FLAMMABILITY OF AUTOMOTIVE PLASTICS

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ABSTRACT

This report compares the flammability of plastic automotive components to that of commodity, engineering, and specialty plastics as well as those used in commercial aircraft cabins with regard to performance in microscale combustion calorimetry tests. Not surprisingly, automotive components used in engine and passenger compartments are as flammable and ignitable as the commodity and engineering plastics of which they are made and much more flammable than those used in the interiors of aircraft.

INTRODUCTION

Automobile fires account for 95% of the 400,000 motor vehicle fires that occur every year in the U.S. and 92% of the 330 fire fatalities. Two thirds of automobile fires originate in and around the engine compartment, with the passenger compartment (17%) and trunk (3%) accounting for most of the remainder. Combustible plastics in the form of electrical wiring, upholstery, and miscellaneous components are the single largest category of materials first ignited in automobile fires (47%) with fuel accounting for 27% of ignitions [1,2]

An average automobile uses approximately 100 kg (200 lbs) of plastic components, which is a fuel load roughly equivalent to a full tank of gasoline (3×10^9 J). Due to the fire hazard plastics create in motor vehicles and the speed with which plastics spread flame, smoke, and combustion products into the passenger compartment, it is preferable to attempt to reduce the risk of fire occurring rather than to rely on potential rescue efforts once a fire is started. This was the aim of Federal Motor Vehicle Safety Standard No. 301 (FMVSS 301), Fuel System Integrity and FMVSS 302, Flammability of Interior Materials issued by the National Highway Traffic Safety Administration (NHTSA). Despite the implementation of these standards in 1968 and 1972, respectively, fires continue to be a serious safety threat [1,2]. Moreover, as automakers continue to replace metal with combustible plastic for lighter and more fuel efficient cars, the nature, incidence, and severity of collision and non-crash auto fires is likely to worsen. The objective of this paper is to benchmark the flammability of automotive plastics against commercial plastics and the type of plastics used in commercial aircraft cabins with regard to performance in microscale combustion calorimetry tests.

FIRE BEHAVIOR OF PLASTICS

The heat release rate (HRR) of a material in flaming combustion is the primary indicator of its hazard in a fire [3]. The HRR is usually expressed in terms of a surface energy balance for steady flaming combustion [4]

$$HRR = \chi \frac{h_{c,v}^0}{L_g} q''_{net} \tag{1}$$

where χ is the completeness of combustion of the fuel gases in the flame, $h_{c,v}^0$ is the heat of complete combustion and $L_g = c(T_s - T_0) + h_v$ is the heat of gasification of the solid in terms of the surface burning temperature T_s, the ambient temperature T_0, , the specific heat of the solid c, and

the heat of vaporization of the thermal decomposition products h_v. A heat release parameter is defined [4]

$$\mathrm{HRP} = \chi \frac{h^0_{c,v}}{L_g} \tag{2}$$

that characterizes the fire response of the polymer to a net heat flux at the surface

$$q''_{net} = q''_{ext} + q''_{flame} - q''_{loss} \tag{3}$$

Equation 3 defines the net heat flux as the difference between the heat entering the surface from an external fire or heater q''_{ext} and/or attached surface flame q''_{flame} and the heat losses from the surface by radiant energy transfer and thermal conduction. If only radiant energy losses at the surface are considered at incipient ignition when $q''_{net} = q''_{flame} = 0$, a critical external heat flux CHF can be defined [4,5]

$$\mathrm{CHF} = q''_{ext}(\mathrm{ign}) = q''_{loss} \approx \varepsilon\sigma T_s^4 \tag{4}$$

In Equation 4, T_s is the surface temperature at ignition/burning, ε is the surface emissivity, and σ is the Boltzmann constant.

Combining Equations 1 and 2 allows HRR to be separated into unforced (HRR_0) and forced ($\mathrm{HRP}\, q''_{ext}$) components of flaming combustion

$$\begin{aligned} \mathrm{HRR} &= \mathrm{HRP}(q''_{flame} - q''_{loss}) + \mathrm{HRP}\, q''_{ext} \\ &= \mathrm{HRR}_0 + \mathrm{HRP}\, q''_{ext} \end{aligned} \tag{5}$$

A physically-based criterion for extinction of diffusion flames correlates a wide range of data and is based on a minimum (critical) heat release rate HRR* $\approx$ 50 kW/m^2 derived from the limit flame temperature [6,7]. The critical HRR criterion states that plastics will burn only if

$$\mathrm{HRR}_0 + \mathrm{HRP}\, q''_{ext} > \mathrm{HRR}^* \tag{6}$$

In tests of flame resistance samples are briefly exposed to the flame of a Bunsen (or similar) burner to force ignition. After the sample is removed from the burner flame, $q''_{ext} = 0$, and the sample will continue to burn only if [8,9]

$$\mathrm{HRR}_0 = \mathrm{HRP}(q''_{flame} - q''_{loss}) \geq \mathrm{HRR}^* \tag{7}$$

If vaporization of polymer thermal decomposition products at the burning surface and subsequent combustion of these gaseous products in the flame are rapid compared to the conversion rate of solid polymer to volatile fuel at the surface, thermal decomposition (fuel generation) will be the rate-limiting step in flaming combustion. Under these conditions the heat release rate in flaming combustion can be expressed

$$HRR = \frac{\chi \, \eta_c}{h_g / \Delta T_p} q''_{net} \tag{8}$$

where $h_g = (1-\mu)L_g$ is the heat of gasification per unit mass of plastic, μ is the char yield, ΔT_p is the temperature interval over which pyrolysis takes place as the material is heated and

$$\eta_c = \frac{Q}{\beta_s} \tag{9}$$

is the heat release capacity [10]. The heat release capacity is the ratio of the specific heat release rate Q (W/g) to the surface heating rate β_s (K/s). The heat release capacity is a molecular level flammability parameter that is a good predictor of fire performance and flame resistance and is easily measured in the laboratory using thermal analysis methods [11]. Figure 1 shows calculations for the heating rate experienced by a typical plastic involved in a small-to-medium sized fire. Surface heating rates on the order of $\beta_s \approx 0.1$-1 K/s are observed for small fires.

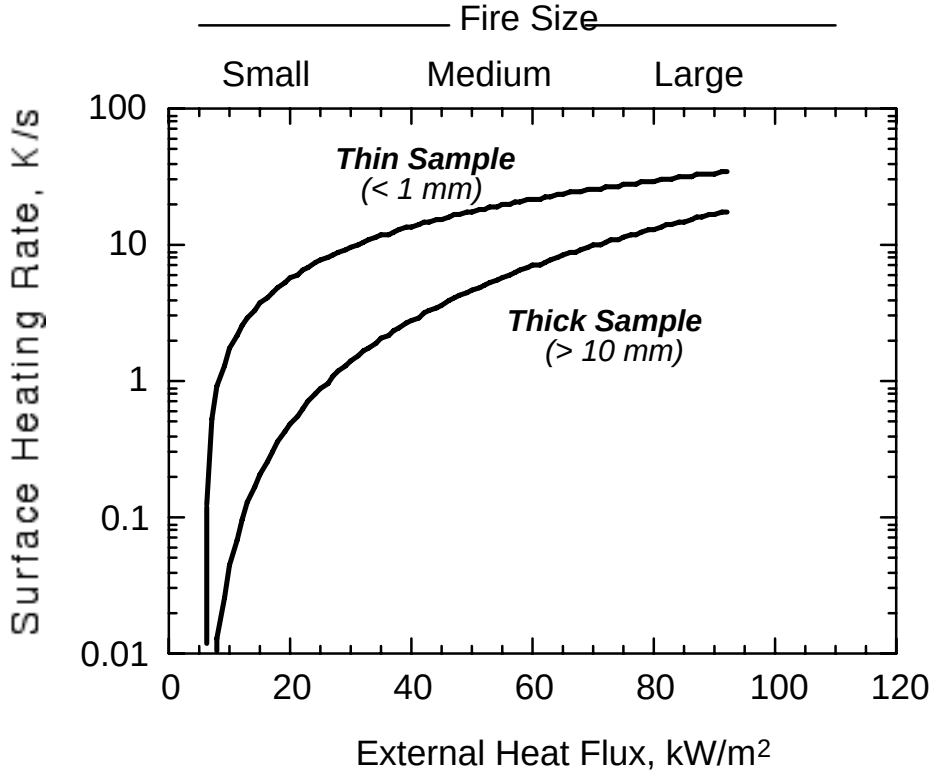

FIGURE 1. SURFACE HEATING RATES OF THIN AND THICK PLASTIC SAMPLE FOR VARIOUS FIRE SIZES.

According to Equation 8 the proportionality factor between HRR and η_c at an external heat flux $q''_{ext} = 50$ kW/m^2 should be of the order

$$\frac{HRR}{\eta_c} = \frac{(0.85)(40 kW/m^2)}{(2.5 kJ/g)/(50K)} \approx 700 \pm 300 \frac{K/s}{m^2/g} \quad (10)$$

Equation 10 assumes a net heat flux as per Equation 3 with $q''_{flame} - q''_{loss} = 10 \pm 5$ kW/m^2 along with typical [5,12] parameter values and uncertainties: χ = 0.85 ±0.10; h_g = 2.5 ±1.0 kJ/g; ΔT_p = 50 ±10K.

According to Equations 7 and 8 there is a heat release capacity η_c^* corresponding to HRR* below which a plastic sample will not continue to burn after a brief exposure to a small flame. For HRR* = 50 ±10 kW/m^2 and typical parameters and uncertainties the critical heat release capacity should be of the order

$$\eta_c^* = \frac{HRR^* h_g}{\chi (q''_{flame} - q''_{loss}) \Delta T_p} = 300 \pm 200 \text{ J/g-K} \quad (11)$$

EXPERIMENTAL

MATERIALS

Samples of automotive components were obtained from late model production vehicles and tested as received. Table 1 lists the samples tested in this study. Several laboratories received sets of the same samples for performing different types of analyses. Southwest Research Institute (SWRI) received a set of samples for performing larger scale flammability evaluations [12]. This work was funded by NHTSA and MVFRI gave a supplementary contract to collect toxic gas measurements from the cone tests. Underwriters Laboratories (UL) received a subset of 75 samples for arc ignition tests. Of the 75 samples that UL received 18 of them were examined in this study. Three of the 18 samples were multi-component samples and had to be separated for analysis using microscale combustion calorimetry. Methane, oxygen, and nitrogen gases used for calibration and testing were dry, ultra high purity (> 99.98%) grades obtained from Matheson Gas Products.

TABLE 1. PART NUMBERS AND DESCRIPTIONS FOR THE 18 SAMPLES EXAMINED IN THIS REPORT. THREE SAMPLES WERE 2 COMPONENTS.

UL Ref. Number	Sample Number	Part Description	Sample Description
45	52458965	Heater Module Blower Motor Housing	Hard Black Plastic
46	4716832B	96 Dodge Caravan Hood Liner Face	Non-Woven Non-Homogeneous Fibrous Mat
47	5235267AB	96 Dodge Caravan Battery Cover - Transparent	Transparent Flexible Plastic Inner layer
47	5235267AB	96 Dodge Caravan Battery Cover - Black	Flexible Black Plastic

48	4683264	96 Dodge Caravan Brake Reservoir	Semi Transparent White Rigid Plastic
49	4860446	96 Dodge Caravan Kick Panel Insulation - Black	Semi Flexible Hard Black Rubber
49	4860446	96 Dodge Caravan Kick Panel Insulation - Grey	Soft Grey Foam
50	4716345B	96 Dodge Caravan Fender Sound Reduction Foam	Black Foam
51	4716051	96 Dodge Caravan Wiper Structure	Hard Black Plastic
52	4861057	96 Dodge Caravan Resonator Top	Hard Black Plastic
53	4857041AB	96 Dodge Caravan Headlight Assembly - Black	Hard Black Plastic
53	4857041AB	96 Dodge Caravan Headlight Assembly - Clear	Hard Clear Plastic
54	4678345	96 Dodge Caravan Air Duct	Hard Black Plastic
55	53030508	Dodge Resonator Intake Tube	Flexible Black Plastic
56	10310333	97 Camaro Windshield Laminate	Inner Layer From Glass Composite
57	10278015	97 Camaro Hood Insulator	Non-Woven Fiber Mat with a Metallic Film Cover
58	10296526	Camaro Front Wheel Well Liner	Hard Black Plastic
59	52465337	Camaro Radiator In/Out Tank	Hard Black Plastic
60	22098787	Camaro Engine Cooling Fan	Hard Black Plastic
61	10297291	97 Camaro Air Inlet	Hard Black Plastic
62	26019594	Chevy Power Steering Reservoir	Hard Black Plastic

METHODS

Specific heat release rate Q was measured at a constant heating rate β = 1 K/s in a pyrolysis combustion flow calorimeter (PCFC) shown schematically in Figure 2. In this study, 1-5 milligram samples of plastic were heated to 900 °C in a stream of nitrogen flowing at 80 cm^3/min. The pyrolyzate/N_2 stream is mixed with 20 cm^3/min O_2 and reacts for 10 seconds in the 900 °C combustor. The combustion gas stream exits through a tube containing anhydrous calcium sulfate (Drierite) to remove moisture prior to passing through a mass flow meter and oxygen analyzer.

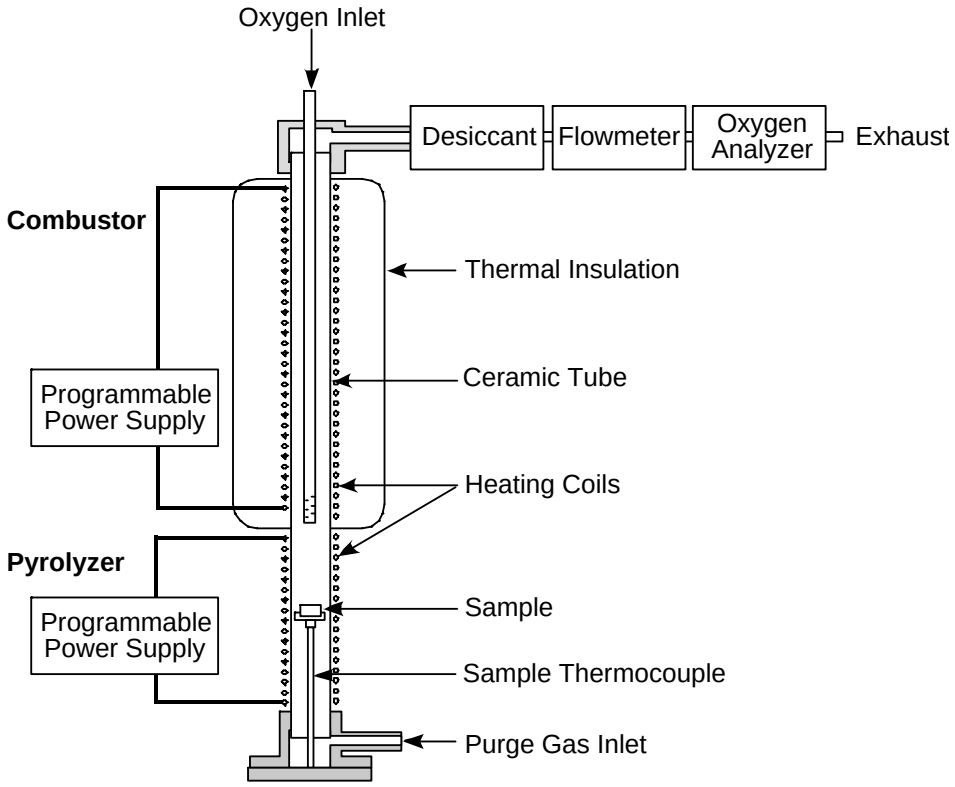

FIGURE 2. SCHEMATIC DRAWING OF PCFC SHOWING PYROLYZER, COMBUSTOR, GAS CONDITIONING, AND MEASURING COMPONENTS.

The specific heat release rate Q(t) at time t is calculated using the oxygen consumption principle from the initial sample mass m_0, the instantaneous change in the mass fraction of oxygen in the dried combustion gas stream [ΔO_2], and the scrubbed gas stream density ρ (kg/m^3) and flow rate F (m^3/s),

$$Q(t) = \frac{\rho C F}{m_0} [\Delta O_2](t) \tag{12}$$

In Equation 12, C = 13.1 ± 0.6 MJ/kg-O_2 is an empirical constant that relates the amount of heat released by complete combustion of the pyrolysis gases to the mass of oxygen consumed in the process at standard temperature and pressure [13]. The constant C is essentially (±5%) independent of the chemical composition of the combustible material [14]. The heat of combustion of the fuel gases per unit mass of initial sample HR (J/g) is obtained by time-integration of Q(t) over the entire test. The char fraction μ, is obtained by weighing the sample before and after the test. The heat release capacity η_c (J/g-K) is obtained by dividing the maximum value of the specific heat release rate by the heating rate in the test

$$\eta_c = \frac{Q(max)}{\beta} = \frac{\rho C F}{\beta m_0} [\Delta O_2](max) \tag{13}$$

The heat release rate data was synchronized with the mass loss and sample temperature by subtracting the transit time of the gases from the pyrolyzer to the oxygen analyzer. In this way, the temperature at maximum specific release rate, T_p, was measured in each test and used in the calculation of CHF as per Equation 4 assuming $T_p = T_s$. Three to five replicates were tested for each sample. Reproducibility of the test for homogeneous samples is about ±5%.

RESULTS

FLAMMABILITY OF GENERIC PLASTICS

Figure 3 shows data for the average HRR of 14 commercial plastics tested at 6-mm thickness and q''_{ext} = 50 kW/m^2 according to standard methods [15] versus the heat release capacity of the same plastics measured by PCFC. The proportionality and expected deviation predicted by Equation 10 are shown as black and grey lines, respectively, in Figure 3. Reasonable agreement is observed between the experimental data and the phenomenological burning model, i.e., Equations 1-10.

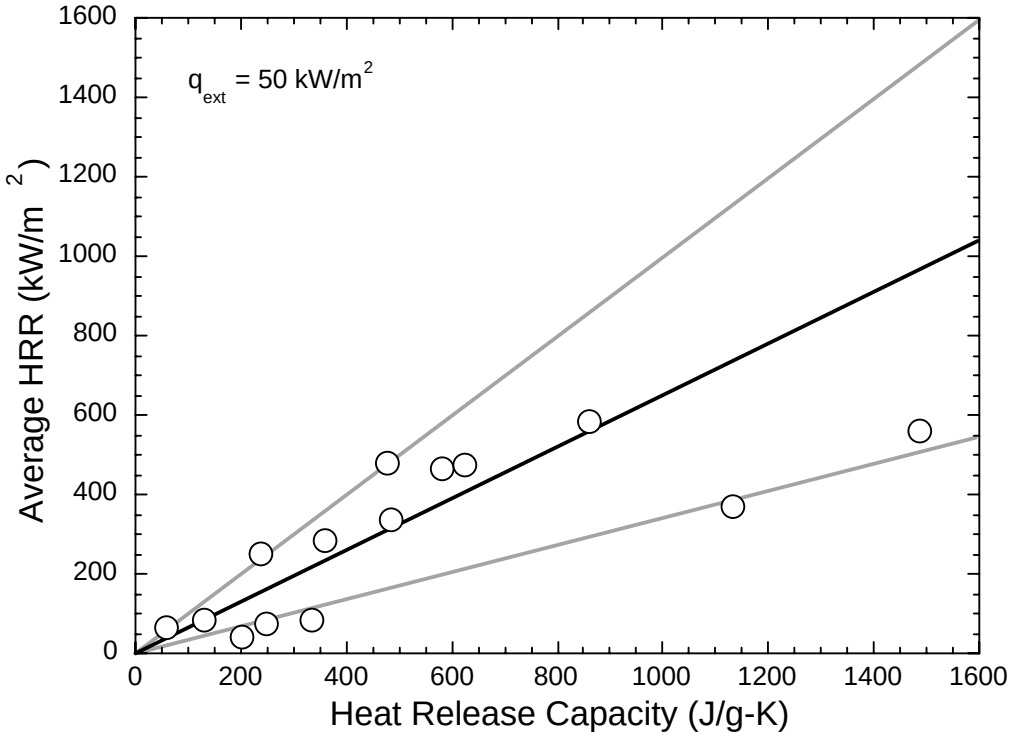

FIGURE 3. AVERAGE HRR IN FLAMING COMBUSTION VERSUS HEAT RELEASE CAPACITY OF 14 COMMERCIAL PLASTICS.

Figure 4 is a plot of flame resistance as measured in the Underwriters Laboratory test for flammability of plastics [16] versus heat release capacity of commercial plastics. The UL ratings correspond to flame resistance roughly characterized as capable of burning in a horizontal

orientation (HB), self extinguishing in a vertical orientation after a few seconds with (V2) and without (V1) flaming drips, and no sustained ignition (V0). Flammability in the UL 94 test increases with heat release capacity in the order HB > V2 > V1 > V0. A transition from self-sustained ignition (HB) to self-extinguishing behavior (V0) occurs over a relatively narrow range of heat release capacities 200-400 J/g-K in agreement with Equation 11 derived from the phenomenological extinction model (Equations 1-10). The Underwriters Laboratory HB rating is equivalent to a FMVSS 302 rating.

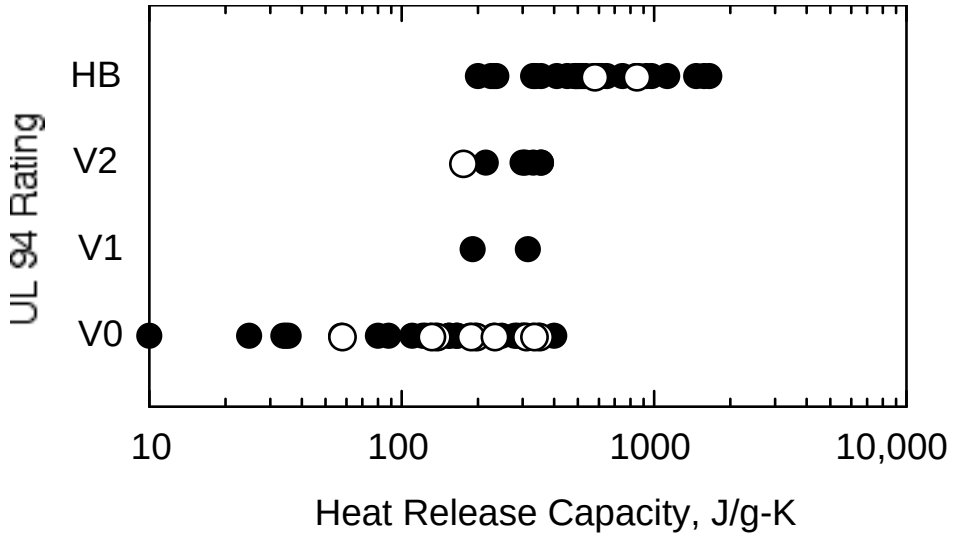

FIGURE 4. FLAMMABILTY RATING OF COMMERCIAL PLASTICS IN UL 94 TEST VERSUS HEAT RELEASE CAPACITY (OPEN CIRCLES ARE HALOGEN CONTAINING PLASTICS).

FLAMMABILITY OF AUTOMOTIVE PLASTICS

Figure 5 shows PCFC data as Q(t) versus temperature for the components with the highest (Brake Fluid Reservoir, Q = 1298 W/g, T_s = 497 °C) and lowest (Windshield Wiper, Q = 98 W/g, T_s = 407 °C) specific heat release rate of the samples tested. Dividing these Q by the heating rate in the test (β = 1 K/s) gives η_c. The CHF is obtained by inserting T_s (K) in Equation 4. Table 2 lists η_c, total heat released HR, char, and CHF for 21 samples of automotive components obtained from the engine compartment, passenger compartment, and exterior of production, late model automobiles. All three flammability properties vary widely within each automotive application, but significant differences are observed between averages of exterior components and engine/passenger compartment components.

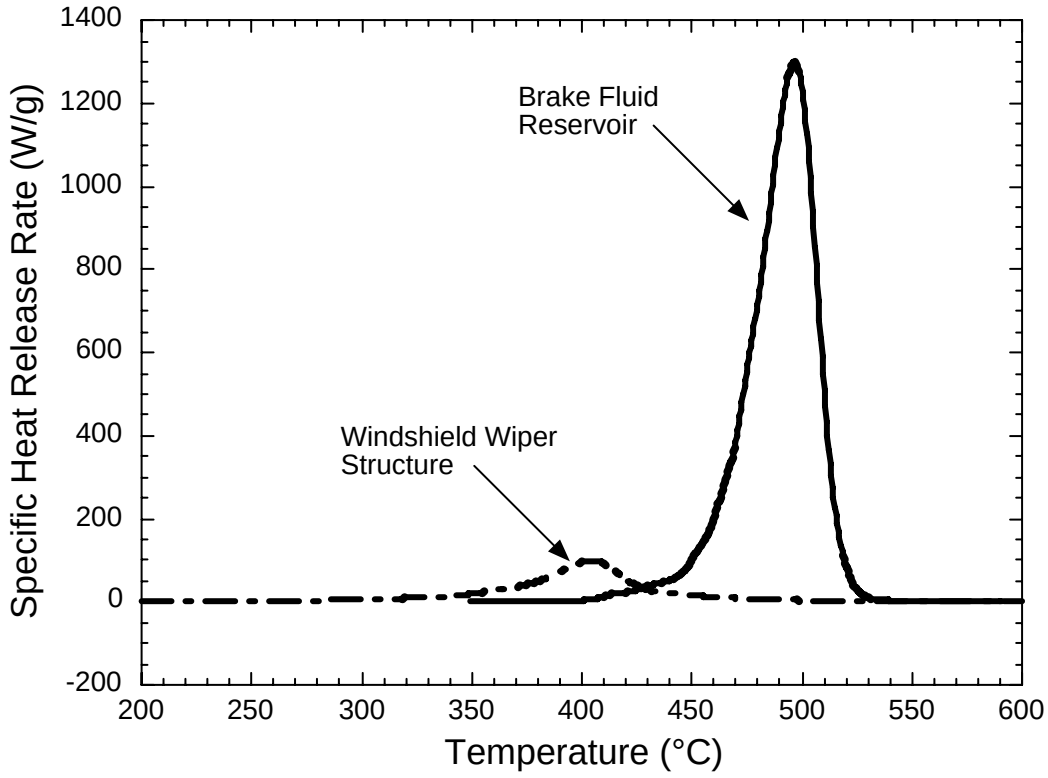

FIGURE 5. PCFC DATA FOR WINDSHIELD WIPER STRUCTURE AND BRAKE FLUID RESERVOIR.

Figure 6 shows the peak heat release rate results for the 18 automotive materials from the cone calorimeter [12] plotted against the heat release capacity from the microscale combustion calorimeter. Results shown are for tests run in the cone calorimeter at two different heat fluxes, 35 and 50 kW/m^2. Several of the samples were of similar composition and had thereby had similar heat release capacities and peak heat release rate temperatures in the microscale combustion calorimeter. The cone calorimeter results showed more variation for those same materials by having up to a factor of two in the difference between the lowest and highest peak heat release rates. Several factors could have influenced this. The test samples were not supplied as flat sheets, but were supplied in the form in which they were used (fabricated parts). Samples that were not large enough to get a cone calorimeter sample were pieced together from the component structures to create a 10 cm square. This introduced more surface area and edge effects which could account for some of the scatter in the data. Additionally some of the materials had flame retardants in them which could also influence the scatter in the flaming versus non-flaming test comparison. Despite the scatter there is a definite trend in the data for increasing heat release rate with increasing heat release capacity.

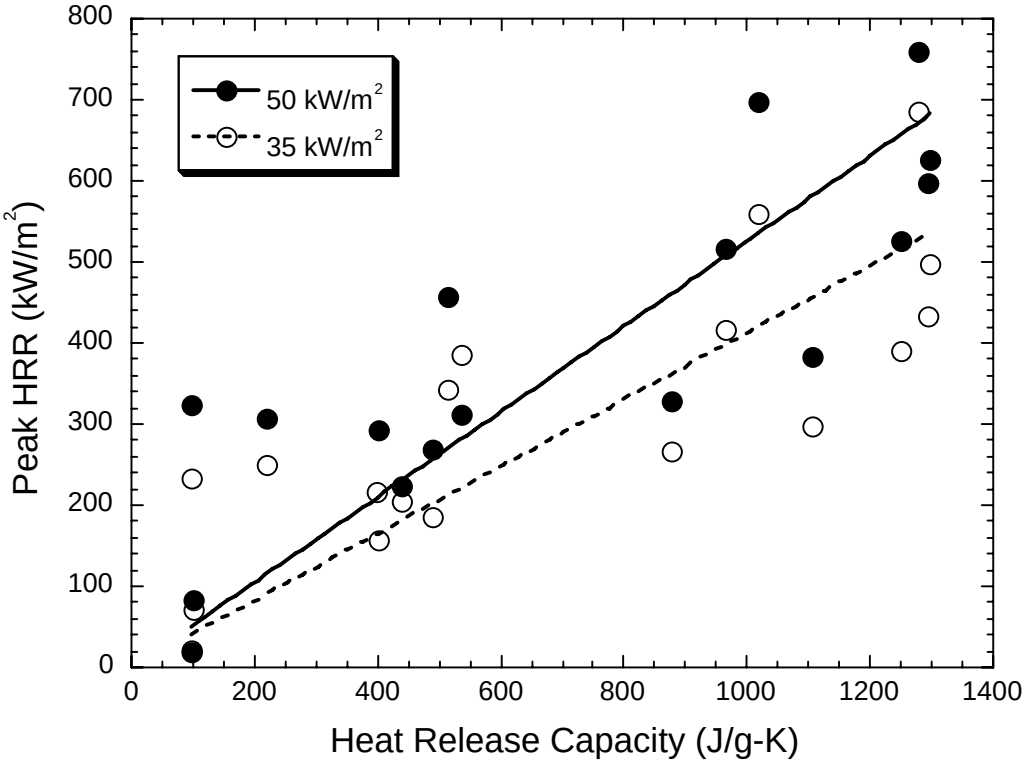

FIGURE 6. PEAK HEAT RELEASE RATE FROM THE CONE CALORIMETER AT 35 AND 50 kW/m^2 VERSUS THE HEAT RELEASE CAPACITY FROM THE MICROSCALE COMBUSTION CALORIMETER.

Table 3 compares the average values of η_c in Table 2 for different applications of automotive plastics to heat release capacities measured for plastics used in aircraft (AC) cabin interiors and overhead/attic compartments. Also listed for comparison are average values for specialty plastics (fluorinated and high heat resistant), engineering plastics (nylon, PET, PBT, ABS, polycarbonate, PVC, POM, PMMA, etc.) and commodity plastics (PE, PP, polystyrene, HIPS, EVA, SBR). Standard deviations (SD) and number of samples (N) are listed in Columns 3 and 4.

The data in Table 3 are presented graphically in Figure 7 in ranked order of flammability. Based on the limited sample set in Table 2, it is seen that automotive plastics fall (on average) between commodity plastics and engineering plastics with regard to heat release capacity. Based on the correlation in Figures 1 and 3, automotive plastics used in engine and passenger compartments would be expected to have HRR = 200-800 kW/m^2 in small-to-medium-sized fires such as engine or fuel fires. Because HRR >> HRR* for these plastic components, they would be expected to spread fire rapidly once ignited. The data in Table 1 indicate that 75% (15/20) of the automotive components tested for this study have $\eta_c \geq 400$ J/g-K. Figure 4 shows that the flame resistance of these components is predicted to be HB, i.e., they should burn in a horizontal orientation after a brief ignition with a small flame (HB or FMVSS 302 rating).

SwRI performed the FMVSS 302 test on the materials examined in this study, all of which passed [12]. In the test 4 x 14 inch x nominal thickness samples are exposed to a 1.5 inch Bunsen burner flame for 15 seconds and the flame spread over a measured length is observed. The maximum flame spread allowed to pass the test is 4 inches per minute. Samples that self extinguish shortly after removal of the flame or before the first mark in the test are given a burning rate of zero. Of the 18 materials they examined, eight of the samples had a burning rate of zero. One sample self extinguished for one test and burned at a slow rate with no drips for a second test. The other nine materials ignited and melted with most of them having flaming droplets that continued to burn on the floor. Although these materials were flammable they were able to pass the criteria for the FMVSS 302 test. Burning rates are understated in the test. Many of the samples melted and dripped which removed fuel and the flame from the sample effecting the flame spread results. The test evaluates the performance of formed parts and is not necessarily a measure of the material performance. The geometry of the part, particularly the thickness, plays a role in the observed flame spread. Samples that are not of similar geometry are compared to each other and are subjected to the same criteria.

TABLE 2. HEAT RELEASE CAPACITY, HEAT RELEASE, CHAR YIELD, AND CRITICAL HEAT FLUX OF AUTOMOTIVE PLASTICS.

COMPARTMENT Component	η_c J/g-K	HR kJ/g	Char %	CHF kW/m^2
ENGINE				
Brake Fluid Reservoir	1298	45.3	0.5	20
Resonator Intake Tube	1293	43.9	1.9	20
Battery Cover - black	1280	43.0	5.1	21
Front Wheel Well Liner	1250	45.3	0.1	19
Battery Cover -transparent	1106	42.9	0.9	21
Resonator Top	966	35.2	21.5	19
Radiator In/Out Tank	514	22.5	25.1	19
Engine Cooling Fan	400	18.6	38.3	18
Power Steering Reservoir	397	19.4	34.0	21
Fender Sound Reduction Foam	218	23.1	36.0	5
Hood Liner Face	101	7.9	32.6	3
Hood Insulator	96	5.2	78.9	8
Average:	**743**	**29.4**	**22.9**	**16**
PASSENGER				
Air Inlet	1279	43.9	2.0	20
Air Duct	1017	35.2	21.4	20
Blower Motor Housing	878	26.6	40.3	20
Kick Panel Insulation - grey	438	24.6	7.1	6
Kick Panel Insulation -black	116	7.1	61.2	6
Average:	**746**	**27.5**	**26.4**	**14**

EXTERIOR				
Headlight Assembly -black	640	22.4	18.9	8
Headlight Assembly -clear	537	20.0	23.7	27
Windshield Laminate Interlayer	490	27.1	2.7	5
Wiper Structure	98	6.6	74.8	15
Average:	**441**	**19.0**	**30.0**	**14**

TABLE 3. HEAT RELEASE CAPACITIES OF AUTOMOBILE COMPONENTS, COMMECIAL AIRCRAFT COMPONENTS, AND GENERIC PLASTICS.

MATERIAL/COMPONENT	η_c J/g-K	SD J/g-K	N
Auto Engine Compartment	743	510	11
Auto Passenger Cabin	746	465	5
Auto Exterior	441	237	4
AC Overhead Compartment	216	168	22
AC Passenger Cabin	98	64	13
Commodity Plastics	1250	307	6
Engineering Plastics	391	197	19
Specialty Plastics	160	110	8

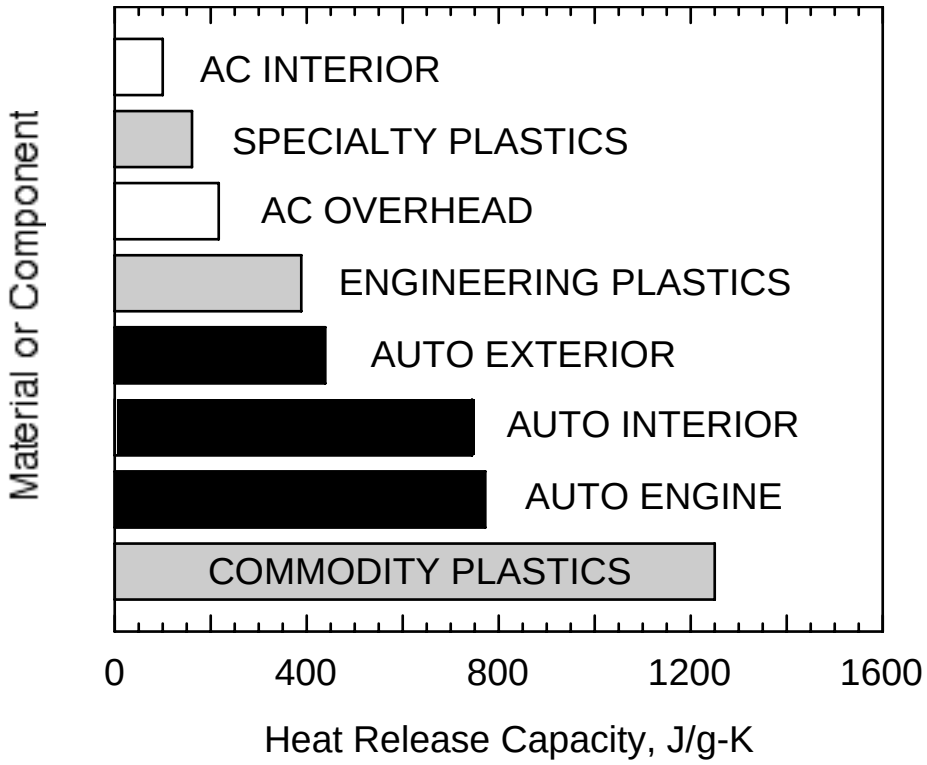

FIGURE 7. FLAMMABILITY OF PLASTIC COMPONENTS AND MATERIALS BY APPLICATION RANKED BY HEAT RELEASE CAPACITY.

Figure 8 compares average CHF (±6 kW/m^2) calculated from the pyrolysis (fuel generation) temperature, T_s for automotive components compared to commodity, engineering, and specialty

plastics as well as aircraft (AC) overhead and cabin interior materials. The CHF values for commodity, engineering, and specialty plastics are in good agreement with published experimental data for these materials [4,5,8]. Higher CHF indicate greater ignition resistance.

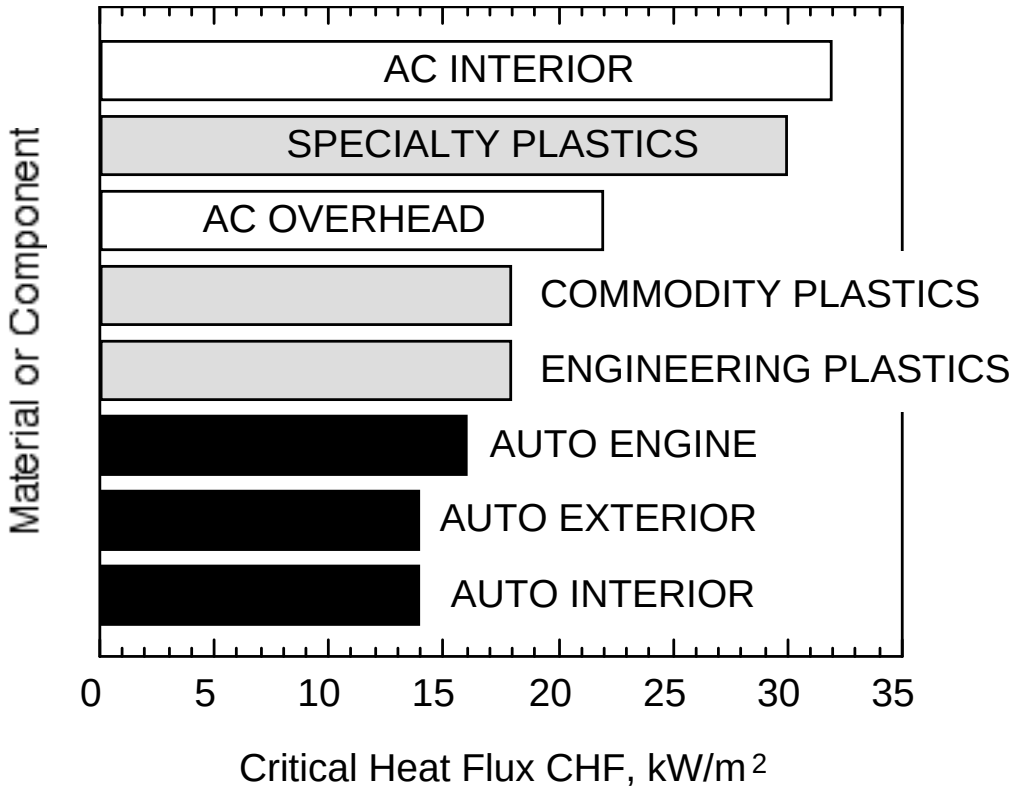

FIGURE 8. IGNITION RESISTANCE OF MATERIALS AND COMPONENTS RANKED BY CRITICAL HEAT FLUX.

The most ignition resistant materials in Figure 8 (CHF = 32 ±6 kW/m^2) are the aircraft interior materials, which are required to have very low heat release rate (< 65 kW/m^2) when subjected to an external heat flux q''_{ext} = 35 kW/m^2. The automotive components, which are only tested for flame resistance (q''_{ext} = 0), have the lowest ignition resistance of all the materials and components surveyed in this study.

Most of the automotive components examined in this study left very little char as indicated in Table 2. Residue that was left behind was comprised of fillers or a fiber content that does not burn. Large surface area passenger aircraft materials inherently leave a carbonaceous char behind due to the aromatic and highly crosslinked structure of the polymers used. Higher char is beneficial for retaining the shape of the component, providing a potential barrier for flame spread. Also higher char means less fuel that can be evolved from a sample. Therefore materials with a higher char content had lower heat release and heat release capacities than the materials that left almost no char.

CONCLUSION

Automotive components tested in this study and used in engine and passenger compartments are several times more flammable than commercial aircraft cabin materials. However, automotive components are as ignition resistant and flammable as the commodity and engineering plastics of which they are made.

ACKNOWLEDGMENTS

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