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General Motors Corporation
Legal Staff

Facsimile
(313) 974-1260

Telephone
(313) 974-1572

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February 3, 1998

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

Dear Mr. Recht:

Re: Settlement Agreement
Section B. Fire Safetv Research

Enclosed is a technical report prepared by Factory Mutual Research Corporation entitled "A Study of the Flammability of Plastics in Vehicle Components and Parts."

This report covers part of the work to be performed under Project B. 10 Study of Flammability of Materials.

Sincerely,

David A. Collins
Attorney

DAC:dld
Enclosure

c: James A. Durkin, Esq.

MC 482-207-745 New Center One Building 3031 West Grand Boulevard, Detroit, Michigan 48202

FMRC J.I. 0B1R7.RC

TECHNICAL REPORT

A Study of the Flammability of Plastics in Vehicle Components and Parts

By:
A. Tewarson

Prepared for:
Research Project B.10 of the Fire Safety Research
Program Safety Research Department
General Motors Corp. Research & Development Center
30500 Mound Road
Building 1-3, Main Code: 480-103-001
Warren, MI 48090-9055
Attention: Dr. Douglas Kononen

October 1997

FACTORY MUTUAL | Factory Mutual System

TECHNICAL REPORT

A STUDY OF THE FLAMMABILITY OF PLASTICS IN VEHICLE COMPONENTS AND PARTS

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October 1997

Approved by:

Robert G. Bill, Jr.,
Director, Materials Research

Factory Mutual System

Factory Mutual Research

1151 Boston-Providence Turnpike
P.O. Box 9102
Norwood, Massachusetts 02062

DISCLAIMER

ABSTRACT

The objective of the study was to evaluate the flammability of plastic components and parts in vehicles. Twenty plastic components and parts of a 1996 Dodge Caravan were selected for the study. Flammability characteristics of plastics associated with ignition, fire propagation, and release of heat and fire products were quantified.

For ignition, ***Critical Heat Flux (CHF)*** and ***Thermal Response Parameter (TRP)*** values were quantified in the ignition tests in the Factory Mutual Research Corporation's (FMRC's) Flammability Apparatus. For the plastics in the 1996 Dodge Caravan components and parts, CHF values were found to be in the range of 10 to 20 kW/m^2 and TRP values in the range of 73 to 483 $kW\text{-}s^{1/2}/m^2$, which were comparable to the values for ordinary plastic materials.

Fire propagation behavior was deduced from the correlation between the ***Fire Propagation Index (FPI)*** values and visual observations for fire propagation in small and large-scale fire tests. The FPI values for the plastic parts of the 1996 Dodge Caravan, examined in the study, ranged from a low value of 8 to a high value of 27 $(m/s^{1/2})/(kW/m)^{2/3}$. The FPI values suggest that out of a total of fifteen plastic parts, three parts were expected to have decelerating propagation, while the rest of them were expected to have slow to rapid fire propagation beyond the ignition zone. The expected fire propagation behavior will be validated by the fire propagation tests in the continuation of the study.

The expected environmental contamination from the combustion of the plastics parts in the 1996 Dodge Caravan was examined by using the estimated FPI values with the heat of combustion and yields of CO, CO_2, and smoke, quantified in the tests. For reduced contamination, FPI is the most important parameter. Reduction in the values of heat of combustion and yields of products would also be beneficial.

Correlation were made between the flammability characteristics quantified in this study and the thermal properties measured at General Motors Research and Development Center by Abu Isa ***et al*** [5]. Ignition temperatures estimated from the CHF values were about 14% higher than the decomposition temperatures from the thermal properties measurements [5]. The experimental TRP values were about 28% higher than the TRP values calculated from the thermal properties measurements [5].

The thermal properties data [1] were used to calculate the TRP values for 72 plastic components and parts of the 1996 Dodge Caravan. Flammability characteristics of other plastic

parts will be quantified in the continuation of the study. A rigorous correlation between the thermal properties and flammability characteristics of the plastics in components and parts of vehicles will be sought.

ACKNOWLEDGMENT

The contributions of the following colleagues of the Factory Mutual Research Corporation are gratefully acknowledged: Mr. Stephen D. Ogden and Mr. Morgan Darcy, Jr., for the performance of tests in the Flammability Apparatus and Mr. La'vrence Orloff for the computer data acquisition.

The author also gratefully acknowledges numerous discussions with Dr. Douglas Kononen, Dr. Ismat A. Abu-Isa, and Dr. Jeffrey Santrock of General Motors Research and Development Center, which greatly enhanced the technical content of this report.

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INTRODUCTION

For improving fire safety in passenger vehicles, the General Motors (GM) Corporation has established a Fire Safety Research Program, following the March 7, 1995, agreement between GM and the U.S. Department of Transportation.

In the Fire Safety Research Program, GM has established a Cooperative Research and Development Agreement (CRADA) with the National Institute of Standards and Technology (NET) and a contract research program[1] with the Factory Mutual Research Corporation (FMRC). The contract research program at FMRC consists of Projects B.3 (Fire Initiation Program Tests) and B.10 (Study of Flammability of Materials). In Project B.3 of the FMRC's program, large-scale vehicle] bum tests are performed under the FMRC's Fire Products Collector [1]. In Project B. 10 of the FMRC's program, flammability tests are performed in the FMRC's Flammability Apparatus, shown in Fig. 2 [2,3,4]. This report is the first report for the B.10 project of FMRC's program.

The B. 10 project of the FMRC's program consists of three tasks:

1. Preliminary assessment of the flammability of plastics in vehicle components and parts;

2. Quantification of flammability of selected plastics on the basis of Task 1 results;

3. Identification of potential alternates and/or modification of plastics on the basis of the results from Tasks 1 and 2 and Project B.3.

A listing of plastic components and parts in a 1996 Dodge Caravan has been prepared by GM (Abu-Isa et *al at* [5]). This listing is included in Table 1 in this report. Some of the components and parts listed in Table 1 are shown in Fig. 3, taken from Ref. 5.

Plastics are inherently combustible organic materials. Their flammability depends on the chemical structures, types and amounts of additives, exposed area, shape, location, thermal environments (magnitude of heat flux and duration of exposure), ventilation and other factors.

Typical generic plastics used in vehicles are listed in Table 2. In post-crash fires, some of the locations in the passenger compartment could be in the fire path, whereas, others could be

[1] Four segment leader vehicles have been chosen: 1) passenger vans (Dodge Caravan (Fig. 1) and Plymouth Voyager); 2) a sport utility vehicle (Ford Explorer); 3) a front wheel drive vehicle (Honda Accord); and 4) a rear wheel drive vehicle (Chevrolet Camaro). Crashed vehicles are used in the large-scale bum tests under the FPC [6].

away from it. Plastics in components and parts located in or close to the fire path would be exposed to a high heat flux environment, whereas, others away from the fire path would be exposed to a lower heat flux environment. Plastics with reduced flammability would resist fire for a longer time. In this report, the flammability of plastics have been assessed and quantified for variety of generic plastics with and without additives.

FRONT VIEW

TOP VIEW OF ENGINE COMPARTMENT

SIDE VIEW

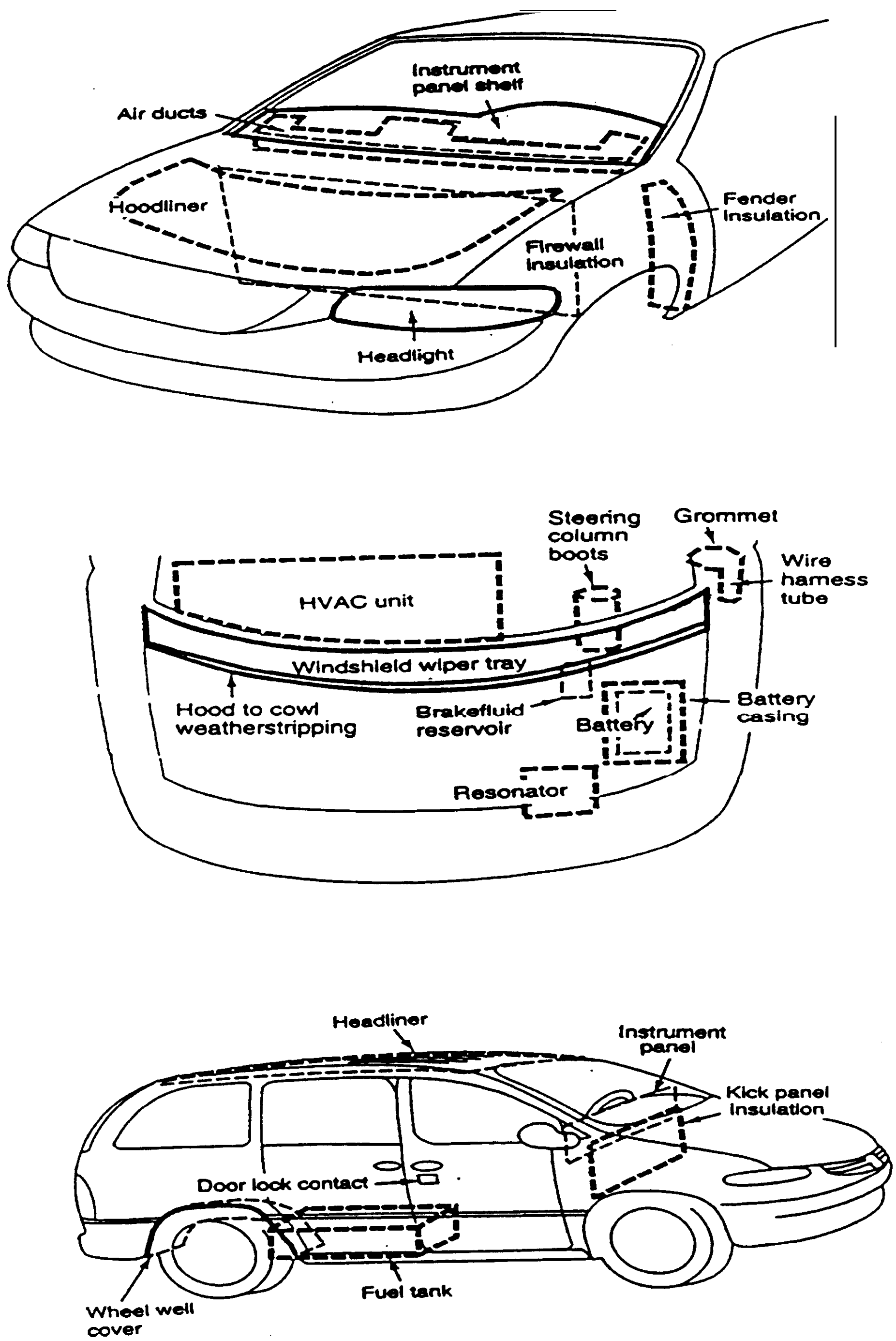

Figure 1. Schematic diagram showing the locations of components and parts of a 1996 Dodge Caravan. Figure is taken from Abu-Isa, Cummings, and LaDue [5].

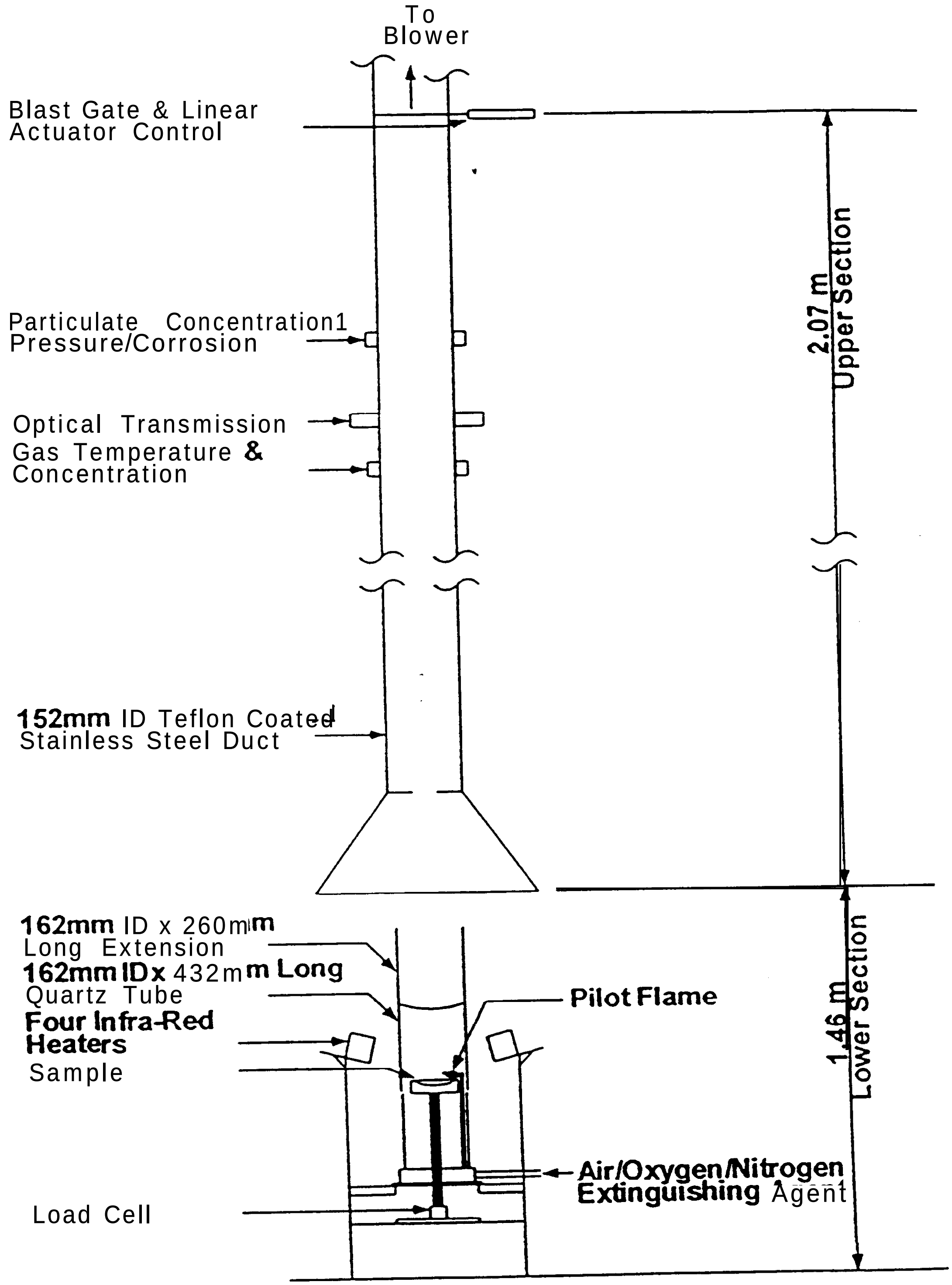

Figure 2. The Factory Mutual Research Corporation's Flammability Apparatus.

Table 1
Selected Parts of a 1996 Dodge Caravan[a]

VAC[b] #	Dodge Part #	Part Description	Plastic	Mass (kg)
743	GJ42SK4A	headliner, backing - top layer, structural support	Polyethylene terphthalate (PET)	NA
	GJ42SK4B	headliner, high density foam - layer 3	Polyether urethane (PEU + methyldiisocyanate, MDI)	NA
	GJ42SK4C	headliner, low density foam - layer 2	Polyester urethane (PESPU) with Surlyn film	NA
	GJ42SK4D	headliner, fabric - exposed surface, bottom layer	Nylon 6	NA
	GJ42SK4E	headliner, center-structural support	PET binder on glass	NA
			Whole system	2.61
645	JF48SKA	instrument panel, foam - between structure and cover	PEU +MDI	NA
	JF48SK5B	instrument panel, cover - exposed surface	Polyvinylchloride (PVC)	NA
	JF48SKC	instrument panel, structure	Polycarbonate (PC)	NA
			Whole system	3.61
611	PL98SX8A	instrument panel shelf, main panel	PC	NA
	PL98SX8B	instrument panel shelf, foam - small seals	PEU	NA
			Whole system	2.15
256	46 125 12A	resonator, structure,	Polypropylene (PP)	0.7 1
	4612512B	resonator, intake tube	Ethylene propylene diene monomer (EPDM) elastomer	0.29
	46 125 12C	resonator, effluent tube	EPDM	0.14
			Whole system	1.14
788	467471 1A	kick panel insulation, foam	Polyether urethane	NA
	46747 11 B	kick panel insulation, backing	PVC	NA
			Whole system	4.82
732	4678345A	air ducts, small ducts	Polyethylene (PE)	NA
	4678345B	air ducts, large ducts	PP	NA
			Whole system	4.26

VAC[b] #	Dodge Part #	Part Description	Plastic	Mass (kg)
673	4680250A (4680151)	Steering column boot, inner interior boot	Natural rubber (NR)	0.04
	4680250B	Steering column boot, cotton shoddy	Mixture of cotton, polyester, and other fibers	0.02
	4680250C (4680152)	Steering column boot, outer interior boot	Polyester co-polyester elastomer	0.10
			Whole system	0.17
736	4683264A	brake fluid reservoir, reservoir	PP	0.67
	4683264B	brake fluid reservoir, cap	PP	0.07
3008	4707580A	wire harness tube, tube	PE	0.07
1019	4707808A	door lock contact, wire coating		
	4707808B	door lock contact, wire mesh - groups wires together		
	4707743C	door lock contact, structure	Poly (acrylonitrile-butadiene-styrene), ABS	NA
			Whole system	NA
967	4716051	windshield wiper tray, structure	Sheet molding compound (SMC)	3.40
868	4716345A	fender insulation, low density foam - sound reduction	Polystyrene (PS)	NA
	4716345B	fender insulation, high density foam - sound reduction	PS	NA
870	4716832A	hood liner, insulation (back)	PET, cellulose and epoxy	NA
	4716832B	hood liner, face	PET	NA
			Whole system	1.00
208	4716895	wheel well cover, fuel tank shield	PP	0.56
676	4734025	HVAC unit-door, foam covering		0.29
	4734033	HVAC unit, door- for thermostat	PVC	0.08
	4734039A	HVAC unit door, structure	Nylon 66	NA
	4734039B	HVAC unit door, rubber seal	Thermoplastic polyolefin (TPO)	NA
			Whole system	NA
676	4734041A	HVAC unit door, structure	Nylon 66	NA
	4734041B	HVAC unit door, rubber seal	TPO	NA
	4734042A	HVAC unit door, structure		NA
	4734042B	HVAC unit door, rubber seal		NA

VAC[b] #	Dodge Part #	Part Description	Plastic	Mass (kg)
676	4734063	HVAC unit, cover	PP	NA
	4734067A	HVAC unit seal, foam - heating coil entrance	ABS and PVC blend	
	4734067B	HVAC unit seal, backing - heating coil entrance	Ethylene vinyl acetate (EVA)	NA
	4734071	HVAC unit , top main housing-contains coils, doors and fan	PP	0.87
	4734072	HVAC unit, bottom main housing - contains coils, doors and fan	PP	1.61
	4734073	HVAC unit, fan top cover	PP	0.29
	4734074	HVAC unit, fan bottom cover	PP	0.11
	4734080	HVAC unit, cover-for directional control	PP	NA
	4734081	HVAC unit, deflector- for air flow	PP	0.09
676	4734225	HVAC actuator, casing	PP	0.15
	4734367	HVAC unit, housing	PP	0.25
	4734370	HVAC unit, seals - both large and small	ABS and PVC blend	0.04
	4734395	HVAC unit, seal		NA
	4734650	HVAC unit, seal		0.02
	4734651	HVAC unit , seal		0.01
	4734724	HVAC unit, defogger tube	TPO	0.03
201	4883140A	fuel tank, tank	PE	NA
201	4883140B	fuel tank, hoses	Nylon 12	NA
	4883140C	fuel tank, threads/seal-for fuel pump	PE	NA
			Whole system	8.48
798	4857041A	headlight, lens	PC	NA
	4857041B	headlight, backing	PC	NA
	4857041C	headlight, retainer	Polyacetal (polyoxymethylene, POM)	NA
	4857041D	headlight, bulb support structure-halogen	Polyimide	NA
	4857041E	headlight, leveling mechanism	PC	NA

VAC[b] #	Dodge Part #	Part Description	Plastic	Mass (kg)
			Whole system	1.70
	4364944A	battery casing, top	PE/PP blend	NA
2221	4364944B	battery casing, sides and bottom	PE/PP blend	NA
			Whole system	1.73
230	5235267	battery cover	PP	0.36
971	4675359A	hood to cowl weather stripping, foam	EPDM	NA
	4675359B	hood to cowl weather stripping, foam, rubber base	EPDM	NA
			Whole system	0.44
959	4716896A	Bulkhead insulation engine side, exterior/face	Mixed fibers: cotton, nylon 66, and glass	NA
	47 168968	Bulkhead insulation engine side, insides	PVC coating over glass	NA
	47 16896C	Bulkhead insulation engine side, support structure	PVC-hydrocarbon elastomer	NA
			Whole system	2.38
3009		grommet - wire harness cap for 3008	EPDM	NA

a: taken from Ref. 1. Abbreviations for plastics are listed at the end of the report. b: VAC: vehicle access number; NA: not available.

Table 2
Plastics Commonly Used in Vehicles [a]

Polymer	Average Weight in lb. Per vehicle (1996)	Typical Applications in Vehicles
Polyurethane (PU)	44	Body panel, fender, roof panel, bumpers, headliner, seat, upholstery
Polypropylene (PP)	40	HVAC, fan & shroud, battery tray, console, radiator, cowl vent, air duct, instrument panel, package shelf
Polyvinylchloride (PVC)	21	Bumper trim, electrical wiring, boots, bellows, seat, cover, steering wheel, floor
Polyethylene (PE)	20	Gas tank, bumper, electrical wire, reservoir, fuel filler pipe
Nylon (polyamide) (PA)	18	Fuel system, fuel line, gas cap, canister, grille head lamp support, brake, radiator end tank, engine cover, intake manifold, lamp housing
Acrylonitrile/styrene/ butadiene (ABS)	16	Bumper beam, console, cowl vent, engine cover, fascia, head liner, duct
Thermoset polyester (SMC/BMC)	16	Door lift gate, fenders, hood, quarter panels, rear deck, spoiler, body panel
Polycarbonate (PC) & ABS	9	Bumper trim, electrical, grille, lamp support, lens, lamp, instrument panel, console, door fender, instrument panel
Thermoplastic polyester Polyethylene and polybutylene terephthalate PET and PBT	8	Body panel, hood, connector, door, fuse junction, HVAC components, fuel rail
Polystyrene (PS) /polyphenylene oxide (PPO)	7	Connectors, console, engine air cleaner, instrument panel
S tyrene maleic anhydride polymer (SMA)	4	Console, head liner, instrument panel
Phenolic	4	Brake system, engine pulley, ash tray, transmission component
Acrylic polymers	3	Emblems, lamp and instrument panel lenses
Polyacetal	2	Radiator fan, door handle, carburetor, fuel pump, fuel filler neck
Epoxy resins	0.3	Electrical, fuel tank (filament wound), adhesives

a: from Ref. 5. Abbreviations for plastics are listed at the end of this report.

II
EXPERIMENTAL APPARATUS, TESTING PROCEDURES AND MEASUREMENTS

2.1 EXPERIMENTAL APPARATUS

The Flammability Apparatus used in the study is shown in Fig. 2 [2-4]. The details of the Apparatus are described in Ref. 2; only key features of the Apparatus are included in this report.

The Apparatus consists of a lower and an upper section. The lower section is used to measure: time-to-ignition and mass-loss rate, as well as, visual observations of flame heights, smoke color, and fire propagation. The upper section, consisting of sampling duct and an exhaust pump, is used for the following measurements:

- gas temperature
- flow of product-air mixture through the sampling duct
- optical transmission through the product-air mixture flowing through the sampling duct
- concentrations of CO, CO_2, O_2, and total hydrocarbons

The measured data are used to calculate the chemical heat release rate, generation rates of CO, C02, mixture of gaseous hydrocarbons, and smoke, and depletion rate of oxygen using relationships discussed in detail in Refs. 3 and 4.

2.1.1 Lower Section of the Flammability Apparatus

The test sample was placed in a horizontal configuration on top of a platform in the lower section of the Apparatus. The platform was connected to the load cell arrangement, which was used to measure the mass loss rate during the combustion test. Since plastics components and parts have different shapes and sizes, both rectangular and circular samples[2] were used in the ignition and combustion testing. The thickness and configuration of each sample is listed in Table 5. The ignition tests were performed under a natural air flow condition, in which case the quartz tubes were not used. The combustion tests were performed in normal air under a co-flow

[2] ***Sample dimensions: rectangular sample:*** about 100 x 100-mm (area of about 0.010 m^2). The rectangular sample is wrapped tightly in a 3-mm thick aluminum sheet with edges covered by a 3-mm thick ceramic paper. ***Circular sample:*** about 99-mm in diameter (area 0.0077 m^2) is placed inside a 100-mm O.D. 3-mm thick aluminum dish. ****Sample Thickness:*** ≤ 100-mm (see table 3).

condition. For the co-flow condition, quartz tubes were placed around the sample. Normal air at a flow rate of 3.3 x 10^{-3} m^3/s entered the gas distribution section at the bottom of the Apparatus. The distribution section consisted of several downward facing holes, beneath a bed of screens; this arrangement was used to achieve a uniform flow across the tube. The air-flow rate was measured by an electronic flow meter and the oxygen concentration by a paramagnetic oxygen analyzer and recorded by a computer as functions of time.

Heat flux to the top surface of the sample was applied by four concentric, water and air-cooled, tungsten-quartz radiant heaters. A controller was used to apply power to the radiant heaters. In the ignition test, samples were exposed to external heat flux values in the range of 20 to 60 kW/m^2. Combustion tests were performed at a fixed value of 50 kW/m^2.

In the ignition tests, a IO-mm long, premixed ethylene-air pilot flame was used to ignite the flammable vapor air mixture. The pilot burner consisted of a 6-mm OD vertical copper tube with a perforated ceramic tip bent at a right angle about 10-mm above the sample surface. The ethylene-air flow rate through the burner was set at about 10 cc/min.

In this report, sample surface area of $0.010\text{-}m^2$ refers to rectangular samples and surface area $0.0077\text{-}m^2$ refers to circular samples. The thickness of each sample is listed in Table 5.

2.1.2 Upper Section of the Flammability Apparatus

The sampling duct in the upper section was used to capture the products generated during the ignition, pyrolysis, combustion, and fire propagation processes along with the ambient air (about 85 times the volume of the products). The product-air mixture entered the sampling duct via an orifice plate. At about five duct diameters downstream of the orifice plate, the velocity profile of the flowing mixture becomes almost flat across the duct, allowing the use of a single point measurement. In the sampling duct, measurements were made for: gas temperature, mass and volumetric flow rates, optical transmission through the fire product-air mixture flowing through the sampling duct, concentrations of CO, CO_2, hydrocarbons and O_2.

The total flow rate of product-air mixture through the sampling duct was 0.28 m^3/s (flow velocity 14 m/s). A small fraction of product-air mixture was pumped out of the sampling duct at a rate of 0.17 x 10^{-3} m^3/s for the measurement of the concentrations of products. The liquids and particulate in the product-air mixture were removed by passing the mixture through a particulate filter, a water condenser, and a drying agent before being introduced into the measuring instruments. The instruments used for the measurements were:l) flowing reference infrared analyzers for CO and C02; 2) a paramagnetic oxygen analyzer for oxygen, 3) a flame ionization analyzer for the low molecular weight gaseous mixtures of hydrocarbons.

2.2 IGNITION AND COMBUSTION TESTS

2.2.1 The Ignition Tests

The ignition tests were performed to determine: 1) ***Critical Heat Flux (CHF)***[3], and 2) ***Thermal Response Parameter (TRP)***[4].

Ignition tests were performed in normal air under natural flow with external heat flux in the range of 20 to 60-kW/m^2. The sample surface was coated with a thin layer of 1: 1 fine mixture of graphite powder and charcoal. The surface was coated to ensure that the surface remains black even for short wave-lengths of the radiant heaters. A water-cooled shield in front of the radiant heaters was used to stabilize the radiant heaters prior to exposing the sample.

The sample was placed horizontally in the Flammability Apparatus at the "sample" location, without the quartz tube (natural flow condition). The pilot burner was adjusted such that the tip of the burner was within IO-mm above the sample surface. The pilot flame was lit. The water-cooled shield was moved up. The radiant heaters were turned on manually and the controller dial was set for the desired heat flux exposure of the sample surface. The radiant heaters were stabilized for about 60 seconds.

After the heaters were stabilized, the water-cooled shield was dropped and the top surface of the sample was exposed to the pre-set external heat flux value; the time was taken as the zero time. In the tests, times for the appearance of the vapors and a self-sustained flame were recorded by a stop watch. This procedure was repeated five to six times, using different external heat flux values in the range of 20 to 60 kW/m^2.

[3] ***Critical Heat Flux (CHF)***: externally imposed heat flux at or below which sustained piloted ignition does not occur. Resistance to ignition is higher for plastics with higher CHF values [3,4]. For the purposes of this study, CHF value was measured in the Flammability Apparatus (Fig. 2).

[4] ***Thermal Response Parameter (TRP):*** indicator of ignition time delay and relates the time-to-ignition to the net heat flux (imposed heat flux minus the CHF value) [3,4]. Resistance to ignition is higher for plastics with higher TRP values [3,4]. A detailed discussion is given in Section 3.1.

In the calculations, time-to-ignition was taken as the time at which a self-sustained flame was observed. At the completion of the ignition test series, data for the time-to-ignition versus external heat flux were used to determine the CHF and TRP values, following the methods described in Section IV, sub-section 4.1 on ignition.

2.2.2 The Combustion Tests

The combustion tests were performed in normal air under co-flow condition at a fixed external heat flux value of 50-kW/m^2. The inlet flow rate of air was 3.3 x 10^{-3} m^3/s. The combustion tests were performed to determine the: 1) chemical heat release rate, 2) generation rates of CO, CO_2, total hydrocarbons, and smoke, 3) consumption rate of oxygen, 4) chemical heat of combustion, and 5) yields of products.

After measuring the initial weight of the sample, it was placed on top of the platform identified as "sample" in Fig. 2, which was attached to the load cell. The lower quartz tube was placed around the bottom aluminum cylinder. The stainless steel cylinder and upper quartz tube then were placed on top of the lower tube. The gas sampling lines, filter, etc., and the analyzers were checked, cleaned or replaced as needed.

The pilot flame, the pump (in the lower section), and the exhaust blower (attached to the sampling duct in the upper section) were turned on. Before starting each test, the gas analyzers were calibrated. The calibrations for the load cell, turbidimeter (obscuration meter), thermocouple, and flow sensors were also checked and adjusted as needed.

After the calibration of the Apparatus, the radiant heaters were turned on and stabilized for about 60 seconds, the sample surface was protected from the heat exposure by the water cooled shield. After the radiant heaters were stabilized, the data acquisition system was turned on and the background data were recorded for 30 seconds, at which time the water-cooled shield was dropped. The sample surface was exposed to the desired external heat flux leading to ignition and combustion of the sample.

During the combustion test, observations were made of the times of appearance of vapors and sustained flames. The physical condition of the sample, flame heights and other pertinent observations were made at various times throughout the test. The test was continued until all the sample activities have ceased (no visible flames and vapors). After the Apparatus cooled down, the sample residue and the particulate filter paper in the gas sampling line were taken out and weighed to determine the weights of sample residue and smoke, respectively.

The data were used to calculate the chemical heat release rate, generation rates of CO, CO_2, total hydrocarbons, and smoke, and consumption rate of oxygen, following the procedures described in Section IV, sub-section 4.2 on combustion.

The results were used to assess the flammability characteristics of plastics in various components and parts of the vehicle and compare the behavior of the same parts in the large-scale fire tests being conducted under Research Project B.3 [1,6].

III
EXPERIMENTAL RESULTS

Twenty plastic parts from a 1996 Dodge Caravan, listed in Table 1, were selected for the first year of the study for the B. 10 project. Information about the generic nature of the plastics, their densities, and inorganic filler types and amounts are also listed in the table. The plastics in the selected parts, listed in the table, consist of polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), polyvinylchloride (PVC), and glass reinforced thermoset polyester resin cross-linked with styrene, referred to as a sheet molding compound (SMC). There were high amounts of inorganic fillers in some of the plastic parts.

3.1 IGNITION

Data pertinent to the ignition of plastics are listed in Table 4. In the table, thickness of the sample was measured in the ignition tests, density and specific heat values were taken from Ref. 5, thermal conductivity values were taken from Ref. 6, and thermal diffusivity values were calculated from the properties of the materials6 listed in the table.

The measured thickness versus the thermal penetration depth governs the ignition behavior of the samples [8, 9, 10][6]. In this study, the thermal penetration depth was calculated from the thermal diffusivity values and measured times-to-ignition [8, 9, 10][6]; the calculated values are listed in Table 5, along with the measured thickness of each sample. The data in the table show that beyond about 30 kW/m^2, the thermal penetration depth is less than the actual thickness of the samples and thus time to ignition is expected to satisfy the thermally thick condition[8, 9, 10][6]:

$$\sqrt{1/t_{ig}} = (\dot{q}''_e - \dot{q}''_{cr}) / \Delta T_{ig} \sqrt{(\pi/4)(k_v \rho_v c_v)} \tag{1}$$

[6] A material behaves as thermally thick for imposed heat fluxes, because the thermal penetration depth, when ignition occurs, is smaller than the material thickness [8, 9, 10]. Thermal penetration depth is of the order of: $\delta_v = \sqrt{\alpha_v t}$, where δ_v is the thermal penetration depth (m), α_v is the thermal diffusivity of the solid (m^2/s), and t is the exposure time until ignition occurs (s). The thermal diffusivity is defined as: $a_v = k_v / \rho_v c_v$, where k_v is the thermal conductivity of the original material (kW/m-K), ρ_v is the density of the original material (kg/m'), c_p is the specific heat of the original material (kJ/kg-K).

where $A\,T_{ig}\sqrt{(\pi/4)(k_v\rho_v c_v)}$ is defined ***as the Thermal Response Parameter (TRP)*** of the plastic. The applicability of the thermally thick condition to the ignition data represented by Eq. 1 has been tested for a variety of polymers [3,4].

For example, for polymethylmethacrylate (PMMA), k_v = 0.268 x 10" kW/m-K, c_v = 2.09 kJ/kg-K, ρ = 1190 kg/m^3 [11] and T_{ig} = 65 1 K [10]. Assuming ambient temperature to be 293 K, the calculated TRP value is 259 kW-s$^{1/2}$/m^2. The TRP value from four ignition data points, measured in the range of 30 to 60 kW/m^2 in the Flammability Apparatus, where the thermally thick condition was applicable, was found to be 274 kW-s$^{1/2}$/m^2 [11], which is 6 % higher than the calculated value. A similar procedure was used for the ignition data for plastics components and parts measured in the Flammability Apparatus in this study. Figure 3 shows a typical example of the ignition time versus heat flux for plastic part VAC #870. In the example, the thermally thick condition is applicable up to 15 kW/m^2.

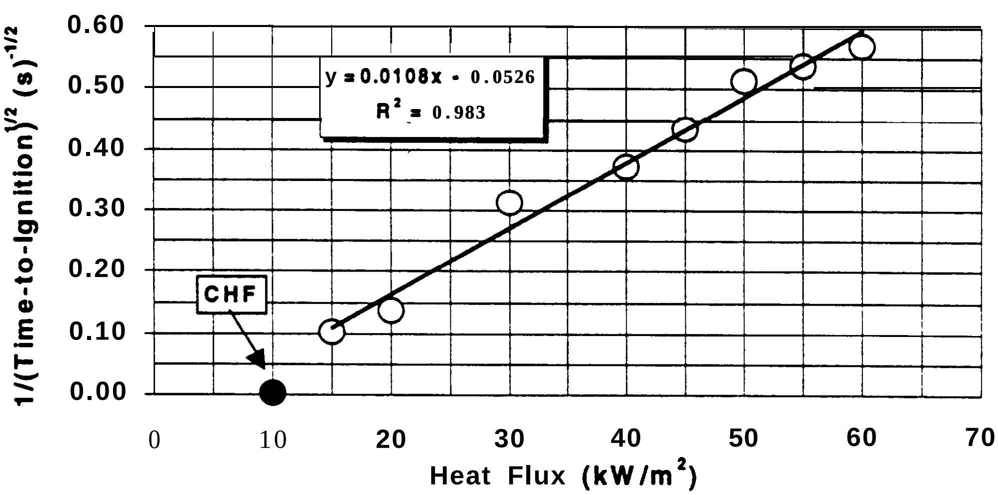

Figure 3. Inverse of the square root of time to ignition versus external heat flux for 25-mm thick sample of VAC #870 (Dodge Caravan part #4716832B, polyethylene terephthalate hood liner face). Measured CHF value (dark symbol) = 10 kW/m^2; TRP (inverse of the slope) = 93 kW-s$^{1/2}$/m^2.

For the determination of the experimental TRP values, times-to-ignition values measured at external heat values of 30 kW/m^2 and higher were used in Eq. 1, to make certain that thermally thick condition was applicable. The experimental TRP values were determined from the inverse of the slope of lines, such as the one shown in Fig. 3. It was assumed that ignition data for all the samples satisfy the thermally thick condition. The experimental TRP values determined in this fashion for the plastic components and parts examined in the study are listed in Table 6, along with the calculated TRP values[7]. The TRP values were calculated from the ignition temperature estimated from the CHF values (see following paragraphs) and the density, specific heat, and thermal conductivity values listed in Table 4. There may be errors in the experimental TRP values for some of the samples, if they do not satisfy the thermally thick condition. A correlation between the experimental and calculated TRP values is shown in Fig. 4. The correlation is reasonable, although higher R^2 values are desirable. It is expected to improve as more data are obtained during the continuation of the study.

Table 6 also lists the measured and estimated CHF values. The CHF value is measured by performing the ignition test at the lowest possible heat flux at which there is no ignition for 15 minutes. For example, a CHF value of 10 kW/m^2 was measured for PMMA following this procedure in the Flammability Apparatus. If the CHF value is considered primarily as the surface heat loss at ignition due to radiation [8], then for a black surface [8]:

$$\dot{q}''_{cr} = \sigma T_{ig}^4 \tag{2}$$

where $\dot{q}''_{cr}$ is the ***Critical Heat Flux (CHF)*** (kW/m^2), σ is the Boltzmann radiation constant (56.7 x 10^{-12} kW/m^2-K^4), and T_{ig} is the ignition temperature (K). Rearranging Eq. 2:

$$T_{ig} \approx \left[\left(\dot{q}''_{cr} \right)^{0.25} x\ 364 \right] \tag{3}$$

For PMMA, from Eq 3 with a CHF value of 10 kW/m^2, the calculated value of T_{ig} is 647 K; it compares well with an ignition temperature value of 65 1 K for 12-mm thick PMMA [10] and a value of 658 K for the decomposition temperature of PMMA [12].

The measured CHF values listed in Table 6 were obtained by the above procedure. The estimated CHF values were obtained following the thermally thin condition approximation [9]. Data in Table 5 show that for low heat flux values, close to the CHF values, thermal penetration depth, calculated from the thermal diffusivity and measured time to ignition, is larger than the thickness of the samples.

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7 Ignition data for the following very small parts were not measured: 1) VAC # 256, part # 4612512B; 2) VAC #673, part # 4680250 A and C; 2) VAC #736, part # 4683264; 3) VAC 3008, part #4707580A.

Under the thermally thin condition, the inverse of time-to-ignition is a linear function of the external heat flux and extrapolation of the linear relationship to zero heat flux provides an estimate of the CHF value. For example, the measured CHF value for PMMA is 10 kW/m^2, and the estimated value from extrapolation is also 10 kW/m^2 [11]. The estimated CHF values in Table 6 were obtained following this procedure.

A comparison of the measured and estimated CHF value (Fig. 5) shows a reasonable correlation. As more data are acquired, the agreement is expected to improve.

Table 3

Plastics Parts of a 1996 Dodge Caravan Examined in This Study[a]

VAC#	Dodge Part #	Description	Type of Plastics	Density (g/cm^3)	Inorganic Fillers	
					Type	%
201	4883 140A	Fuel tank	PE	0.94	NA	0.0
208	47 16895	Wheel well cover, fuel tank shield	PP	0.93	NA	2.2
230	5235267	Battery cover	PP	0.90	NA	0.2
256	4612512A	Resonator structure	PP	1.06	NA	20.4
	46125128	Resonator intake tube	EPDM	1.15	Si, Ca	1.9
611	PL98SX8A	Instrument panel shelf, main panel	PC	1.18	NA	0.2
654	JF48SK5B	Instrument panel cover, exposed surface	PVC	1.20	Si, Ca	8.0
67'3	4680250A (468015 1)	Steering column boot, inner interior boot	Natural rubber (NR)	1.26	Si, S, Ca, Zn	7.7
	4680250C (4680152)	Steering column boot, outer interior boot	polyether co-polyester elastomer	1.15	Si, Ca, S	18.1
676	473407 1	HVAC unit, top main housing, outer top'	PP	NA	NA	NA
	4734370	HVAC unit, seals-both large and small	ABS and PVC blend	0.07	Mg, Si, S, Ca	18.5
732	4678345B	Air ducts, large ducts	PP	1.04	Mg, Si (talc)	18.8
736	4683264	Brake fluid reservoir	PP	0.90	NA	0.0
743	GJ42SK4D	Headliner, fabric-exposed surface	Nylon6	0.12	NA	1.4
788	46747 11 B	Kick panel insulation backing	PVC	1.95	Si, S, Ca, Ba	52.9
798	4857041A	Headlight lens	PC	1.19	NA	0.20
868	4716345B	Fender sound reduction foam	PS	0.13	Al, Si, Ti, Zn, (Kaol)	39.0
870	4716832B	Hood liner face	PET	0.66	Mg, Si, Ca, Sb	1.3
967	4716051	Windshield wiper structure	SMC	1.64	Mg, Al, Si, Ca (gl fibers, CaC03	47.2
3008	4707580A	Grommet-wire harness cap for 3008	HDPE	0.95	NA	0.3

a: from Ref. 5; PE: polyethylene: PP: polypropylene; PS: polystyrene; PET: polyethylene terephthalate; PVC: polyvinylchloride; SMC: sheet molding compound; gl: glass; kao: kaolin; **NA:** not available.

Table 4

Thermal Properties of Plastics Parts of a 1996 Dodge Caravan Examined in This Study

VAC #	Dodge Part #	Description	Type of Plastics[a]	δ^b (mm)	$\rho_v^c \times 10^{-3}$ (kg/m^3)	c_v^d (kJ/kg-K)	$k_v^e \times 10'$ (kW/m-K)	α_v^f (mm^2/s)
201	4883 140A	Fuel tank	PE	6	0.94	2.147	0.42	0.2 1
208	47 16895	Wheel well cover, fuel tank shield	PP	4	0.93	2.200	0.20	0.10
230	5235267	Battery cover	PP	5	0.90	2.216	0.20	0.10
256	4612512A	Resonator structure	PP	5	1.06	2.082	0.20	0.09
	4612512B	Resonator intake tube	EPDM	6	1.15	1.745	0.22	0.11
611	PL98SX8A	Instrument panel shelf, main panel	PC	5	1.18	1.510	0.20	0.11
654	JF48SK5B	Instrument panel cover, exposed surface	PVC	5	1.20	1.374	0.21	0.13
673	4680250A (4680151)	Steering column boot, inner interior boot	Natural rubber (NR)	9	1.26	1.391	0.28	0.12
	4680250C (4680152)	Steering column boot, outer interior boot	Poiyether co-polyester elastomer	16	1.15	1.785	0.17	0.08
676	473407 1	HVAC unit, top main housing, outer top	PP	5	NA	NA	0.20	
	4734370	HVAC unit, seals-both large and small	ABS and PVC blend	25	0.07	2.015	0.27	1.9
732	4678345B	Air ducts, large ducts	PP	5	1.04	1.934	0.20	0.10
736	4683264	Brake fluid reservoir	PP	5	0.90	2.247	0.20	0.10
743	GJ42SK4D	Headliner, fabric-exposed surface	Nylon 6	13	0.12	2.192	0.24	0.91
788	46747 11 B	Kick panel insulation backing (silencer?)	PVC	20	1.95	1.141	0.2 1	0.09
798	4857041A	Headlight lens	PC	5	1.19	2.061	0.20	0.08
868	47 163458	Fender sound reduction foam	PS	16	0.13	1.624	0.16	0.76
870	47 16832B	Hood liner face	PET	25	0.66	1.319	0.15	0.17
967	4716051	Windshield wiper structure	SMC	5	1.64	1.140	0.75	0.40
3008	4707580A	Grommet-wire harness cap for 3008	HDPE	5	0.95	2.122	0.42	0.21

a: information reported by Abu-Isa, Cummings, and LaDue [5]; b: measured (overall component or part thickness between about 15 to 25-mm); c: density from Ref. 5; d: specific heat from Ref. 5; e: thermal conductivity from Ref. 7; f: calculated thermal diffusivity from the property data in the table; NA: Not available.

Table 5

Measured Thickness and Calculated Thermal Penetration Depth in mm for Plastics Parts of a 1996 Dodge Caravan Examined in This Study

VAC #	Plastic	Actual thickness (mm)	α (mm/s)	Calculated Thermal Penetration Depth from Measured Time to Ignition and a at Various External heat Flux Values (kW/m²)[a]									
				10	15	20	25	30	40	45	50	55	60
201	PE	6	0.21			7		6	4	4	3	3	3
208	PP	4	0.10			4		3	2		2		1
230	PP	5	0.19			5		3	2		2		2
256[b]	PP	5	0.09		8	5		3	2		2		1
611	PC	5	0.11					5	3		2		2
654	PVC	5	0.13	10	4	3		2	2		2		1
676	PP	25	1.9			20		5	3		2		2
732	ABS-PVC	5	0.10			6		4	3		2		2
743	Nylon 6	13	0.91				7	6	4		3		3
788	PVC	20	0.09		4	3		2	2		1		1
798	PC	5	0.08					5	3		3		2
868	PS	16	0.76					2	3		2		1
870	PET	25	0.17		4	3		1		1	7	1	1
967	SMC	5	0.40					8	3		5		5

a: calculated from the thermal diffusivity and measured time-to-ignition [8]. b : Ignition data were not measured as sample amounts were not enough: VAC# 256-461 25 12B; VAC #673-4680250 A and B; VAC #736-4683264; VAC 3008- 4707580A.

Table 6

Critical Heat Flux, Thermal Response Parameter, Ignition and Decomposition Temperatures for Plastic Parts of a 1996 Dodge Caravan Examined in this Study

VAC #	Plastic	CHF (kW/m^2)		TRP ($kW\text{-}s^{1/2}/m^2$)		T_{ig} (°C)	T_d (°C)
		Measured’	Estimated[b]	Measured’	Calculated[d]	Estimated’	Literature’
201	PE	15	13	454	342	443	440
208	PP	15	13	288	231	443	429
230	PP	15	15	323	226	443	423
256	PP	10	13	277	241	374	430
611	PC	20	21	357	222	497	440
654	PVC	NM	9	263	130	357’	269
676	PP	15	15	310	NA	443	NA
676	ABS-PVC	NM	19	73	81[g]	487’	NA
732	PP	15	15	333	230	443	430
743	Nylon 6	20	20	154	106	497	497
788	PVC	10	7	215	142	374	255
798	PC	20	23	434	264	497	445
868	PS	20	20	146	62	497	401
870	PET	10	6	174	98	374	325
967	SMC	20	20	483	434	497	414

a: external heat flux at or below which there was no ignition for 15 minutes; b: from extrapolation of the linear relationship between inverse of time to ignition versus external heat flux to zero heat flux value; c: from the relationship between inverse of the square root of time to ignition versus external heat flux for thermally thick condition. All the samples were assumed to be thermally thick above 30 kW/m^2. There may be some errors for those samples which do not satisfy the thermally thick condition; d: from density, thermal conductivity, and specific heat values from Table 4 and decomposition temperature listed in the table; e: from the measured CHF value and Eq. 3; f: from Ref. 5; g: from the estimated CHF value; NM: not measured; NA: not available.

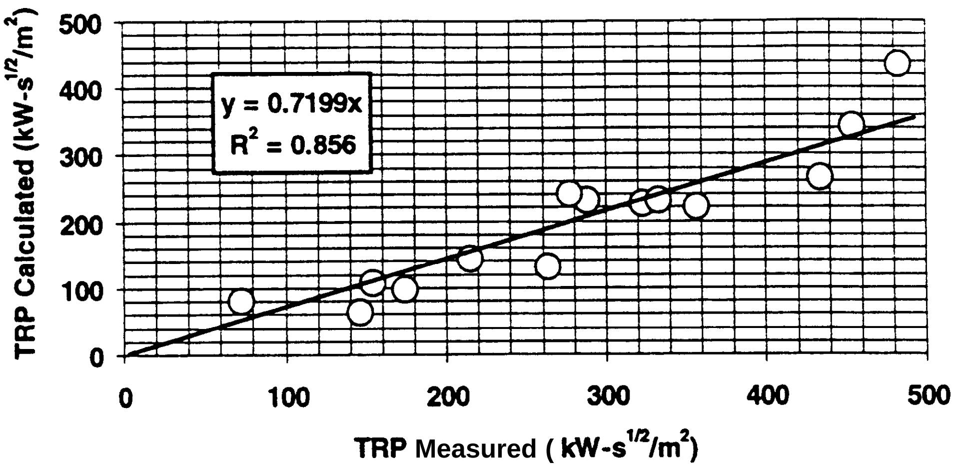

Figure 4. Correlation between the measured and calculated Thermal Response Parameter Values for the plastic parts examined in this study. Ignition data were measured in the Flammability Apparatus. Measured TRP values are obtained from the relationship between inverse of the square root of measured time-to-ignition versus external heat flux (Eq. 1). The TRP values are calculated from the Abu-Isa et al's [5] data for the density, specific heat, and thermal conductivity (Table 4) and ignition temperature estimated from the measured CHF value (Table 5), assuming ambient temperature to be 293 K.

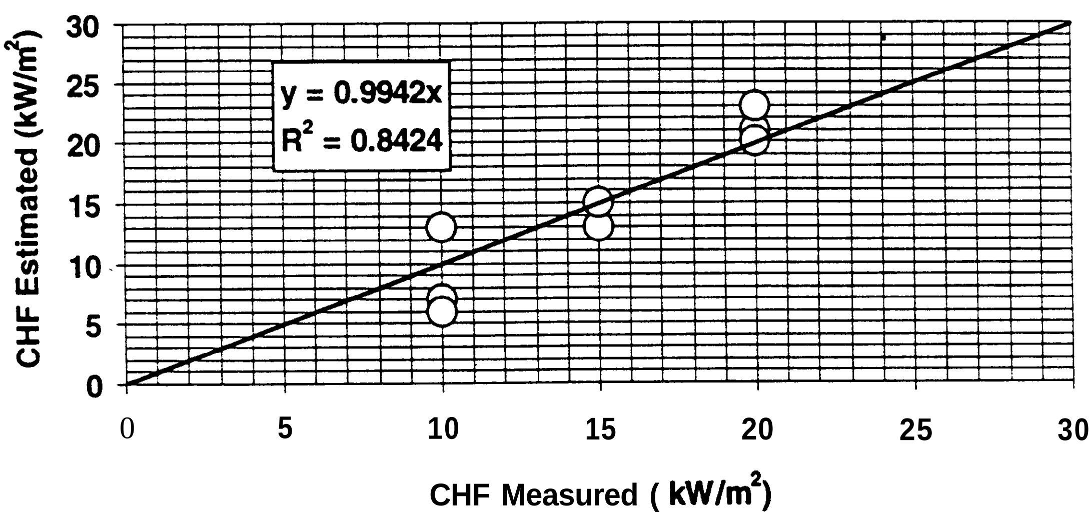

Figure 5. Comparison between the measured and estimated Critical Heat Flux Values for the plastic parts examined in this study. Ignition data were measured in the Flammability Apparatus.

3.2 COMBUSTION

In the combustion test, data were measured for mass loss and heat and concentrations of products. The data were used to derive the following:

3.2.1 Mass Loss Rate

Mass loss rate was obtained from the data measured by the load cell as function of time. The fifteen second running average of the mass loss rate was used, such as shown in Fig. 6, as an example for VAC # 201 (PE fuel tank) sample burned in a circular dish. Data for the mass loss rate reported in Table 7 is the peak value of the fifteen second running average of the mass loss rate The total sample mass loss in the combustion test was measured directly as well as calculated from the summation of the mass loss rate:

$$W = A \sum_{n=t_i}^{n=t_f} \dot{m}''(t_n)\Delta t_n \qquad (5)$$

where W is the total sample mass loss (g), ti is the time for the appearance of vapors (s), tf is the time at which vapors and/or flame disappear (s), and A is the total exposed surface area of the sample (m^2). Fig. 7 shows an example of the data obtained from the summation of the mass loss rate for VAC #230 (PP battery cover).

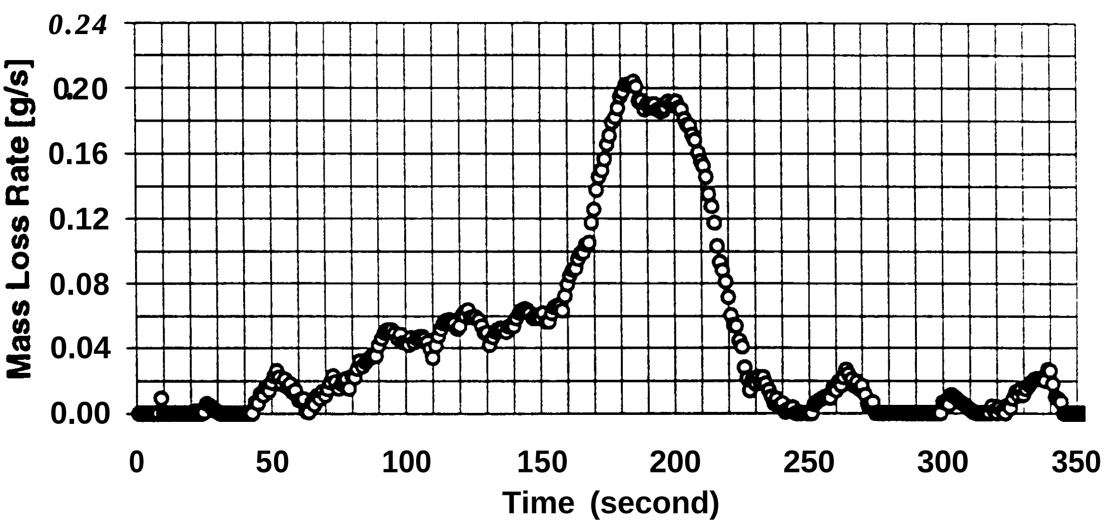

Figure 6. Fifteen second running average mass loss rate versus time for the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) at 50 kW/m^2 of external heat flux in normal air. Combustion test was performed in a circular dish. The sample surface area was *0.0077* m^2.

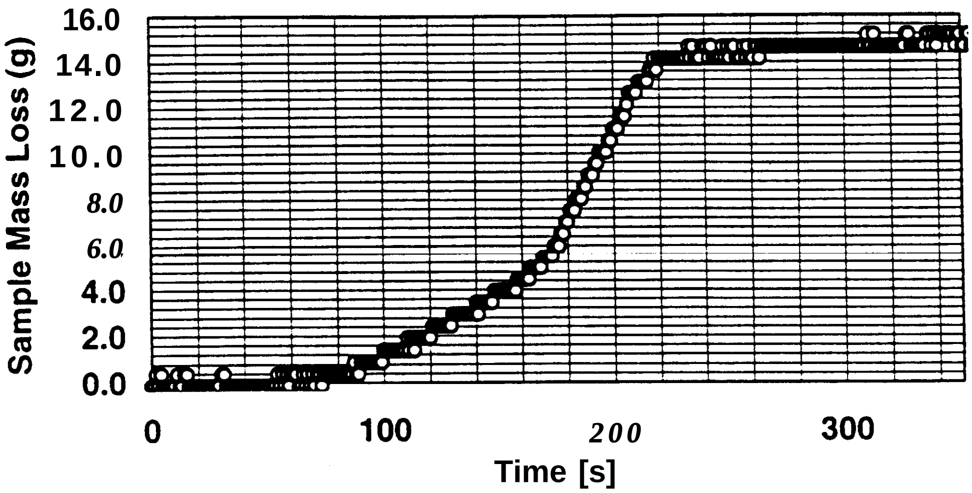

Figure 7. Total sample mass loss versus time during the combustion of VAC #230 (Dodge part #5235267, polypropylene battery cover) sample contained in a round dish. The sample was exposed to 50 kW/m^2 in normal air in the Flammability Apparatus.

The measured and calculated total mass loss agreed within ± 5 %. However, for some samples there was greater disagreement. The percent-residue was calculated from the difference between the initial mass and final sample mass. Total sample loss and percent residue for the samples examined in this study are reported in Table 7.

3.2.2 Generation Rates of Products and Depletion Rate of Oxygen

Concentrations of products measured in the combustion tests were used to calculate the generation rates of products, consumption rate of oxygen, and chemical heat release rate, using the following relationships:

1. Generation Rates of Products [3,4]

$$\dot{G}''_j = f_j \dot{V} \rho_j / A = f_j \dot{W} (\rho_j / \rho_g A) \qquad (6)$$

where $\dot{G}''_j$ is the mass generation rate of product j (g/m^2-s), fj is the measured volume fraction of product j, $\dot{V}$ and $\dot{W}$ are the measured total volumetric and mass flow rates of the products air mixture in m^3/s and g/s respectively, ρ_j and ρ_g are the densities of product j and fire-product mixture respectively at the temperature of the mixture (g/m^3); and A is the total exposed surface area of the sample (m^2). On-line gas analyzers were used to measure the volume fractions of the gaseous products (CO, CO_2, mixture of gaseous hydrocarbons, and oxygen).

The volume fraction of smoke was calculated from the following relationship [13] and used in Eq. 6 to calculate its generation rate:

$$f_s = D\lambda \; x \; 10^{-6} / \Omega \qquad (7)$$

where f_s is the volume fraction of smoke, λ is the wave length of the light source (μm), Ω is the coefficient of particulate extinction equal to 7.0 [13], and D is the optical density (l/m):

$$D = \ell n (I_0 / I) / \ell \qquad (8)$$

where I/I_0 is the fraction of light transmitted through smoke, and P is the optical path length (m). The optical density is measured at three wavelengths: 0.4579 μm (blue), 0.6328 μm (red), and 1.06 μm (IR). For the calculation of the generation rate, smoke particulate density value of 1.1 x 10^6 g/m^3 [13] is used in Eq. 6. All the data were used in the analysis as fifteen-second running average rates.

Examples of the fifteen second running averages for the generation rates of CO, CO_2, hydrocarbons, and smoke are shown respectively in Figs. 8 to 11 for VAC #230 (PP battery cover) sample burned in a circular dish. The rate of oxygen consumption for the same sample is also shown in Fig. 9. The peak values of the fifteen-second running average rates for the samples examined in the study are listed in Table 8.

2. <u>Consumption Rate of Oxygen</u> [3,4]

Consumption rate of oxygen is also calculated from Eq. 6, where $\dot{G}''_j$ is expressed as $\dot{C}''_O$, the consumption rate of oxygen (g/m^2-s); f_j expressed as f_O, the measured volume fraction of oxygen consumed; and ρ_j expressed as ρ_O, the density of oxygen (g/m^3).

Table 7

Average Peak Mass Loss Rate, Total Mass Loss and Residue in the Combustion of Plastic Parts of a 1996 Dodge Caravan Examined in this Study

VAC’ #	Dodge Part’ #	Description’	Type of Plastics’	Mass Loss Rate[b] (g/m^2-s)	Total Mass Loss[c] (g)	Residue[d] (%)
201	4883140A	Fuel tank	PE	37.4	31.6	4.0
208	47 16895	Wheel well cover, fuel tank shield	PP	26.7	11.7	1.1
230	5235267	Battery cover	PP	26.0	15.2	0.1
256	4612512A	Resonator structure	PP	25.7	17.4	15.7
	46125128	Resonator intake tube	EPDM	9.1	27.4	16.9
611	PL98SX8A	Instrument panel shelf, main panel	PC	27.9	25.9	4.2
654	JF48SK5B	Instrument panel cover, exposed surface	PVC	21.7	39.1	6.3
673	4680250A (468015 1)	Steering column boot, inner interior boot	Natural rubber (NR)	16.2	10.3	4.6
	4680250C (4680152)	Steering column boot, outer interior boot	polyether co-polyester elastomer	17.2	14.9	4.1
676	473407 1	HVAC unit, top main housing, outer top	PP	21.1	11.6	4.3
	4734370	**HVAC** unit, seals-both large and small	ABS and PVC blend	8.7	9.0	1.2
732	4678345B	Air ducts, large ducts	PP	31.6	14.7	2.3
736	4683264	Brake fluid reservoir	PP	35.1	14.9	0.0
743	GJ42SK4D	Headliner, fabric-exposed surface	Nylon6	8.9	4.4	1.1
788	46747 11 B	Kick panel insulation backing (silencer?)	PVC	15.0	15.9	51.8
798	4857041A	Headlight lens	PC	31.9	26.9	5.8
868	4716345B	Fender sound reduction foam	PS	17.5	8.8	30.6
870	4716832B	Hood liner face	PET	7.8	10.1	5.3
967	4716051	Windshield wiper structure	SMC	14.4	11.0	70.5
3008	4707580A	Grommet-wire harness cap for 3008	HDPE	35.5	15.0	0.0

a: from Ref. 5; b: peak value of the fifteen-second running average mass loss rate for the combustion of the sample in a round dish in normal air at 50 kW/m^2. Sample surface area: $0.0077 m^2$; c: from the difference between initial and final mass of the sample measured by a balance; d: from the difference between the initial mass and final mass loss measured by a balance.

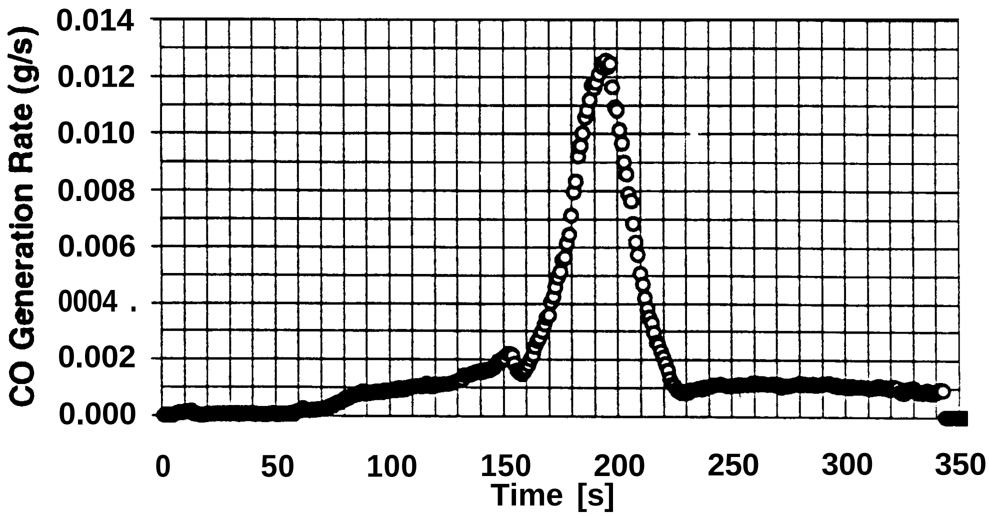

Figure 8. Fifteen second running average generation rate of CO versus time for the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) at 50 kW/m^2 of external heat flux in normal air. Combustion test was performed in a circular dish with a sample surface area of 0.0077 m^2.

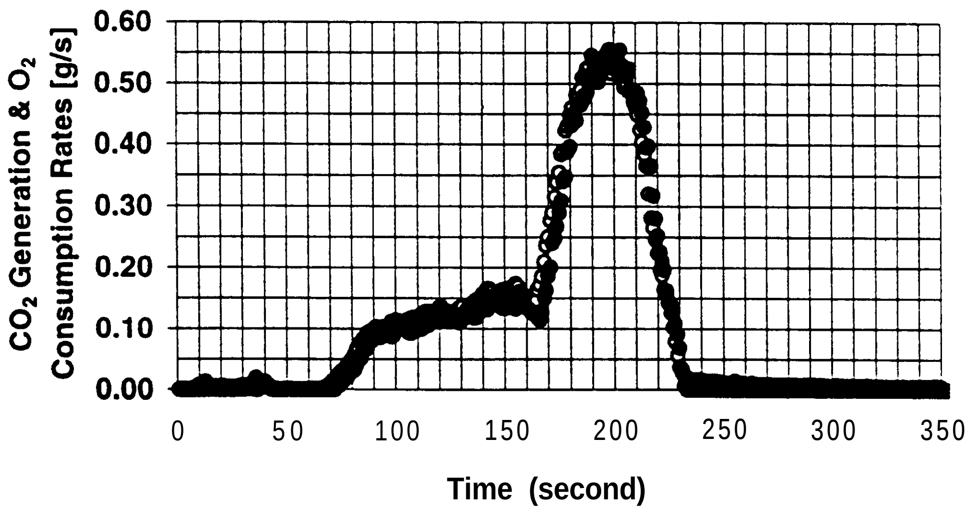

Figure 9. Fifteen second running average generation rate of CO_2 (open symbols) and consumption rate of O_2 (dark symbols) for the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) at 50 kW/m^2 of external heat flux in normal air in a circular dish with a sample surface area of 0.0077 m^2.

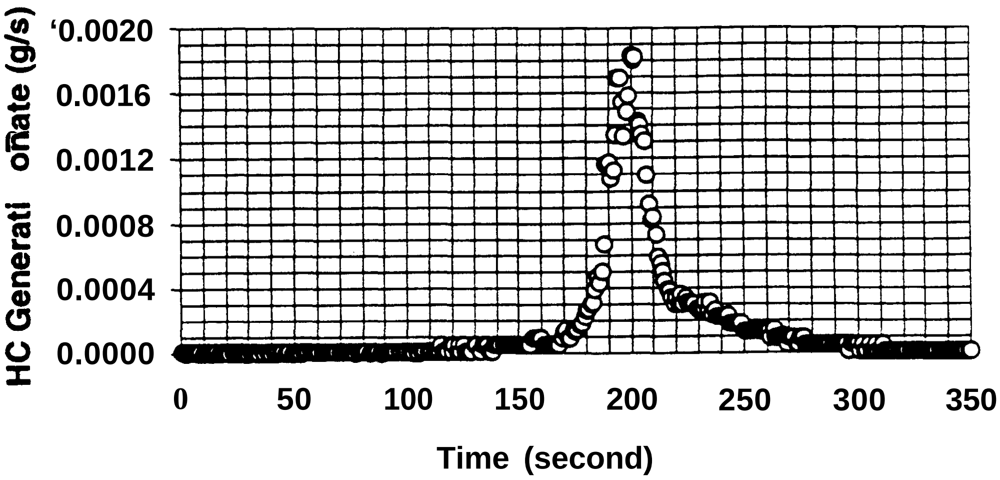

Figure 10. Fifteen second running average generation rate of hydrocarbons in the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) at 50 kW/m^2 of external heat flux in normal air in a circular dish with a sample surface area of 0.0077 m^2.

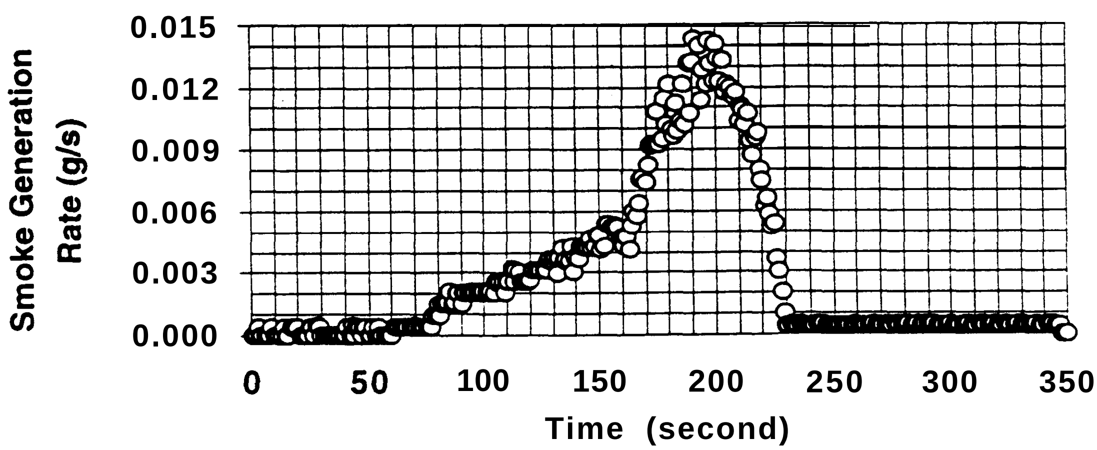

Figure 11. Fifteen second running average generation rate of smoke in the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) at 50 kW/m^2 of external heat flux in normal air in a circular dish with a sample surface area of 0.0077 m^2.

3.2.3 Chemical Heat Release Rate

Chemical heat release rate is calculated from: 1) the generation rate of CO, (the ***Carbon Dioxide Generation (CDG) Calorimetry)*** [3,4], corrected for the generation rate of CO; and 2) the consumption rate of oxygen (the ***Oxygen Consumption (OC) Calorimetry)*** [14].

The CDG Calorimetry [3,4]

$$\dot{Q}''_{ch} = A\ H^*_{co2}\ \dot{G}''_{co2} + A\ H^*_{co}\ \dot{G}''_{co} \tag{9}$$

where $\dot{Q}''_{ch}$ is the chemical heat release rate (kW/m^2); $A\ H^*_{co2}$ is the net heat of complete combustion per unit mass CO2 generated (kJ/g); the average value is 13.3 ± 11% (kJ/g) [3,4]; $A\ H^*_{co}$ is the net heat of complete combustion per unit mass CO generated (kJ/g); the average value is 11.1 ± 18% (kJ/g)[3,4].

The OC Calorimetry [14]

$$\dot{Q}''_{ch} = \Delta\ H^*_{o}\ \dot{C}''_{o} \tag{10}$$

where $A\ H^*_{O}$ is the net heat of complete combustion per unit mass 02 consumed (kJ/g); the average value is 12.8 ± 7% (kJ/g) [3,4]

An example of the chemical heat release rate calculated from the CDG and OC Calorimetry is shown in Fig. 12, where fifteen-second running averages for the rates are shown for VAC # 230 (PP battery cover). The peak values of the fifteen-second running average of the chemical heat release from the CDG and OC Calorimetry are in good agreement (± 5%). The peak values for the samples examined in this study are listed in Table 8.“

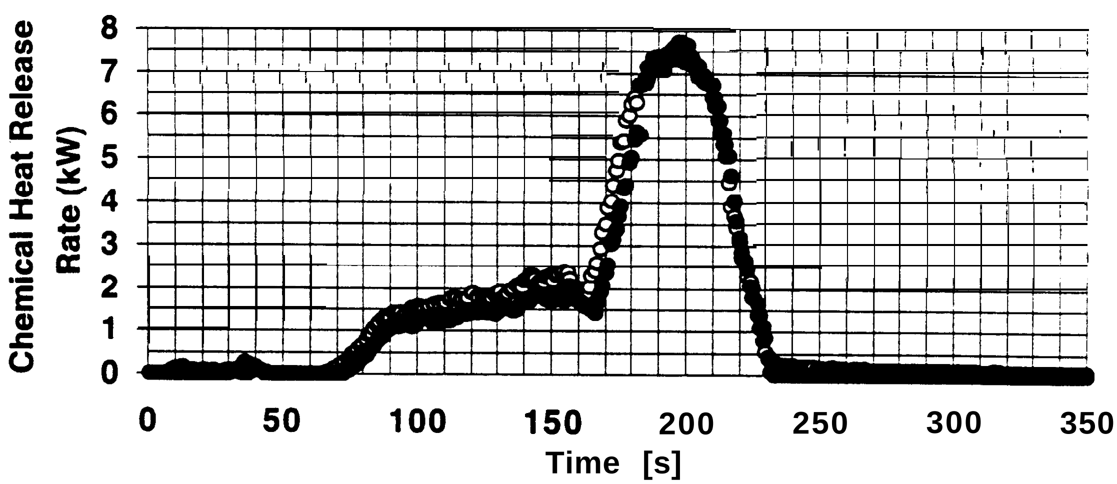

Figure 12. Fifteen second running average chemical heat rate. Open symbols: CDG Calorimetry; Dark symbols: OC Calorimetry. The chemical rates are for the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) at 50 kW/m^2 of external heat flux in normal air in a circular dish. Sample surface area of 0.0077 m^2.

Table 8

Average Peak Generation Rates of Products and Chemical Heat Release Rate in the Combustion of Plastic Parts of a 1996 Dodge Caravan Examined in this Study

VAC[a] #	Dodge Part[a] #	Description[a]	Type of Plastics[a]	Generation Rate[b] (g/m^2-s)				Chemical Heat Release Rate[c] (kW/m^2)
				CO	CO_2	HC[d]	Smoke	
201	4883140A	Fuel tank	PE	2.34	91.4	0.57	2.04	1296
208	47 16895	Wheel well cover, fuel tank shield	PP	1.43	77.0	0.16	2.35	1078
230	5235267	Battery cover	PP	1.64	71.4	0.23	2.40	1004
256	4612512A	Resonator structure	PP	1.00	66.2	0.08	2.09	926
	46125128	Resonator intake tube	EPDM	0.60	18.0	0.01	0.91	242
611	PL98SX8A	Instrument panel shelf, main panel	PC	1.26	44.7	0.08	3.29	486
654	JF48SK5B	Instrument panel cover, exposed surface	PVC	1.42	37.3	0.2 1	3.08	527
673	4680250A (4680151)	Steering column boot, inner interior boot	NR	0.79	29.2	0.05	3.34	396
	4680250C (4680 152)	Steering column boot, outer interior boot	Polyester	0.53	36.3	0.03	1.51	488
676	473407 1	HVAC unit, top main housing, outer top	PP	0.78	54.0	0.08	1.73	755
	4734370	HVAC unit, seals-both large and small	ABS-PVC	0.60	11.5	0.03	1.oa	158
732	4678345B	Air ducts, large ducts	PP	1.95	78.8	0.36	2.86	1110
736	4683264	Brake fluid reservoir	PP	3.52	88.3	1.17	3.35	1254
743	GJ42SK4D	Headliner, fabric-exposed surface.	Nylon6	0.40	22.5	< 0.01	0.66	301
788	46747 11 B	Kick panel insulation backing (silencer?)	PVC	1.05	15.6	0.12	1.64	219
798	485704 1 A	Headlight lens	PC	1.74	51.2	0.21	4.75	559
868	4716345B	Fender sound reduction foam	PS	0.64	28.1	0.07	2.34	381
870	47 16832B	Hood liner face	PET	0.20; 0.34	9.74; 9.10	0.01; 0.03	0.75; 0.13	132; 117
967	4716051	Windshield wiper structure	SMC	0.61	25.5	0.03	2.26	345
3008	4707580A	Grommet-wire harness cap for 3008	HDPE	3.95	93.1	1.40	2.52	1341

a: from Ref. 5; b: peak value of the fifteen-second running average of the generation rates of the products in the combustion of the sample in a round dish in normal air at 50 kW/m^2. Sample surface area: 0.0077m^2; c: from the CDG Calorimetry; d: mixture of gaseous hydrocarbons.

3.2.4 Cumulative Yields of Products

The cumulative yield of a product is determined from the ratio of the total amount of a product generated and the total sample mass loss (Eq. 5):

$$y_j = W_j / W \tag{11}$$

where yj is the yield of product j (g/g) and Wj is the total amount of product generated (g), obtained from the summation of the generation rate of the product:

$$W_j = A \sum_{n=t_i}^{n=t_f} \dot{G}''_j(t_n)\, \Delta t_n \tag{12}$$

An example of the total amount of a product (CO) generated, as determined from the summation of its generation rate, versus time is shown in Fig. 13. The cumulative of yields of products for various plastics are listed in Table 9.

3.2.5 Cumulative Chemical Heat of Combustion

The cumulative chemical heat of combustion is determined from the ratio of the total amount of energy (enthalpy) released and the total sample mass loss (Eq. 5):

$$\Delta H_{ch} = E_{ch} / W \tag{13}$$

where Ech is the chemical energy (enthalpy) released in kJ, obtained from the summation of the chemical heat release rate:

$$E_{ch} = A \sum_{n=t_i}^{n=t_f} \dot{Q}''_{ch}(t_n)\, \Delta t_n \tag{14}$$

The cumulative chemical heats of combustion for various plastics are listed in Table 9. Figure 14 shows an example of the energy (enthalpy) released in the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) obtained from the summation of the chemical heat release rate.

Table 9

Cumulative Yields of Products and Cumulative Chemical Heat of Combustion in the Combustion of Plastic Parts of a 1996 Dodge Caravan Examined in this Study

VAC[a] #	Dodge Part' #	Description'	Type of Plastics'	Yield (g/g)[b]				Chemical Heat of Combustion[b,c] (kJ/g)
				CO	CO_2	HC[d]	Smoke	
201	4883140A	Fuel tank	PE	0.032	2.33	0.005	0.042	32.7
208	4716895	Wheel well cover, fuel tank shield	PP	0.054	2.45	0.002	0.065	34.5
230	5235267	Battery cover	PP	0.045	2.59	0.004	0.071	36.2
256	4612512A	Resonator structure	PP	0.041	2.46	0.002	0.072	34.6
	4612512B	Resonator intake tube	EPDM	0.045	2.51	0.001	0.100	33.8
611	PL98SX8A	Instrument panel shelf, main panel	PC	0.051	1.86	0.002	0.105	20.2
654	JF48SK5B	Instrument panel cover, exposed surface	PVC	0.057	1.72	0.005	0.109	24.4
673	4680250A (4680151)	Steering column boot, inner interior boot	NR	0.061	1.87	0.003	0.130	25.6
	4680250C (4680152)	Steering column boot, outer interior boot	Polyester	0.039	2.17	0.002	0.087	29.4
676	4734071	HVAC unit, top main housing, outer top	PP	0.057	2.49	0.002	0.060	35.0
	4734370	HVAC unit, seals-both large and small	ABS-PVC	0.089	1.62	0.001	0.060	22.6
732	4678345B	Air ducts, large ducts	PP	0.056	2.52	0.004	0.080	35.5
736	4683264	Brake fluid reservoir	PP	0.058	2.41	0.011	0.072	33.9
743	GJ42SK4D	Headliner, fabric-exposed surface	Nylon6	0.086	2.09	0.001	0.045	28.8
788	4674711B	Kick panel insulation backing (silencer?)	PVC	0.061	1.26	0.006	0.070	17.4
798	4857041A	Headlight lens	PC	0.049	1.67	0.004	0.112	18.2
868	4716345B	Fender sound reduction foam	PS	0.064	1.80	0.002	0.098	24.6
870	4716832B	Hood liner face	PET	0.041	1.47	0.003	0.022	20.0
967	4716051	Windshield wiper structure	SMC	0.061	1.86	0.003	0.100	25.5
3008	4707580A	Grommet-wire harness cap for 3008	HDPE	0.064	2.67	0.012	0.058	38.2

a: from Ref. 5; b: cumulative values of the fifteen-second running average of the generation rates of products and heat release rate in the combustion of the sample in a round dish in normal air at 50 kW/m^2. Sample surface area: 0.0077m^2; c: from the CDG Calorimetry; d: mixture of gaseous hydrocarbons.

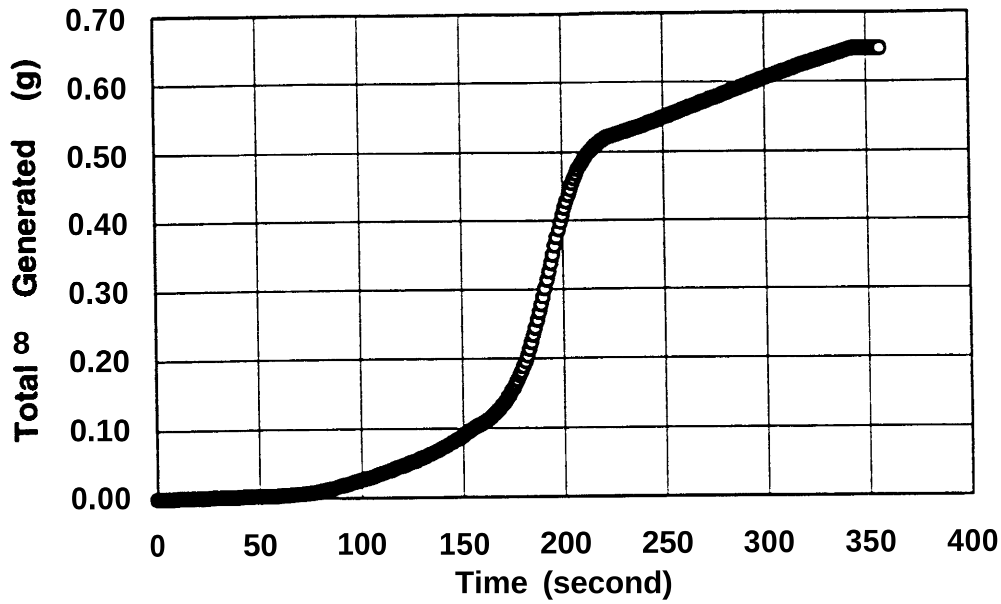

Figure 13. Total amount of CO generated versus time for the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) in a circular dish at 50 kW/m of external heat flux in normal air. Sample surface area: 0.0077 m^2.

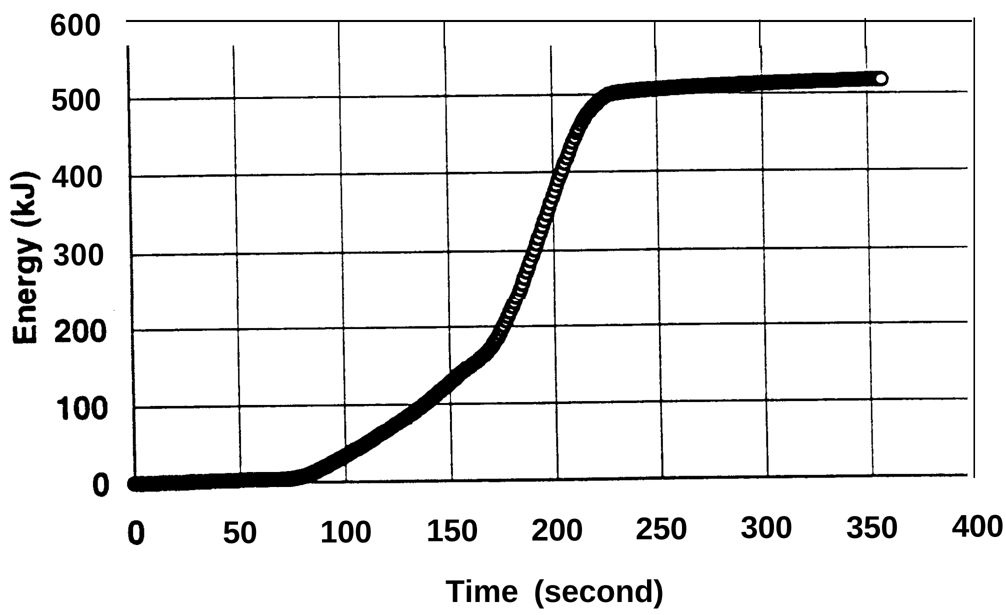

Figure 14. Energy (Enthalpy) released versus time for the combustion of VAC # 230 (Dodge part # 5235267, polypropylene battery cover) in a circular dish at 50 kW/m of external heat flux in normal air. Sample surface area: 0.0077 m^2.

IV
DISCUSSION

The objective of our study is to evaluate the flammability of plastics used in motor vehicles. In this report, data are presented for 20 plastic components and parts of a 1996 Dodge Caravan.

4.1 IGNITION

The experimental ignition data for CHF and TRP for the plastic components and parts of the 1996 Dodge Caravan are reported in Table 6. The TRP values, calculated from the thermal properties, using the expression, $\Delta T_{ig}(k\rho c_p \pi/4)^{1/2}$ for the thermally-thick condition, are also listed in the table. The correlation between the measured and calculated TRP values is shown in Fig. 4.

The TRP values for plastic parts of the 1996 Dodge Caravan for which ignition tests were not performed, have been calculated from the expression for the thermally thick condition, using decomposition temperature and thermal properties reported in Ref. 5. Table 10.

The relationship between the ignition temperature (T_{ig}) and the decomposition temperature (T_d) in Fig. 15, show that generally $T_{ig} > T_d$. The calculated TRP values in Table 10 using T_d values thus are conservative values.

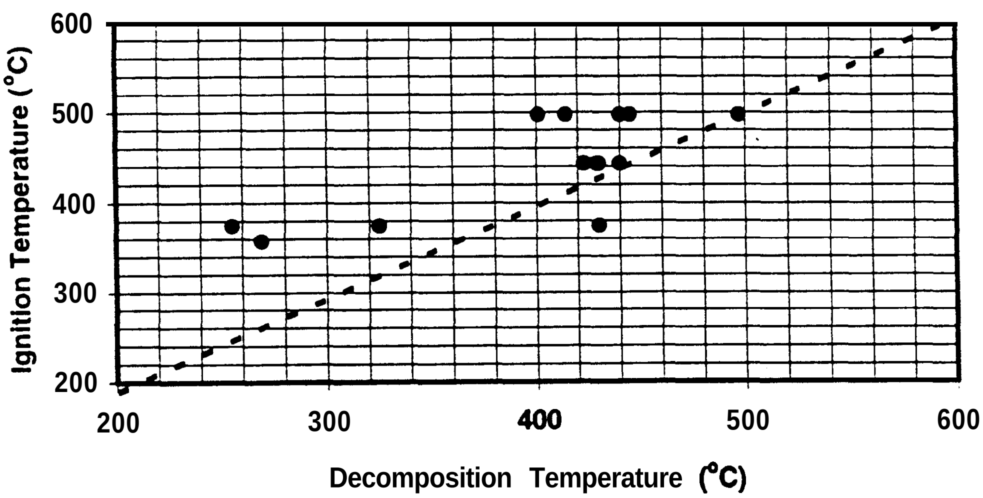

Figure 15. Decomposition temperature versus the ignition temperature for plastics parts of a 1996 Dodge Caravan. Data are taken from Table 6. Decomposition temperature is taken from Ref. 5. Ignition temperature is estimated from the CHF value.

Table 10

Thermal Properties and Calculated Thermal Response Parameter for Plastic Parts of a 1996 Dodge Caravan

VAC' #	Dodge Part' #	Plastic'	T_d [a] °C	ρ_v [a] $\times 10^{-3}$ kg/m^3	C_v [a] (kJ/kg-K)	k_v [b] (kW/m-K)	TRP (kW-s$^{1/2}$/m^2)	
							Calculated'	Experimental[d]
743	GJ42SK4A	PET	442	0.69	I.558	0.15	150	NM
743	GJ42SK4B	PEU	286	0.10	2.242	0.3 1	62	NM
743	GJ42SK4C	PESPU	344	0.06	2.162	0.31	58	NM
743	GJ42SK4D	Nylon 6	497	0.12	2.192	0.24	106	154
645	JF48SKA	PEU	346	0.11	1.768	0.31	71	NM
645	JF48SKB	PVC	269	1.20	I.374	0.21	130	263
654	JF48SKC	PC	413	1.12	1.679	0.20	214	NM
611	PL98SX8A	PC	440	1.18	1.510	0.20	222	357
611	PL98SX8B	PEU	344	0.09	1.556	0.31	60	NM
256	4612512A	PP	430	1.06	2.082	0.20	241	277
256	4612512B	EPDM	450	1.15	1.745	0.22	253	NM
256	4612512C	EPDM	452	1.16	1.394	0.22	281	NM
788	46747 11A	PEU	269	0.02	1.653	0.3 1	22	NM
788	46747 I1B	PVC	255	1.95	I.141	0.21	142	215
732	4678345A	PE	438	0.95	2.025	0.42	333	NM
732	4678345B	PP	430	1.04	1.934	0.20	230	333
673	4680250A	NR	428	1.26	I.391	0.28	253	NM
673	4680250B	fiber mixture	332	0.22	2.102	NM	NM	NM
673	4680250C	PES	416	1.15	1.785	0.17	207	NM
736	4683264A	PP	413	0.90	2.247	0.20	222	NM
736	46832648	PP	416	0.90	2.476	0.20	223	NM
3008	4707580A	PE	442	0.95	2.122	0.42	344	NM
1019	4707808A	NR	363	1.16	1.752	NM	NM	NM
1019	4707808B	NR	382	1.10	1.315	NM	NM	NM
1019	4707808C	ABS	365	1.07	I.733	0.33	239	NM
967	4716051	SMC	414	1.64	1.140	0.75	413	483
868	4716345A	PS	394	0.90	1.700	0.16	164	NM
	4716345B	PS	401	0.13	1.624	0.16	62	146
870	4716832A	PET, Cellu, Epoxy	322	0.09	1.664	0.15	40	NM
870	47168328	PET	325	0.66	1.319	0.15	98	174
208	47 16895	PP	429	0.93	2.200	0.20	232	288

VAC’ #	Dodge Part’ #	Plastic’	T_d [d] °C	ρ_v [a] $\times 10^{-3}$ kg/m’	C_v [a] (kJ/kg-K)	k_v [b] (kW/m-K)	TRP ($kW\text{-}s^{1/2}/m^2$) Calculated’	Experimental[d]
676	4734025	NR	308	0.11	1.334	NM	NM	NM
676	4734033	PVC	437	1.38	1.412	0.21	236	NM
676	4734039A	Nylon 66	418	I.46	1.813	0.24	281	NM
676	4734039B	TPO	433	0.93	1.961	0.36	297	NM
676	4734041A	Nylon 66	428	1.50	1.691	0.24	282	NM
676	473404 1 B	TPO	440	0.97	1.865	0.36	300	NM
676	4734042A	NR	428	1.50	1.910	NM	NM	NM
676	4734042B	NR	440	0.98	1.933	NM	NM	NM
676	4734063	PP	437	1.19	1.895	0.20	248	NM
676	4734067A	ABS-PVC	233	0.10	I.345	0.27	36	73
676	4734067B	EVA	462	2.10	1.025	NM	NM	NM
676	473407 I	PP	NM	NM	NM	0.20	NM	310
676	4734072	PP	NM	NM	NM	0.20	NM	NM
676	4734073	PP	NM	NM	NM	0.20	NM	NM
676	4734074	PP	373	1.21	1.760	0.20	204	NM
676	4734080	PP	NM	NM	NM	0.20	NM	NM
676	473408 1	PP	NM	1.21	NM	0.20	NM	NM
676	4734225	PP	428	1.11	I.947	0.20	238	
676	4734367	PP	447	1.20	NM	0.20	NM	NM
676	4734370	ABS-PVC	226	0.07	2.015	0.27	36	NM
676	4734396	NR	428	0.12	NM	NM	NM	NM
676	4734650	NR	NM	0.11	NM	NM	NM	NM
676	473465 1	NR	NM	0.17	NM	NM	NM	NM
676	4734724	TPO	430	0.97	1.872	0.36	238	NM
201	4883 140A	PE	440	0.94	2.147	0.42	343	454
201	4883140B	Nylon 12	416	1.04	1.787	0.25	239	NM
201	4883 140C	PE	430	0.95	NR	0.42	NM	NM
798	485704 1 A	PC	445	1.19	2.06 1	0.20	264	NM
798	485704 I B	PC	476	I.20	2.177	0.20	292	434
798	485704 1 C	POM	310	1.41	1.918	0.44	280	NM
798	4857041D	Polyimide	522	1.59	1.050	0.11	191	NM
798	485704 I E	PC	454	1.18	1.095	0.20	196	NM
222	4364944A	PE-PP	411	0.91	1.983	0.36	279	NM
222	4364944B	PE-PP	409	0.88	2,147	0.36	284	NM
230	5235267	PP	423	0.90	2.216	0.20	226	323
971	4675359A	EPDM	305	0.44	2.304	0.22	119	NM

VAC[a] #	Dodge Part' #	Plastic'	T_d [a] °C	ρ_v[a] x10^{-3} kg/m^3	C^a_v (kJ/kg-K)	k^b_v (kW/m-K)	TRP (kW-s$^{1/2}$/m^2) Calculated'	Experimental[d]
971	4675359B	EPDM	310	0.4 1	1.507	0.22	95	NM
959	4716896A	Mixed fibers	288	1.60	1.400	NM	NM	NM
959	4716896B	PVC-Glass	274	1.00	1.052	0.21	106	NM
959	4716896C	PVC-Hyd elasto	726	1.60	1.239	0.21	403	NM
3009	NR	EPDM	375	1.21	1.484	0.22	198	NM

a: from Ref. 5; b: thermal conductivity, values taken from Ref. 7 for similar generic plastics; c: calculated from the density (column 5), specific heat (column 6), thermal conductivity (column 7), and decomposition temperature (column 4); d: from the measurements for time-to-ignition; NM: not measured; NR: not reported.

The expression for the thermally thick condition suggests that TRP value will increase with increase in the thermal property values. Thermal conductivity appears to have a strong affect on the TRP value. Thermal conductivity values range from 1 x 10^{-4} to 6 x 10^{-4} kW/m-K and 10" kW/m-K for foamed plastics [6]. The inert additives increase the thermal conductivity values from a few percent to over ten times the values of unfilled plastics [6]. This is supported by the data for the composite systems in Fig. 16, taken from Ref. 15. The TRP values follow the trends in the thermal conductivity values in Table 11, taken from the Handbook of Chemistry and Physics (59^{th} Edition, 1978-79).

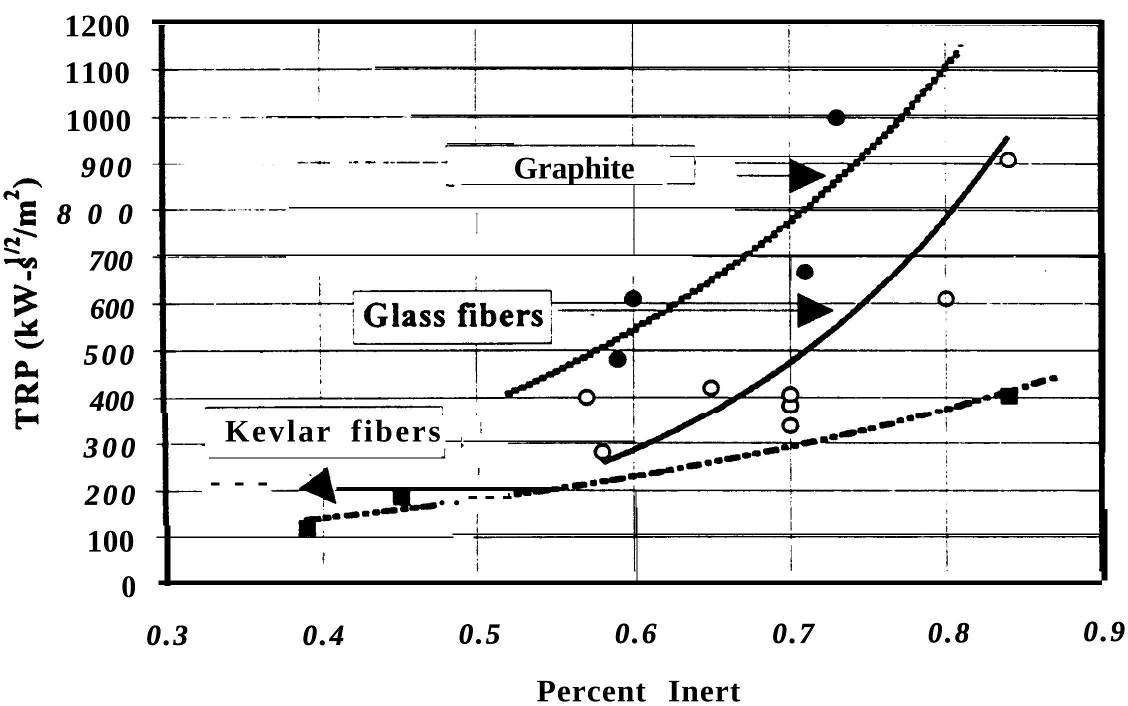

Figure 16. Thermal Response Parameter (TRP) for fiber reinforced polyester and epoxy under thermally-thick condition versus amounts of graphite, glass, and kevlar fibers as inert additives in the plastics. Data are taken from Ref. 15.

The above discussion points out TRP values for plastics can be increased by the ***incorporation of effective inert additive,*** such as the use of reinforcing fibers.

Table 11

Thermal Conductivity Values'

Inert	Thermal Conductivity (kW/m-K) x 10^3
Kevlar	0.20
Glass	1.05
Quartz	1.72
Graphite	5.02
Sapphire(aluminum oxide)	24
Silicon carbide	85

a: Handbook of Physics and Chemistry (59th Edition, 1978-79)

4.2 Fire Propagation

The fire propagation propensity of materials has been correlated with a Fire Propagation Index (FPI) (see Appendix), expressed by the following semi-empirical approach relationship [3,4]:

$$FPI = 1000(0.42\dot{Q}'_{ch})^{1/3} / TRP \ (m/s^{1/2})/(kW/m)^{2/3} \qquad (15)$$

Comparisons with large-scale fire tests indicate that the fire propagation propensity increases with increase in the FPI value. Note that increase in the TRP value indicates increased resistance to ignition, while decrease in the chemical heat release rate is expected to decrease the flame heat flux, which supports the fire propagation. This gives an explanation for the correlation between the FPI values and the large-scale test fire propagation behavior. The constants in the FPI has been selected to express the Index as convenient numbers in the chosen units.

The estimated FPI values' for the plastic parts of 1996 Dodge Caravan are listed in Table 12 and are shown in Fig. 17. The estimated FPI[9] values for the fifteen plastic parts suggest that the following three parts, with FPI values less than 10, are expected to have decelerating fire propagation, whereas the other 12 plastic parts are expected to have steady or accelerating fire propagation beyond the ignition zone:

1) Polyethylene fuel tank (VAC #201, Part # 4883 140A,
2) Polycarbonate headlight lens (VAC # 798, Part # 4857041A), and
3) SMC windshield wiper structure (VAC #967, Part # 47 1605 1).

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[8] estimated from the relationship between the FPI and HRP values (Appendix)
[9] from FPI values in Table 12 along with visual observations for fire propagation (Table A- 1 in the appendix)

Table 12
Estimated Fire Propagation Index Values for the Plastics in Parts of the 1996 Dodge Caravan Examined in this Study

VAC #	Dodge Part #	Description	Plastics	FPI[b]
201	4883 140A	Fuel tank	PE	8
208	47 16895	Wheel well cover, fuel tank shield	PP	13
230	5235267	Battery cover	PP	12
256	4612512A	Resonator structure	PP	14
	4612512B	Resonator intake tube	EPDM	ND
611	PL98SX8A	Instrument panel shelf, main panel	PC	11
654	JF48SK5B	Instrument panel cover, exposed surface	PVC	15
673	4680250A (468015 1)	Steering column boot, inner interior boot	NR	ND
	4680250C (4680152)	Steering column boot, outer interior boot	Polyester	ND
676	473407 1	HVAC unit, top main housing, outer top	PP	12
	4734370	HVAC unit. seals-both large and small	ABS -PVC	57
732	4678345B	Air ducts, large ducts	PP	11
743	GJ42SK4D	Headliner, fabric-exposed surface	Nylon 6	26
788	46747 11 B	Kick panel insulation backing (silencer?)	PVC	18
798	485704 1A	Headlight lens	PC	9
868	47 16345B	Fender sound reduction foam	PS	27
870	4716832B	Hood liner face	PET	23
967	4716051	Windshield wiper structure	SMC	8

a: TRP values taken from Table 6; **b:** estimated values using the TRP values from column 5 and correlation from Fig. 16. **ND** : not determined as samples were very small.

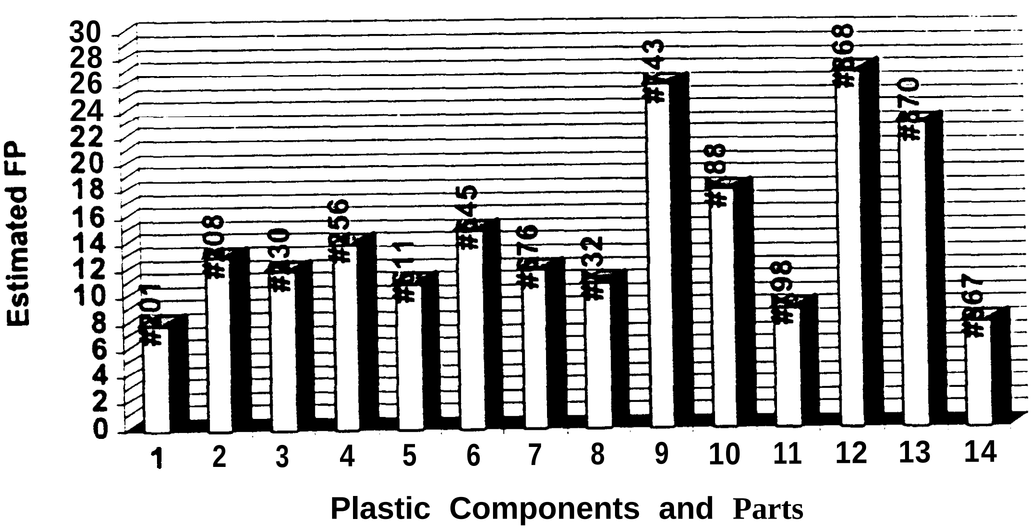

Figure 17. FPI values for plastic parts of the 1996 Dodge Caravan estimated from the TRP values in Table 6 and correlation in Fig. 16. The estimated FPI values will be validated by fire propagation tests in the Flammability Apparatus.

4.3 Release of Heat and Products

Heat and products are released in small amounts from non-propagating or decelerating fires, resulting in a limited contamination of the environment. The degree of contamination depends on the values of FPI, heat of combustion and yields of products for the plastics. Figures. 18 to 21 show plots of FPI values versus the heat of combustion, and yields of CO, CO_2, and smoke respectively for plastic components and parts of the 1996 Dodge Caravan. In the figures, FPI values are estimated values taken from Table 12 and heat of combustion and yields of products are taken from Table 9. The lines in the figures indicate the average values.

There is no correlation between the FPI values and the values for the heat of combustion and yields of CO, CO_2, and smoke. Thus the most important property that needs to be reduced is the FPI value. Reduction in the heat of combustion and yields of products would also be beneficial.

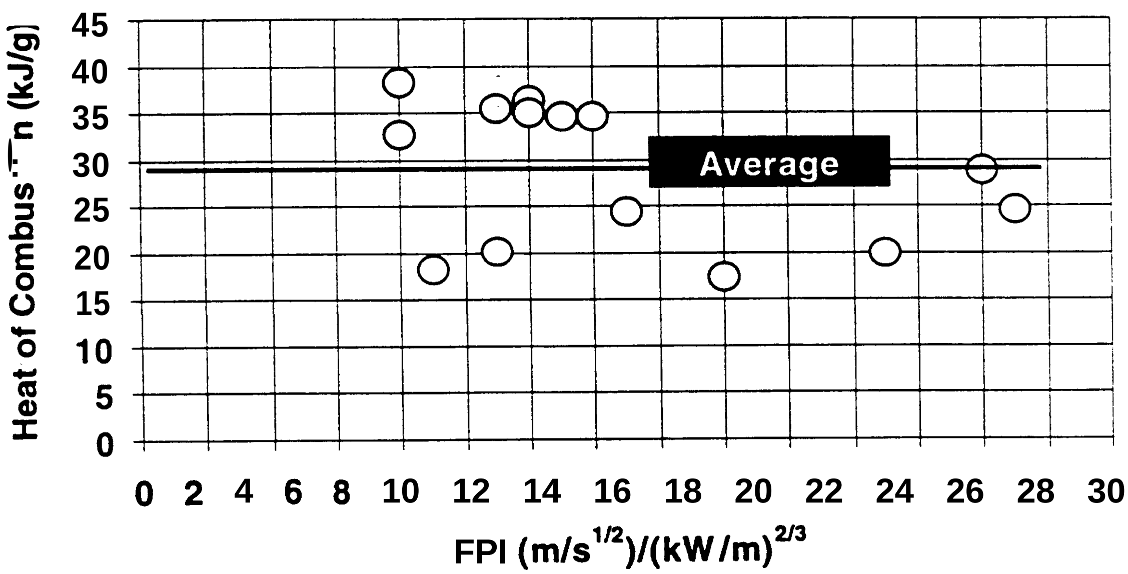

Figure 18. Chemical heat of combustion versus the estimated FPI values for plastic parts of the 1996 Dodge Caravan. Heat of combustion values are taken from Table 9 and the estimated FPI values are taken from Table 12.

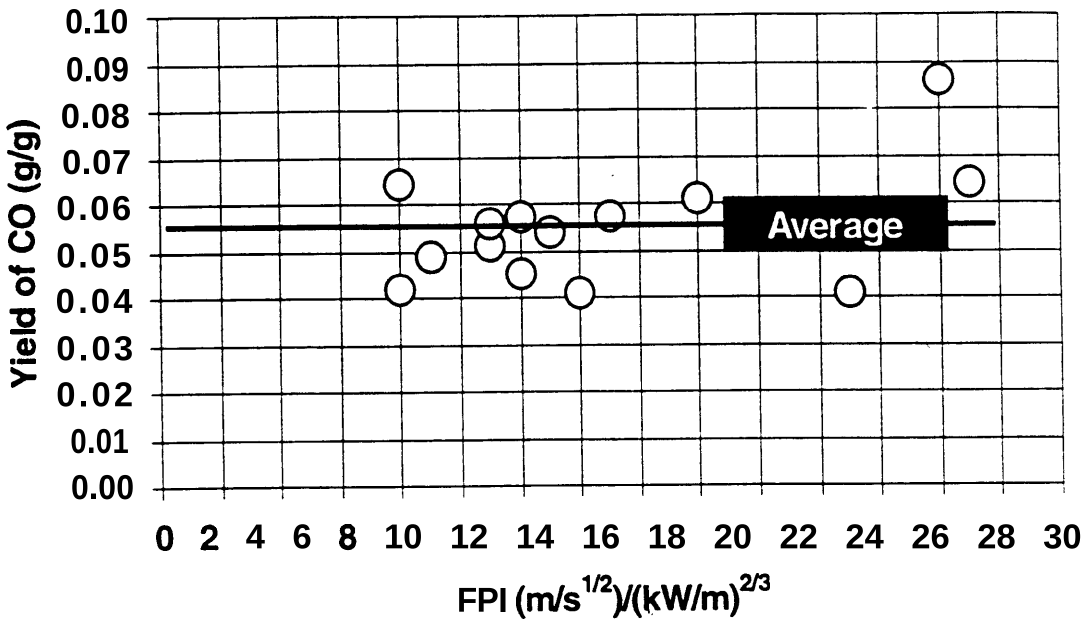

Figure 19. Yield of CO versus the estimated FPI value for plastic parts for the 1996 Dodge Caravan. The values for the yield of CO are taken from Table 9 and the estimated FPI values are taken from Table 12.

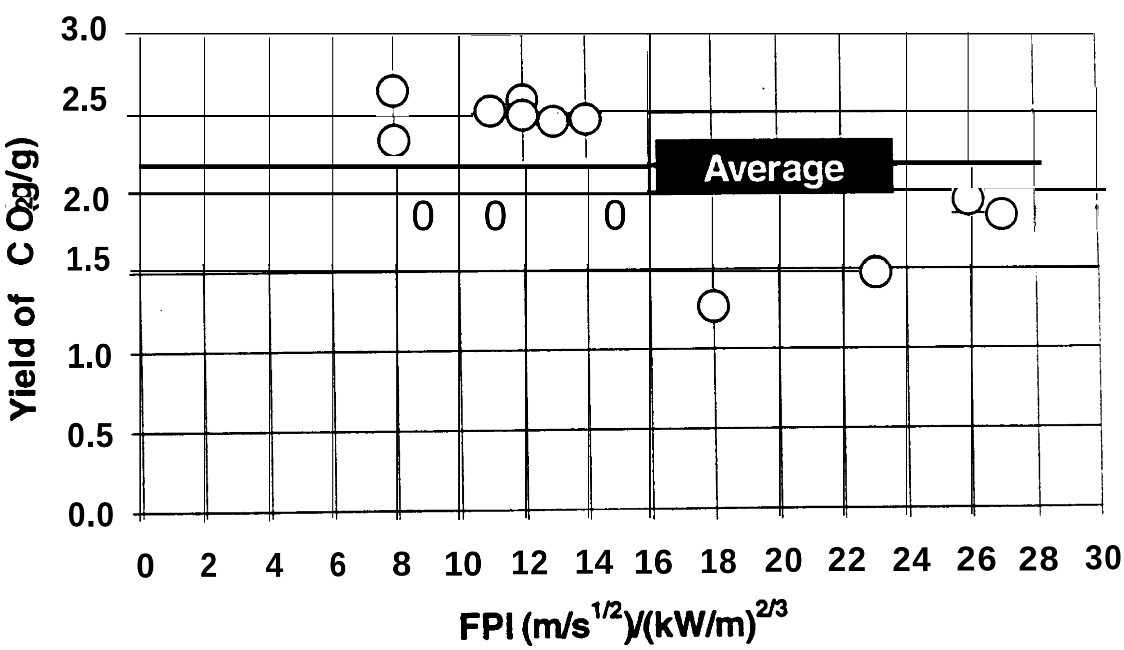

Figure 20. Yield of' CO_2 versus the estimated FPI value for plastic parts for the 1996 Dodge Caravan. The values for the yield of CO_2 are taken from Table 9 and the estimated FPI values are taken from Table 12.

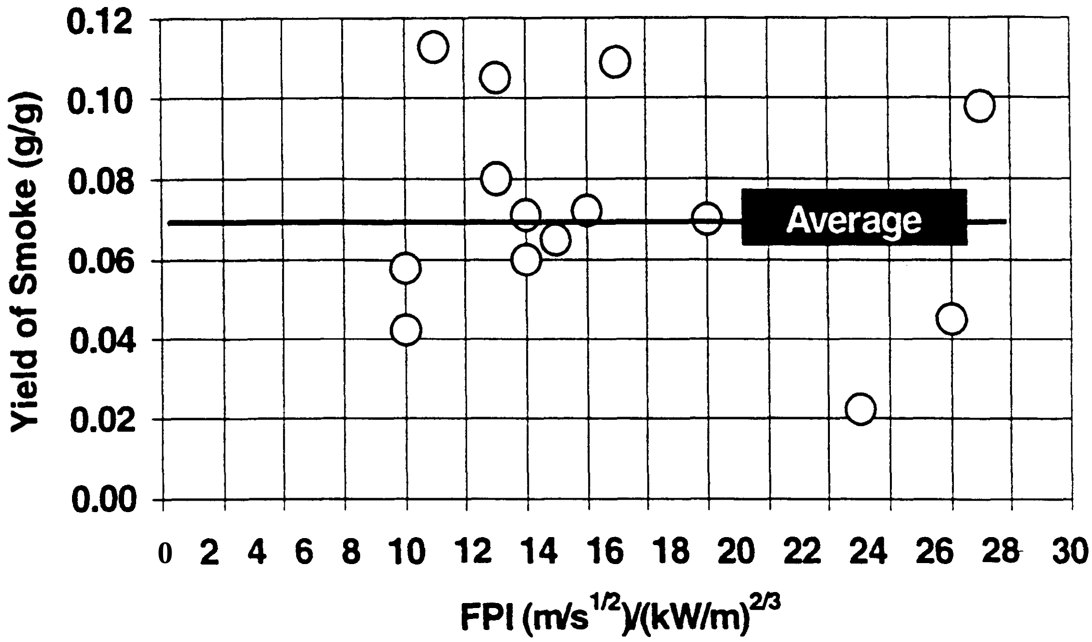

Figure 21. Yield of smoke versus the estimated FPI value for plastic parts for the 1996 Dodge Caravan. The values for the yield of smoke are taken from Table 9 and the estimated FPI values are taken from Table 12.

V
SUMMARY

The objective of the study is to evaluate the flammability of plastic parts of vehicles. In the study, 20 plastic parts were examined. For the flammability evaluation, the following flammability characteristics of the plastics were quantified:

a) ***Critical Heat Flux (CHF):*** defined, as the externally imposed heat flux at or below which sustained piloted ignition does not occur. Resistance to ignition is higher for plastics with higher CHF values. The CHF values of the plastics components and parts of the 1996 Dodge Caravan, examined so far are comparable to the values for ordinary plastics. The ignition temperatures estimated from the CHF values are about 15% higher than the decomposition temperature of the plastics measured by Abu-Isa et *al* [5].

b) ***Thermal Response Parameter (TRP):*** this parameter is an indicator of the ignition time delay. Resistance to ignition is higher for plastics with higher TRP values The TRP values of the plastics in components and parts of the 1996 Dodge Caravan were obtained from the ignition data assuming a thermally thick condition.

The experimental TRP values were about 28% higher than the calculated values from the thermal properties of the plastic components and parts measured by Abu-Isa et *al* [5]. The calculated values are conservative because decomposition temperatures instead of ignition temperatures were used in the calculations. TRP values have been calculated for 72 plastic components and parts of the 1996 Dodge Caravan.

c) Fire Propagation Index (FPI): this parameter is an indicator of the fire propagation behavior of plastics beyond the ignition zone. Resistance to fire propagation is higher for plastics with lower FPI values. FPI values for 15 plastic components and parts of the 1996 Dodge Caravan have been estimated. The estimated FPI values have been compared with the large-scale fire data for the FPI values versus the extent of fire propagation.

The estimated FPI values suggest that out of 15 plastic parts of the 1996 Dodge Caravan, three parts are expected to have decelerating fire propagation beyond the ignition zone, whereas the 12 other plastic parts are expected to have steady or accelerating fire propagation beyond the ignition zone.

d) ***Environmental Contamination:*** The most important parameter that needs to be reduced is the FPI value. Reduction in the heat of combustion, and yields of CO, CO_2, and smoke would also be beneficial.

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ABBREVIATIONS FOR PLASTICS

ABS	acrylonitrile-butadiene-styrene
EPDM	ethylene propylene diene monomer
EVA	ethylene vinyl acetate
NR	natural rubber
PA	polyamide
PBT	polybutylene terephthalate
PC	polycarbonate
PE	polyethylene
PES	polyester
PEU	polyether urethane
PESU	polyester urethane
PEST	polyester
PET	polyethylene terephthalate
POM	polyoxymethylene
PP	polypropylene
PPO	polyphenylene oxide
PS	polystyrene
PU	polyurethane
PVC	polyvinylchloride
TPO	thermoplastic polyolefin

NOMENCLATURE

A	total exposed surface area of the material (m^2)
CHF	Critical Heat Flux (kW/m^2)
c_p	heat capacity (kJ/g-K)
E	Chemical energy (enthalpy) (kJ)
FPI	Fire Propagation Index (1000 x $(0.42\dot{Q}'_{ch})^{1/3}$ / *TRP* } $(m/s^{1/2})/(kW/m)^{2/3}$
ΔH_{ch}	chemical heat of combustion per unit mass of material gasified (kJ/g)
ΔH_g	heat of gasification of the material (kJ/g)
k	thermal conductivity (kW/m-K)
$\dot{q}''_e$	external heat flux (kW/m^2)
$\dot{q}''_{cr}$	Critical Heat Flux [CHF] (kW/m^2)
$\dot{Q}''_{ch}$	chemical heat release rate per unit sample surface area (kW/m^2)
$\dot{Q}'_{ch}$	chemical heat release rate per unit sample width (kW/m)
t_{ig}	time-to-ignition (s)
ΔT_{ig}	ignition temperature above ambient (K)
TRP	Thermal Response Parameter for thermally thick condition, $[\Delta T_{ig} (\pi k \rho c_p \pi/4)^{1/2}]$ $(kW\text{-}s^{1/2}/m^2)$
y_j	yield of product j (W_j/W_f) (g/g)
a	thermal diffusivity $(k/\rho c_p)$ (m^2/s)
ρ	density (g/m^3)
δ	actual thickness (m)
λ	wave length of light source (μm)
σ	Stefan-Boltzmann constant (56.7 x 10^{-12} $kW/m^2\text{-}K^4$)
Ω	coefficient of particulate extinction equal to 7.0

Subscript

ch	chemical
cr	critical
e	external
f	flame
g	gasification
ig	ignition
rr	surface re-radiation
v	original

Superscripts

.	per unit time (s^{-1})
'	per unit width (m“)
"	per unit area (m^{-2})

APPENDIX

FIRE PROPAGATION INDEX (FPI)

A.1 Fire Propagation

The propensity of a material to support fire propagation has been correlated with a Fire Propagation Index (FPI). The FPI values have been quantified for variety of plastics and their products in small- and large-scale fires.

A.l.l Electrical Cables

Figure A-l shows examples of large-scale fire propagation data for electrical cables. In the figure, extent of fire propagation is represented by the measured char length fraction. The FPI values in the figure were calculated from Eq. 15 using heat release rates measured in the large-scale fire propagation tests and TRP values were obtained from the ignition tests performed separately in small-small tests. The data show that the extent of fire propagation increases with increase in the FPI value.

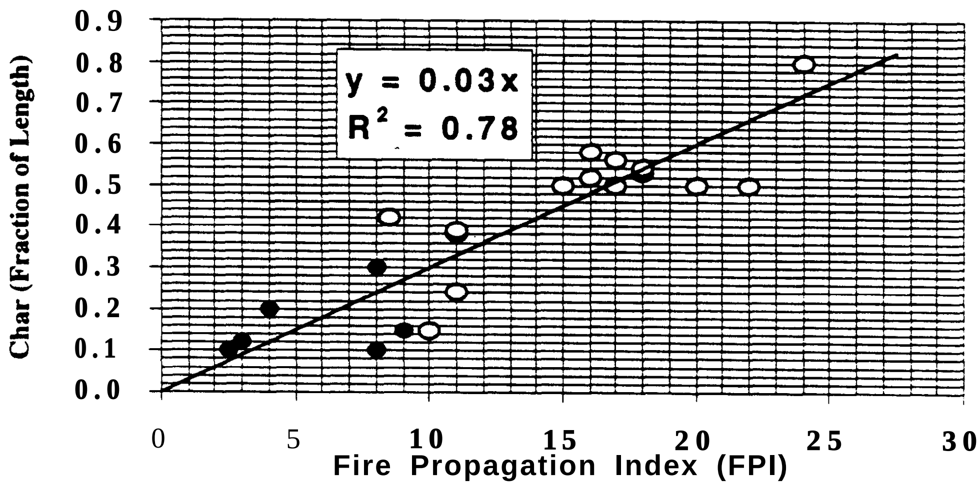

Figure A-l. Extent of fire propagation as indicated by char versus the Fire Propagation Index in large-scale fire propagation tests for electrical cables. Open symbols: vertical samples (2.4-m long and 0.15-m wide trays filled with cables). Ignition zone: 10% of the length. Dark symbols: horizontal samples (7.3-m long and 0.3-m wide trays filled with cables). Ignition zone: 20% of the length. Data are taken from Ref. 19.

The correlation shown in Fig. A-l is reasonable, considering the variability in the large-scale fire propagation tests for electrical cables. The correlation shows that fire propagation is limited to the ignition zone for FPI = 6 (ignition zone is represented by the char length fraction of 0.2). There are some variations in the extent of fire propagation for FPI values between 6 and 10; two test data (FPI = 8 and 9) show that fire propagation is limited to the ignition zone, whereas one test data (FPI = 8) show that it is not. The data in the figure indicate that the extent of fire propagation as fraction of the length of the sample ≅ 0.03 FPI.

A.1.2 **Small and Large Scale Fire Propagation Tests**

Small and large-scale fire propagation tests with electrical cables [20,21] and slabs of plastics [18, 22, 23] have been performed in the Flammability Apparatus and under the Fire Products Collector. The FPI values calculated from the data measured in the Flammability Apparatus and the Fire Products are shown in Fig. A-2. The correlation between the FPI values from the small and large-scale tests in the figure is acceptable, although more data for FPI values between 10 and 30 is desirable.

The relationship between the FPI values and extent and rate of fire propagation has also been examined in several large-scale fire propagation tests; results are summarized Table A- 1.

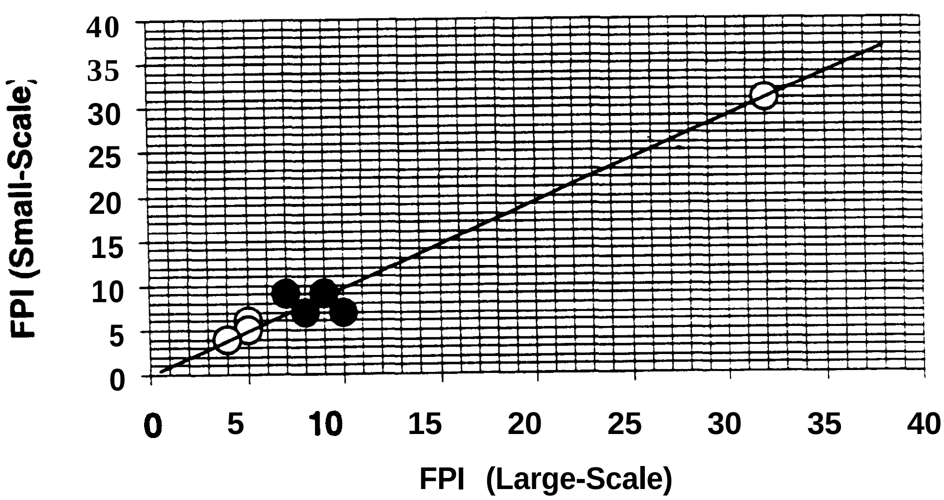

Figure A-2. Fire Propagation Index Values calculated from Eq. 16 from the small- and large-scale fire propagation and ignition test data measured in the Flammability Apparatus and the Fire Products Collector. Data are taken from Refs. 21 and 22. In the small fire propagation tests, 300 to 600-mm long and 25-mm wide vertical sheets were used. In the large-scale fires, 2.4 to 4.8-m long and 600-mm wide vertical slabs facing each other were used.

simple approximation for the heat release rate [3,4]:

$$\dot{Q}''_{ch} \approx (\Delta H_{ch} / \Delta H_g)(\dot{q}''_e - \dot{q}''_{rr}) \qquad \text{(A-1)}$$

In Eq. A-l, ΔH_{ch} is the chemical heat of combustion of the plastic (kJ/g) and AH, is the heat of gasification of the plastic (kJ/g). The ratio $\Delta H_{ch}/\Delta H_g$ is identified ***as*** the ***Heat Release Parameter (HRP)***. Using the relationship for the heat release rate from Eq. A-l in Eq. 15:

$$FPI \approx \frac{1000\, x\, [0.42\, (\Delta H_{ch} / \Delta H_g)\, \dot{q}''_n]^{1/3}}{TRP} \qquad \text{(A-2)}$$

where $\dot{q}''_n$ is the net heat flux per unit width of the sample (kW/m^2). Although $\dot{q}''_n$ can vary from a low of 22 to a high of 80 kW/m^2 [3,4][A-1]. The variations in the $\dot{q}''_n$ values depend on the chemical structure of the plastic and additives, in addition to fire size and configuration of the burning materials. As an approximation, assuming $\dot{q}''_n \approx 50$ kW/m^2 for a 0. l-m wide plastic sample:

$$FPI \approx \frac{1000\, x\, HRP^{1/3}}{TRP} \qquad \text{(A-3)}$$

Correlation between the FPI value and the ratio of HRP to TRP is shown in Fig. A-3. Although more data are needed, for this report we have used the correlation in the figure to ***estimate the FPI values*** for the plastic components and parts for the 1996 Dodge Caravan.

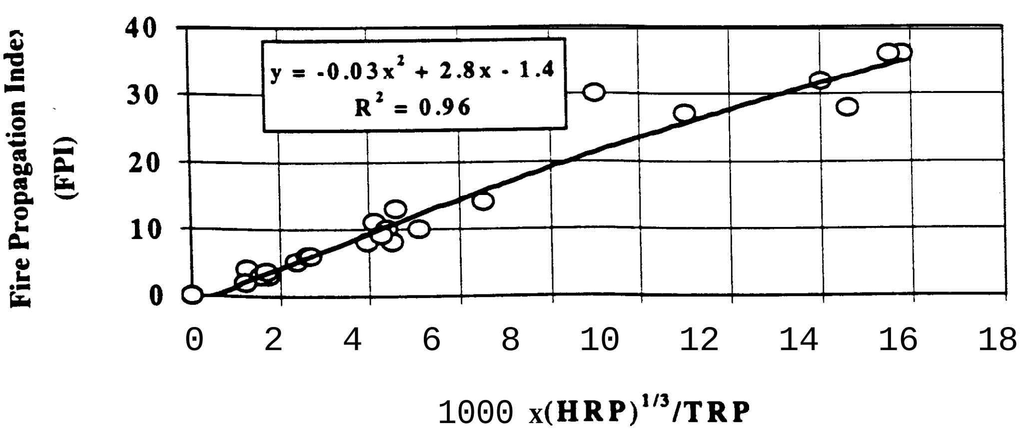

Figure A-3. Relationship between the Fire Propagation Index (FPI) and the ratio of Heat Release Parameter (HRP) to Thermal Response Parameter (TRP). Data are taken from our other studies [3,4,18].

[A-1] under conditions where plastic parts is engulfed by flames, the heat flux can be as high as 120 to 140 kW/m^2 [23].

Table A-l
Fire Propagation Index (FPI) and Flame Propagation Behavior of Plastics in Large Scale Fires'

Large Scale Test	Plastic	FPI	Flame Propagation[b] (distance in m)
Plastic slabs 2.4-m-long x 600-mm wide parallel wall arrangement	Polyvinylchloride (PVC) - 1	5	none
	Poiyvinylidine fluoride (PVDF)	5	none
	PVC-2	4	none
	Polymethylmethacrylate	32	propagating
	Polypropylene (PP)	34	propagating
	Fire retarded PP	32	propagating
Electrical Cables (vertical) in 4.8-m x 600-mm wide trays Marinite parallel sheets covered with cables	Polyethylene (PE)-neoprene	7	decelerating (1.5)
	PVC-PVDF	8	decelerating (0.91)
	Polyolefin (PO)-PO	9	decelerating (3 .O)
	PE-ethylvinyl acetate	10	decelerating (3.0)
	PE-PVC	33	propagating
Electrical cables in 7.3-m long x 0.3-m wide horizontal trays	several types of plastic insulation and jacket	<6	none
		6-8	decelerating
		10	propagating
Conveyor belts horizontal 9. l-m long x 1.5-m wide inside a 27. l-m long x 0.09-m^2 tunnel	several types of plastics	5	none
		7	decelerating
		8	propagating
Ducts: 0.3-m diameter, 4.5-m long vertical section and 7.3- m horizontal section	several types of plastics	6	none
		6-8	decelerating
		>12	propagation

a: from Ref. 2 1; **b:** propagation beyond the ignition zone; decelerating propagation: fire propagates beyond the ignition zone in a decaying fashion.

A.1.3 Estimated Fire Propagation Index Values for Plastic Components and Parts of the 1996 Dodge Caravan

The FPI values for the plastic component and parts have not yet been determined experimentally in the fire propagation tests. We have, however, estimated the FPI values using a