigidity and strong inter-chain forces [28]. In the GM Fire Safety Research Program,  $T_d$  and  $T_v$  values and changes in the extent of decomposition or vaporization with and without the fire retardants in the polymers were quantified in the mini-scale and small-scale tests for the automotive polymers [2,3,4,8,9]. The  $T_d$  and  $T_v$  values for the automotive polymers were in the range of 240 to 572 °C [2,4] compared with the values in the range of 270 to 789 °C for other generic polymers [29], suggesting significant differences in the thermal stability of the polymers. The nature and amounts of chemical compounds released in the decomposition and vaporization of the polymers were also quantified in the mini-scale tests [5,6,7].

The data in Table 1 indicate that the fire retardant treatment of PP is effective in reducing the extent of decomposition and vaporization at low heat exposure. The decomposition or vaporization of the polymer results in the ignition of the polymer and thus FR treatment has to be effective for increasing thermal stability under heat exposure conditions expected in vehicle crashes.

The  $T_d$  and  $T_v$  values, nature, and amount of chemical compounds associated with them provide information for the assessment of untenable conditions that may be created in the passenger compartment due to heat penetration prior to flame penetration in vehicle crashes.

## Ignition

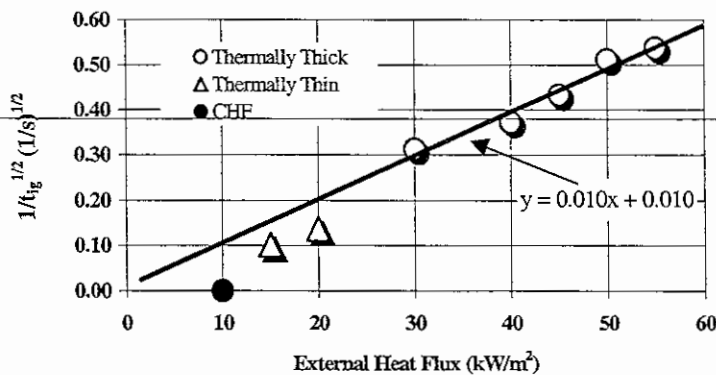
The following is the most commonly used expression for the relationship between the ignition-time and external heat flux based purely on the argument for the thermally thick condition [30,31]:

$$1/t_{ig}^{1/2} = a(\dot{q}_e'' - \dot{q}_{cr}'') / \Delta T_{ig} \sqrt{(\pi k \rho c) / 4} \quad [1]$$

where  $t_{ig}$  is the ignition-time (s),  $a$  is the polymer surface absorptivity,  $\dot{q}_{cr}''$  is the minimum heat flux at or below which there is no ignition, defined as the critical heat flux (CHF)<sup>1</sup> ( $\text{kW}/\text{m}^2$ ),  $\Delta T_{ig}$  is the ignition temperature above ambient ( $^{\circ}\text{C}$ ). The term  $\Delta T_{ig} \sqrt{(\pi k \rho c) / 4}$  is defined as the thermal response parameter (TRP) of the polymer ( $\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$ ) [32]. Resistance to ignition increases with increase in the CHF and TRP values.

In the GM Fire Safety Research Program,  $k$ ,  $\rho$ , and  $c$  values for automotive polymers were measured in the mini-scale tests by GM [2,3,8]. These values were used in Eq. 1 to calculate the TRP values assuming  $T_a = 293 \text{ K}$ ,  $a = 1.0$  and  $T_{ig} = T_v$  or  $T_d$ , based on the literature data for variety of ordinary and high temperature polymers. The calculated TRP values were found to be in the range of 57 to 495  $\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$  for the automotive polymers. The average value of  $\sqrt{\pi k \rho c / 4}$  for the automotive solid polymers was found to be approximately constant ( $0.778 \pm 18\%$ ) and similar to the average values of  $0.640 \pm 15\%$  for the high temperature solid polymers and  $0.624 \pm 18\%$  for highly halogenated solid polymers calculated from the literature data [28,33,34,35]. The  $\sqrt{\pi k \rho c / 4}$  values for solid automotive and other polymers thus are similar with an overall average value of  $0.781 \pm 18\%$ . Thus the differences in the CHF and TRP values between automotive polymers are mainly due to differences in the  $T_v$  or  $T_d$  values which are between 240 to 572  $^{\circ}\text{C}$  as measured by GM [2,4].

The CHF and TRP values were also derived from the ignition tests in the ASTM E 2058 apparatus by FM Global Research as shown in Fig. 2 as an example [10,11,12]. Note that in Fig. 2, CHF = 10



**Figure 2.** Ignition data for polyethylene terephthalate hood liner face used in the 1996 model of Dodge Caravan as measured in the ASTM E 2058 apparatus [10].

$\text{kW}/\text{m}^2$  and TRP = 100  $\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$  (inverse of the slope) which compare well with the measured  $T_v$  and the calculated TRP value for the polymer.

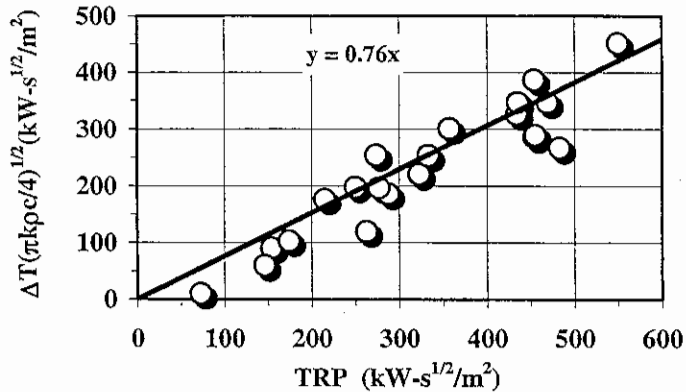
The TRP values derived from the ignition data from the ASTM E 2058 apparatus and calculated from the thermo-physical-chemical properties for other automotive polymers were also in agreement as shown in Fig. 3. The calculated TRP value is about 24 % lower than the value derived from the ignition data.

The decomposition, vaporization, and ignition data measured for the automotive polymers would be reflected in their thermal response in

the large-scale vehicle burn tests. The gas and surface temperatures measured in the large-scale

<sup>1</sup>  $T_{ig} (^{\circ}\text{C}) = [(\dot{q}_{cr}'')^{0.25} \times 364] - 273$

vehicle burn tests at numerous locations indicated that within a short time, the  $T_d$ ,  $T_v$  and  $T_{ig}$  values of the polymers at various locations within the passenger compartment were exceeded as indicated in Table 2.



**Figure 3.** Calculated versus derived ignition resistance parameter for automotive polymers. Data are taken from [2,3,4,5,10,11,12].

polyethylene, polyvinylidene fluoride and polytetrafluoroethylene.

Thus, in order to increase the passenger escape or survival time from a vehicle fire in a crash, it is necessary to increase the TRP value. The effective technology to increase the TRP value appears to be one that would influence the gas phase chemistry. The reason being that the  $\sqrt{\pi k \rho c / 4}$  values of polymers are approximately constant and there is a limit to which  $T_d$ ,  $T_v$  and  $T_{ig}$  values can be increased. For example, there is a large increase in the TRP values as increased numbers of H atoms are replaced by F atoms, as in

**Table 2.** Temperature measured at various surfaces of a burning rear crashed 1996 model Plymouth Voyager<sup>a</sup>

Location in the vehicle	Time after ignition (s)		Peak Temperature	
	Initial response	To peak temperature	Duration (s)	Average (°C)
10-mm below the headliner	130-160	207-274	2-25	302-824
Close to rear wheelhouse	20-70	124-345	2-134	138-833
Upper surface of floor pan (inside temperature)	20-70	239-397	2-115	97-784
10-mm below surface floor pan (outside temperature)	20-30	51-436	2-218	307-812
Fuel tank	30	35-478	4-299	220-823
Rear hatch trim panel	40-210	58-333	2-36	54-847
Rear seat bottom (10-mm below the foam pad)	40-160	183-230	4-23	304-819

a: data are taken from Ref. 22. Fire was initiated under the vehicle by a gasoline pool fire in the rear. Fire was extinguished rapidly as soon as untenable conditions were reached in the passenger compartment.

### Combustion and Fire Spread

Fire spread and release of heat and chemical compounds depend on the thermo-physical-chemical and fire properties of the polymers and the environmental conditions [29, 30, 31, 32,36]. The release rates of heat and compounds along with the environmental conditions affect the gas temperature and concentration that are responsible for thermal and non-thermal hazards.

*Fire spread* [30,31,32,36]:

$$v^{1/2} \propto (\chi_{rad} / \chi_{ch}) (\dot{Q}_{ch})^{1/3} / \Delta T_{ig} \sqrt{(\pi k \rho c / 4)} \quad [2]$$

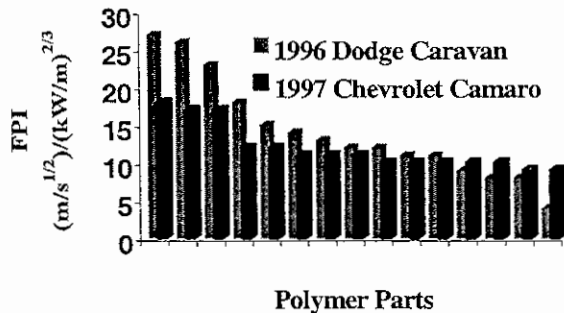
where  $v$  is fire spread rate (mm/s),  $\chi_{rad}$  is radiative component of the combustion efficiency,  $\chi_{ch}$ , and  $\dot{Q}_{ch}$  is the chemical heat release rate per unit width (kW/m). A simplified form of Eq. 2 is used in the 4910 Test Protocol<sup>2</sup>, where right hand side is identified as the Fire Propagation Index (FPI) [32,36]:

$$FPI = 1000 \left( (0.42 \dot{Q}_{ch}')^{1/3} / \Delta T_{ig} \sqrt{(\pi k \rho c / 4)} \right) = 750 (\dot{Q}_{ch}')^{1/3} / TRP \quad [3]$$

The following behaviors have been found in small-scale and large-scale fire spread tests [32,36]:

- 1)  $FPI \leq 6$  (m/s<sup>1/2</sup>)/(kW/m)<sup>2/3</sup>: no fire spread beyond the ignition zone;
- 2)  $6 < FPI \leq 10$  (m/s<sup>1/2</sup>)/(kW/m)<sup>2/3</sup>: decelerating fire spread beyond the ignition zone;
- 3)  $FPI > 20$  (m/s<sup>-1/2</sup>)/(kW/m)<sup>2/3</sup>: accelerating fire spread beyond the ignition zone.

In the GM Fire Safety Research Program, ignition, combustion, and fire spread tests were performed in the ASTM E 2058 apparatus for 21 polymer parts from the 1996 model of Dodge Caravan consisting of polypropylene (PP), polyethylene (PE), polystyrene (PS), nylon, polyvinylchloride (PVC), ethylene-propylene-diene rubber copolymer (EPDM), polyethyleneterephthalate (PET),



**Figure 4.** Fire Propagation Indices of polymers from some selected parts of 1996 Dodge Caravan and 1997 Chevrolet Camaro as determined from the measurements in the ASTM E 2058 Apparatus.

polyester, polycarbonate (PC), acrylonitrile-butadiene-styrene copolymer (ABS), and sheet molding compound (SMC). In addition, 16 polymer parts from the 1997 model of Chevrolet Camaro were also tested consisting of PP, PE, nylon, ABS, polyurethane (PU), and polyester fibers. The FPI values for these polymers are shown in Fig. 4.

There are large variations in the fire spread behavior of polymers from parts of the 1996 model of Dodge Caravan and 1997 model of Chevrolet Camaro. With one exception, all the selected polymer parts are expected to spread the fire at different rates under conditions expected in vehicle crash fires. It is, therefore, important to reduce the fire spread rate for increasing passenger escape or survival time from a vehicle fire in a crash. This can be

achieved possibly by reducing the heat release rate and increasing the TRP value as suggested by Eq. 3. Nano composite technology appears to be attractive and thus was examined in the GM Fire Safety research Program in a very limited fashion.

*Release rates of heat and chemical compounds:* the rates are expressed as [32]:

$$\dot{Q}_{ch}'' = \dot{m}'' \Delta H_{ch} = (\Delta H_{ch} / \Delta H_g) \dot{q}_n'' \quad [4]$$

$$\dot{G}_j'' = \dot{m}'' y_j = (y_j / \Delta H_g) \dot{q}_n'' \quad [5]$$

where  $\dot{Q}_{ch}''$  is the chemical heat release rate in the combustion or fire spread process (kW/m<sup>2</sup>),  $\dot{m}''$  is the mass loss rate in the combustion or fire spread process (g/m<sup>2</sup>-s),  $\Delta H_{ch}$  is the chemical (effective) heat of combustion (kJ/g),  $\Delta H_g$  is the heat of gasification (kJ/g),  $\dot{q}_n''$  is the net heat flux to the polymer surface in the combustion or fire spread process (kW/m<sup>2</sup>),  $\dot{G}_j''$  is the release rate of compound  $j$  in the combustion or fire spread process (g/m<sup>2</sup>-s) and  $y_j$  is the yield of the compound (g/g).

<sup>2</sup> 4910 Test Protocol is used to list polymeric materials for use in the clean rooms of the semi-conductor industry [32,36].

The gas temperature and concentration in the environment are direct functions of  $\dot{Q}_{ch}''$  and  $\dot{G}_j''$  [32]:

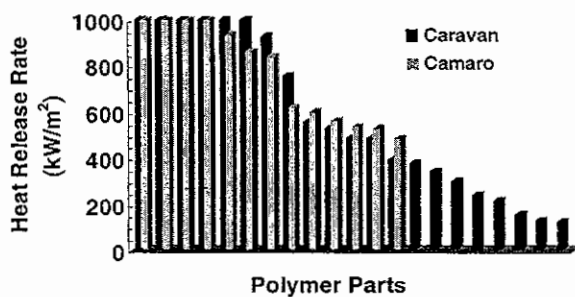
$$\Delta T_g = \chi_{con} A \dot{Q}_{ch}'' / \dot{M}_a c_a = A \chi_{con} (\Delta H_{ch} / \Delta H_g) \dot{q}_n'' / \dot{V}_a \rho_a c_a \quad [6]$$

$$C_j = A \dot{G}_j'' / \dot{V}_a = A (y_j / \Delta H_g) \dot{q}_n'' / \dot{V}_a \quad [7]$$

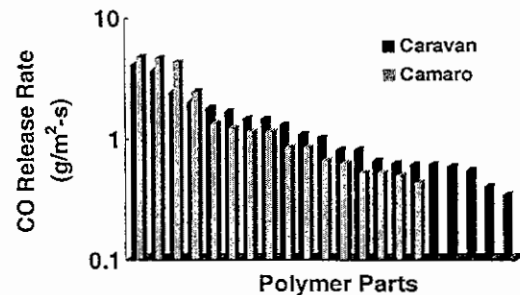
where  $\Delta T_g$  is the gas temperature above ambient ( $^{\circ}\text{C}$ ),  $\chi_{con}$  is the convective component of the combustion efficiency,  $A$  is the surface area of the polymer burning ( $\text{m}^2$ ),  $\dot{M}_a$  is the mass flow rate of air-chemical compound mixture ( $\text{g/s}$ ),  $c_a$  is the heat capacity of air ( $\text{kJ/g}^{\circ}\text{C}$ ),  $\dot{V}_a$  is the volumetric flow rate of air ( $\text{m}^3/\text{s}$ ),  $\rho_a$  is the density of air ( $\text{g/m}^3$ ),  $C_j$  is the concentration of compound  $j$  ( $\text{g/m}^3$ ) and  $y_j$  is the yield of compound  $j$  ( $\text{g/g}$ ).

The above relationships show that the gas temperature and concentrations depend: 1) on the thermo-physical-chemical and fire properties through  $\chi_{con}$ ,  $\Delta H_{ch}$ ,  $\Delta H_g$ , and  $y_j$ ; 2) on fire size through  $A$  and  $\dot{q}_n''$ , and 3) on environmental conditions through  $\dot{M}_a$ ,  $\dot{V}_a$ ,  $\rho_a$ , and  $c_a$ . Thus, in the GM Fire Safety Research Program,  $\dot{Q}_{ch}''$  and  $\dot{G}_j''$  ( $j = \text{CO}, \text{CO}_2, \text{hydrocarbons}, \text{and smoke}$ ) were measured in the small-scale tests for automotive polymers [10], in the intermediate-scale automotive parts [13], and in the large-scale crashed vehicle burn tests [21,22,23,24,25,26,27]. Fire properties were derived from these measurements and relationships with thermo-physical and chemical properties were established [10,11,12]. Figures 5 to 8 show large variations in the release rates between different polymers and polymer parts.

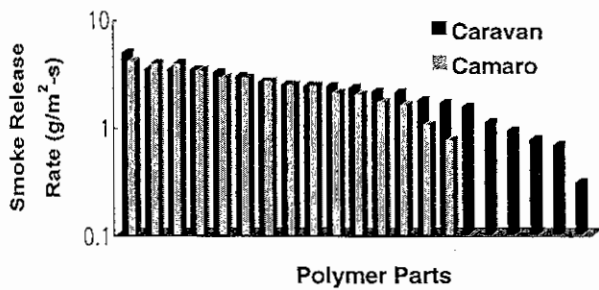
As indicated by Eqs. 4 to 7, reducing  $\Delta H_{ch}$ ,  $y_j$  and  $\dot{q}_n''$  values and increasing the  $\Delta H_g$  values would reduce the release rates and gas temperature and concentrations. Attempts were made in the GM Fire Safety Research Program to follow these concepts [4,6,8,9,14,15]. Data in Fig. 9 show that inert fillers used for the proper functioning of some of automotive parts also appear to be effective in reducing the heat release rate by increasing the  $\Delta H_g$  values and quenching the flame that reduces the  $\dot{q}_n''$  value (Eq. 4). Consequently, release rates of compounds would also be reduced (Eq.5).



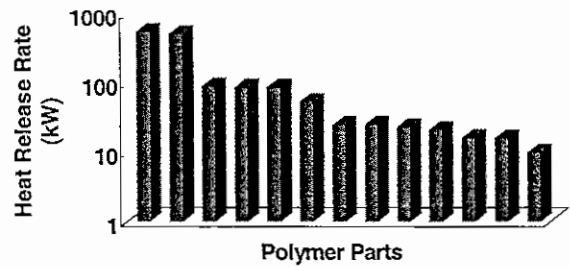
**Figure 5.** Heat release rate in the combustion of selected polymers from 1996 Dodge Caravan and 1997 Chevrolet Camaro parts derived from the tests in the ASTM E 2058 Apparatus.



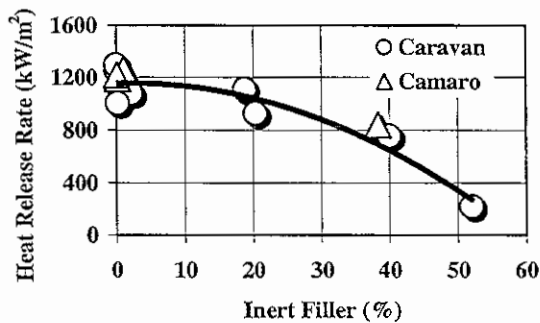
**Figure 6.** CO release rate in the combustion of selected polymers from 1996 Dodge Caravan and 1997 Chevrolet Camaro parts derived from the tests in the ASTM E 2058 Apparatus.



**Figure 7.** Smoke release rate in the combustion of selected polymers from 1996 Dodge Caravan and 1997 Chevrolet Camaro parts derived from the tests in the ASTM E 2058 Apparatus.



**Figure 8.** Heat release rate in the combustion of selected polymer parts from 1996 Dodge Caravan derived from the tests in the NIST Calorimeters [13].

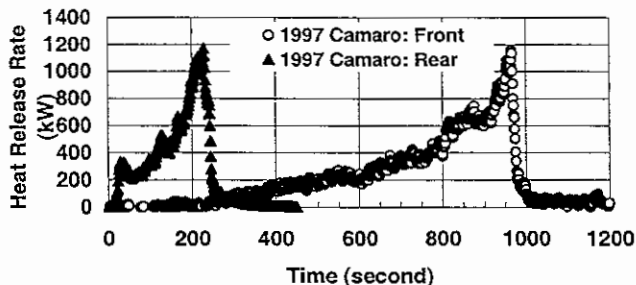


**Figure 9.** Heat release rate versus inert fillers in automotive polymers.

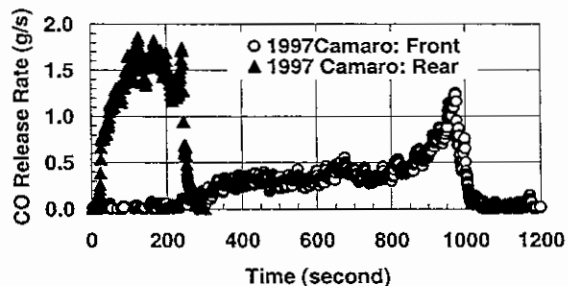
were burned in each set of tests, one crashed in the front and the other crashed in the rear. The crash tests were performed at the GM Proving Grounds prior to the burn tests at the FM Global Technology Center. Table 3 lists some observations and Figs. 10 and 11 show some examples of the release rates of heat of CO.

### Large-scale vehicle burn tests

The large-scale burn tests were performed to: 1) identify fire paths into the passenger compartment; and 2) to identify technologies to increase passenger escape or survival time from a vehicle crash fires. The automobiles burned in the tests were 1996 model of Dodge Caravan, 1996 model of Plymouth Voyager, 1997 and 2000 models of Chevrolet Camaro, 1998 and 2000 models of Ford Explorer, and 1999 model of Honda Accord. Two vehicles



**Figure 10.** Heat release rate versus time in the large-scale vehicle burn tests for front and rear ignition of crashed 1997 model of Chevrolet Camaro.



**Figure 11.** CO release rate versus time in the large-scale vehicle burn tests for front and rear ignition of crashed 1997 model of Chevrolet Camaro.



**Table 3.** Fire behavior observed in the large-scale vehicle burn tests performed at the Technology Center of the FM Global Research

Type of ignition	Fire path into the passenger compartment from
<i>Rear crashed 1996 model of Plymouth Voyager: fire extinguished in ~210 seconds [22]</i>	
Gasoline pool fire in the rear under the vehicle	Rear-left: vent window, open seams near wheelhouse. In ~150 s, items burning in the rear; in ~175s flames spreading forward along the headliner.
<i>Front crashed 1996 model of Dodge Caravan: fire extinguished in ~660 seconds [21]</i>	
Electrical in the engine compartment	Windshield and dash board
<i>Rear crashed 1997 model of Chevrolet Camaro: fire extinguished in ~210 seconds [23]</i>	
Gasoline pool fire in the rear under the vehicle	Rear-left: open seam near wheelhouse, under the driver's door, floor pan drain hole, and heating of carpet. In ~170 s, items burning in the rear; in between ~180 to 190s fires spreading forward along the headliner.
<i>Front crashed 1997 model of Chevrolet Camaro: fire extinguished in ~960 seconds</i>	
Flame from propane torch impinging on HVAC in the engine compartment	Windshield and HVAC ; items burning in the front in about 300 s; section of windshield fell in ~660s; flames in the right under the instrument panel in ~780 s
<i>Left rear crashed 1998 model of Ford Explorer: fire extinguished in ~170 seconds</i>	
Gasoline pool fire in the rear under the vehicle	Rear-left: window opening, seam near wheelhouse and seam in the right and lift gate.
<i>Left front crashed 1998 model of Ford Explorer: fire extinguished in ~250 seconds</i>	
Gasoline pool fire in the rear under the vehicle	Drain holes and electrical openings in the floor panel
<i>Front crashed 1999 model of Chevrolet Camaro</i>	
Electrical in the engine compartment	Fire retardant treatment of the HVAC module in the vehicle did not affect the fire path, however, CO concentration increased 27 times.

The test data from the large-scale vehicle burn tests show that:

- The untenable conditions in the passenger compartment are reached very rapidly in the rear-crash-simulated fires than in the front-crashed-simulated fire;
- Times to reach untenable conditions in the passenger compartment for the rear-crash-simulated fires are very repeatable. These times are 210, 210, 170 and 250 seconds even though several models of vehicles were tested in the period of 1996 to 2000;
- The mode of ignition in the engine compartment has an effect on the time to reach the untenable conditions in the passenger compartment, flaming ignition being shorter than the electrical ignition;
- Certain automotive parts are quite vulnerable to heat exposure and allow flame penetration in to the passenger compartment and flame to spread. For example, head liner, seams near the wheelhouse, rear windows, HVAC, windshield and others;
- Ordinary fire retardant treatments are not effective in preventing the flame to penetrate the passenger compartment and thus concepts based on the modifying the fundamental thermo-physical-chemical and fire properties under high heat flux exposure conditions need to be utilized to enhance the fire retardancy of automotive polymers;
- Techniques to increase the passenger escape or survival times from fires in vehicles involved in rear crashes need to be given higher priority than from fires in vehicles involved in front crashes;

- There is need to emphasize penetration of not only the flame, but also the thermal wave ahead of the flame that is responsible for creating untenable conditions in the passenger compartment due to non-thermal hazards ahead of the thermal hazards.

## SUMMARY

- Times to reach untenable conditions in the passenger compartment in the front-crashed-simulated vehicle fires were three to four times longer than for the rear-crashed-simulated vehicle fires. Thus, increase in the passenger escape or survival times from vehicle fires from rear crashes is more critical than from vehicle fires from front crashes;
- Certain polymer parts were found to be ineffective in preventing the flame penetration and fire spread in the passenger compartment and thus need to be modified for enhanced fire retardancy;
- Thermal wave penetration preceding the flame penetration into the passenger compartment is equally important than the flame penetration and thus needs to be investigated. The thermal wave penetration would be associated with creating untenable conditions due to compounds associated with non-flaming conditions.
- Relationships have been developed between thermo-physical-chemical and fire properties that can be used to assess the efficiencies of various technologies to enhance the fire retardancy of automotive polymers to be effective under vehicle crash fire conditions;
- Enhancing the ignition resistance via gas phase chemistry and reducing heat release rate via nano-composite technology are expected to be effective for increased fire resistance of automotive polymers under vehicle crash fire conditions.

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