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6th Asia-Oceania Symposium on Fire Science and Technology
17-20, March, 2004, Daegu, Korea

Experimental Investigation of Burning Behavior of Automobiles

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ABSTRACT

Full-scale experiments of automobiles fire were carried out to develop a design fire source for structural fire resistance design of car park buildings. Tested vehicles include five four-doors sedans. Each vehicle was tested one by one. Side windows on drivers and attendant seats were left open at about 10cm width. Driver's seat was ignited by a cloth dipped with methyl alcohol. An open-air test and four calorimeter tests were carried out. In all of the tests, radiant heat flux was measured at neighboring positions of front, rear and sides. Burning behavior were observed by eye and recorded by videotapes. In calorimeter tests, tested vehicle was put on a loading table to measure mass loss rate. Heat release rate was measured by oxygen calorimetry.

After ignition, fire spread rapidly to front part of cabin. Soon after that, fire spread toward engine room. Then fire spread to rear part of cabin and to trunk room. Finally front and rear bumpers burned. Total fire duration was about 40~80 minutes. Peak heat release rate were 3 to 4MW. The result shows that total burning duration is proportional to body weight of vehicle. Burning duration of internal parts and time to fire spread to adjacent parts also have correlation with body weight. Height of flame ejected from windows, from front grill or from trunk depends on body weight as well. On the other hands, height of flame from burning tires and bumpers did not vary significantly with body weight. Total heat release rate could be expressed by the sum of cabin and external combustion. HRR of cabin combustion is correlated by ventilation factor of vehicle window openings (ventilation- controlled burning). Peak HRR of external combustion is almost constant regardless with body weight.

KEYWORDS : automobiles, full-scale experiments, fire growth model, heat release rate

INTRODUCTION

In the trend of performance-based fire safety design, design fire source came to play an important role. On the other hand, engineering data of fire behavior is not well developed. In case of car park structure design, fire behavior of automobiles shall be understood before initiation of design. For
this purpose, full-scale experiments of automobiles are needed

Several experiments were carried out previously. Butcher *et al.* carried out experiments in indoor parking area (1968) [1]. Two experiments of automobiles made in 1980's were carried out by Martin *et al.* at FRS (1991) [2]. Rate of burning, heat release, smoke and toxic gas release, surface temperature distribution and emitted thermal radiation were measured. Peak heat release rate was about 4.5MW and 7.5MW. In the experiments by Mangs et al. at VTT, peak heat release rate was 1.5~2MW [3]. CTiCM experiments by Zhao *et al.* showed peak heat release rate of 70-80's car and 90's car was 2MW and 8MW respectively [4]. Experimental data of heat release rate and radiant heat flux is still not enough for use in fire safety design of car park buildings considering wide variation of automobiles.

In this study, full-scale experiments were carried out to examine burning behavior including burning duration of representative parts of vehicle, time to fire growth from one part to another part, flame height of each part and radiant emission to neighboring area and heat release rate.

FULL-SCALE EXPERIMENTS

Specimen

Five passenger sedans (1800cc~3000cc displacement) were served for testing. One is burnt in open air, while the rest four were burnt in oxygen calorimetory. To study burning behavior of automobiles, indoor and outdoor experiments were carried out. Specifications of tested cars are shown in Table 1.

In the outdoor experiment, a 3000cc sedan was burnt in an open atmosphere. Engine displacement was 3000cc. Body length was 4.8m. Body weight was 1920kg. Both front seat windows were left open by 10cm. Very little gasoline was left in fuel tank.

In the indoor experiments, four sedans were tested individually. Engine size was in the range of 1800 to 3000cc. Body length was in the range of 4.4 to 4.7m. Body weight was in the range of 1162 to 1920kg. In experiments 1 and 3, very little gasoline was left in fuel tank. In the experiments 2 and 4, gasoline was left in one-forth of fuel tank.

TABLE 1. Specification of tested cars

Type of test	No.	Size (length, width, height) [mm]	Engine Displacement [cc]	Measured Body Weight [kg]	Estimated Weight of Combustible Materials*2 [kg]	Ceiling
Outdoor	1	4850 x 1750 x 1360	3,000	1,920*1	365	No
Indoor	1	4430 x 1430 x 1370	1,800	1,162	221	Yes
	2	4600 x 1630 x 1340	2,000	1,470	279	Yes

	3	4400 x 1500 x 1350	3,000	1,920*1	365	Yes
	4	4690 x 1690 x 1370	2,000	1,380*1	262	No

*1 Catalog Value *2 19 % of body weight assumed

Experimental Procedure

Outdoor and indoor experiments layout is shown in Figures 1 and 2. Ceiling was placed over the car to examine the effect of thermal feedback from smoke layer above burning car in case of indoor experiments 1, 2 and 3.

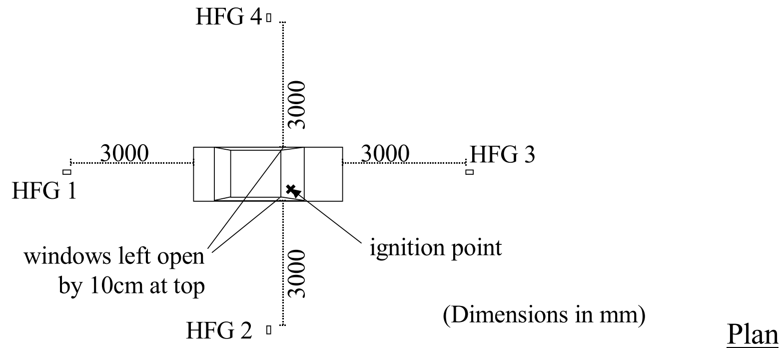


FIGURE 1. Layout of outdoor experiment (HFG = heat flux gauge, dimensions in mm)

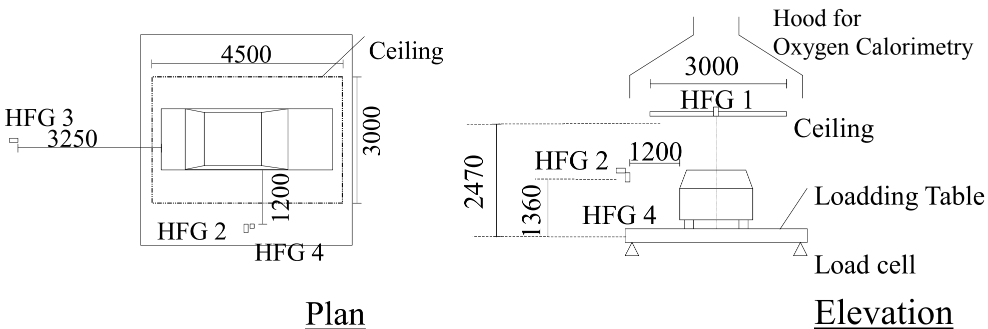


FIGURE 2. Layout of indoor experiments (HFG = heat flux gauge, dimensions in mm)

Outdoor Experiments

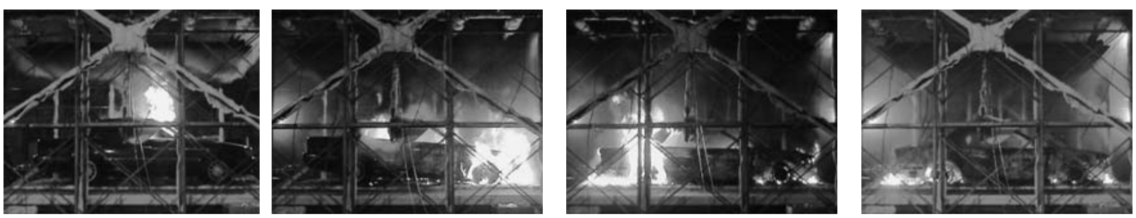
The specimen was ignited at driver's seat by using methanol soaked fiber blanket. Burning growth and flame height were observed by eye and recorded by videotapes from front, rear and both sides. Radiation heat flux was measured by using heat flux gauges placed at 5m away in the directions of front, rear and both sides at the same height of automobile roof (1300mm above ground).

Indoor Experiments

Tested car was ignited by the same way as in outdoor experiment. Ceiling was placed over automobiles in experiment 1,2 and 3. In the same way as outdoor experiment, burning behavior and flame height was observed by eye and recorded by videotapes from front, rear and both sides of automobiles. Radiation heat flux was measured by using heat flux gauges 1 placed vertically downward at ceiling and heat flux gauge 2 placed at right side of automobile 1.2m away, 1.36m high in the direction of automobiles horizontally. Heat flux gauge 3 was set horizontally at 3.25m away from car body, 2.04m above ground. Heat flux gauge 4 was set upward at same potion with gauge 2. By using four load cells, mass loss rate was measured. At the same time, heat release rate was measured by oxygen consumption.

Test Results

Among the experiments, the result for indoor experiment 2 is described below as an example. Burning behavior is shown in Figure 3. After ignition at driver's seat, seat materials burned rapidly at first. However, as the oxygen originally in the cabin was consumed, burning was ventilation- controlled to very slow burning. At 8minutes, front glass broke down. Then cabin fire (Front seat + Dashboard (FS), Rear seat (RS)) reached flashover as shown in Figure 3a. Fire spread to rear seat at 15 minutes, to engine room (ER) at 24 minutes, to front tires (Front right tire (FRT), Front left tire (FLT)) at 25 minutes. At 30 minutes, front objects (FOB) (bumper, headlights and so on) melted down and burned extensively as shown in Figure 3b. Around 40 minutes, fire spread to rear part (trunk room (TR), rear tires (Rear right tire (RRT), Rear left tire (RLT)), rear objects (ROB)). As shown in Figure 3c, these materials melted and burned extensively in a similar way to front materials. Around 60 minutes, fire almost burnt out as shown in Figure 3d. Gasoline didn't burn so heavily.



(a) flashover at 8 minutes | (b) fully-developed burning of front part at 30 minutes | (c) fully-developed burning of rear part at 47 minutes | (d) burnout at 60 minutes

FIGURE 3. Burning process observed in indoor experiment 2

To summarize growth and decay, major burning parts are separated into 10 pieces. Burning period of respective parts are shown in Figure 4. Routes and the time to fire spread between parts are shown as arrow in this figure. Cabin burned for 31minutes after flash over. Front and rear part of automobiles burned for 22minutes respectively. Front part burned for 30minutes. Rear part burned for 45minutes. The duration of simultaneous burning of front and rear part was not very long.

Heat release rate was calculated by mass loss rate multiplied by heat of combustion of plastic materials (32MJ/kg). The result is shown in Figure 5. Burning duration of each part is also shown in the same figure using the aberrations shown in Figure 4. Until 8minutes, heat release was below 400kW. After flash over, heat release rate increased rapidly to about 2MW. At 24minutes, fire spread to engine room, but HRR was not changed considerably. At 30minutes, front part burned heavily. As a result, HRR reached about 4MW. At 35minutes, HRR began to decrease. At 44minutes, HRR began to increase again to 4.5MW at 47minutes due to the burning of rear part. After that, HRR decreased rapidly to burnout.

Results of radiation heat flux measurements are shown in Figure 6. Radiation heat flux on ceiling reached peak value when flame ejected from front window impinged on ceiling at 10minutes. After that, radiation heat flux continued to decrease. At 47 minutes, heat flux reached second peak of about 20kW/m² as rear part burned heavily. Radiation heat flux at right side was about 10~15 kW/m² for horizontal direction, 5 kW/m² for vertical direction. During the period of rear part burning, horizontal flux was about 30 kW/m^2, while vertical flux was about 9kW/m². Comparing between directions, horizontal component was dominant. Backward radiation heat flux is small except the period of rear part burning during 35 and 40minutes.

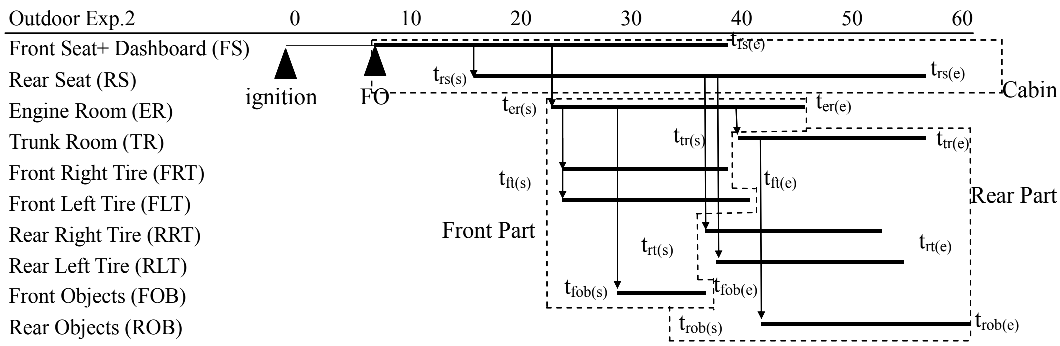


FIGURE 4. Burning Duration of Parts (Indoor Experiment 2)

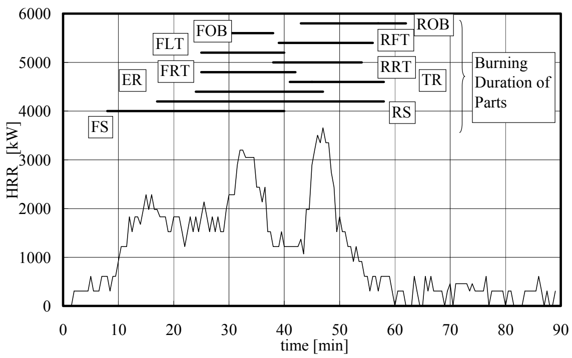


FIGURE 5. Heat Release Rate (Indoor Experiment 2)

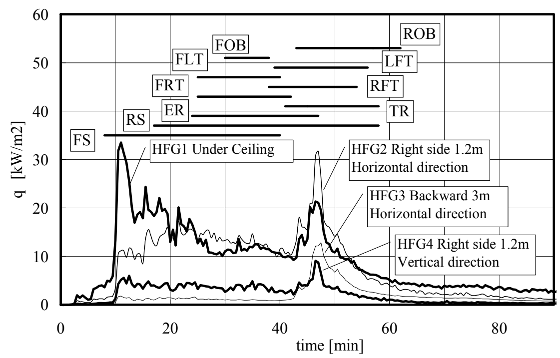


FIGURE 6. Radiation Heat Flux (Indoor Experiment 2)

Summary of Experimental Measurements

All experimental results are shown in Table 2. Time to initial growth (time from ignition to flash over) is about 5~12 minutes. Total burning duration (time from flash over to burnout) is about 40 ~ 80 minutes. Measured weight loss was in the range of 165~239 kg. The weight fraction of actually burnt materials to estimated weight of combustible materials (Table 1) was in the range of 0.654~0.747. Total heat release was 5280~7648 MJ / car. Peak HRR was 3.7~5.1MW. Heat release rate curves of all the experiment are shown in Figure 7. By comparison between experiments 1 - 3 and 4, the effect of the thermal feedback is not significant in this experimental layout.

TABLE 2. Summary of experimental Results

Experiment No.		Time to Initial Growth [min]	Total Burning Duration [min]	Measured Weight Loss[kg]	Burnt Fraction[%]	Total Heat Release[MJ]	Peak HRR [MW]
Outdoor	1	6	66	-	-	-	-
Indoor	1	5	35	165	74.7	5280	3.8
	2	8	54	186	66.6	5952	3.7
	3	12	76	239	65.4	7648	3.3
	4	12	40	192	73.3	6144	4.1

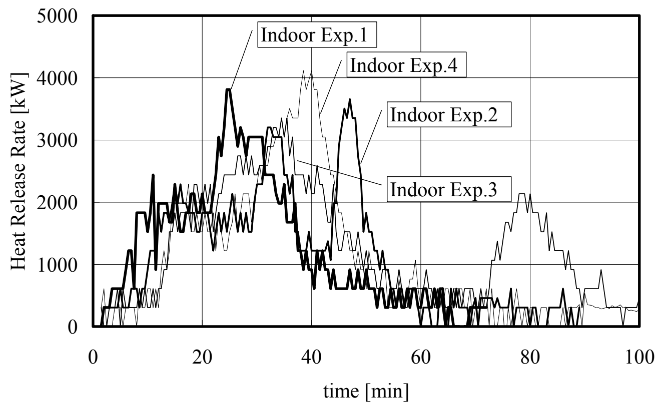


FIGURE 7. Heat Release Rate (Indoor Exp.1~4)

ANALYSIS OF EXPERIMENTAL RESULTS

To develop general understanding of burning behavior, fire growth, flame height, heat release rate were analyzed.

Growth behavior

Relationships between weight of automobiles and burning duration of each part and time to fire spread between parts were analyzed. Namely, burning duration and time to fire spread as in Figure 4 were developed for each experiment. The results were correlated with body weight.

Total Burning Duration

Total burning duration (time from cabin flashover to end of flammable burning) is plotted versus body weight as shown in Figure 8. The total burning duration is almost proportional to body weight. The relationship is expressed by using the symbols in Figure 4 as

(Total burning duration [min.])

$$= t_{rob(e)} - t_{fr(s)} = 0.035W \qquad (1)$$

where W is the body weight of car [kg].

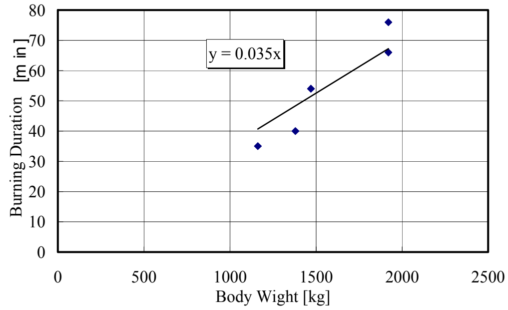


FIGURE 8. Relationship between total burning duration and body weight

Burning Duration of Individual Parts

Burning duration of individual parts was correlated in a similar way for the parts determined in Figure 4 (FS, RS, ER, TR, FRT, FLT, RRT, RLT, FOB, and ROB). For example, results for FS (time from front window breakage to the end of burning) is shown in Figure 9. Burning duration was again in proportion with body weight as

(burning duration of FS) = $t_{fr(e)}$ - $t_{fr(s)}$ = $0.0203W$ [min]. (2)

As to FO, similar plot was made for the time from fire spread from ER to burnout of FO. The result is shown in Figure 10. In this case, burning duration is independent of body weight. The average value is

(burning duration of FO) = $t_{fob(e)}$ - $t_{fob(s)}$ = 10 [min]. (3)

The correlation results are summarized in Table 3. As to internal burning, (FS, RS, ER, TR), burning duration seems to be proportional with body weight. This is because of the fact that burning rate inside the cabin is controlled by the amount of airflow rate to cabin. Considering that the window size does not vary widely among conventional sedans, burning rate is also invariant. On the other hands, the total amount of combustible materials is proportional to body weight. Thus the burning duration might be proportional with body weight.

As to external burning, parts such as FRT, FLT, RRT, RLT and FO, RO burned in free environment. Burning duration may depend on mass of combustible materials, but there is almost no correlation between external burning duration and body weight in these experiments.

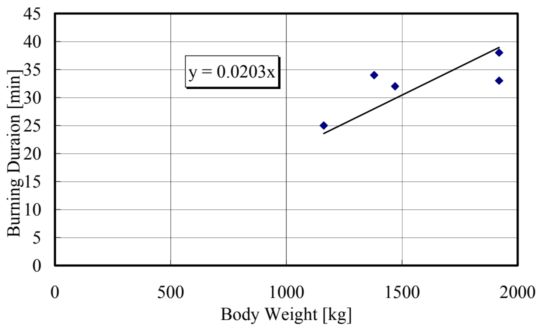


FIGURE 9. Relation between body weight and burning duration of Front Seat

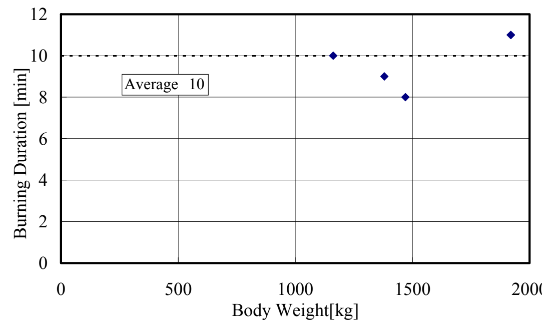


FIGURE 10. Relation between body weight and burning duration of Front Objects

TABLE 3. Summary of corralated formula of burning duration

parts		formula (*W* : body weight in kg)
internal burning	*FS*	0.0203 *W*
	RS	0.0251*W*
	ER	0.0129*W*
	TR	0.0075*W*
external burning	*FRT, FLT*	14
	RRT, RLT	14
	FOB	10
	ROB	12

Fire Growth Between Parts

In a similar way, time to fire spread between parts was analyzed. For instance, time to fire spread from FS to ER (time to flame ejection via front grill since cabin flashover) is shown in Figure 11. There is almost no correlation, but the time to spread is almost constant. This is because fire spread through holes for ventilation and electric code, which do not vary by body weight.

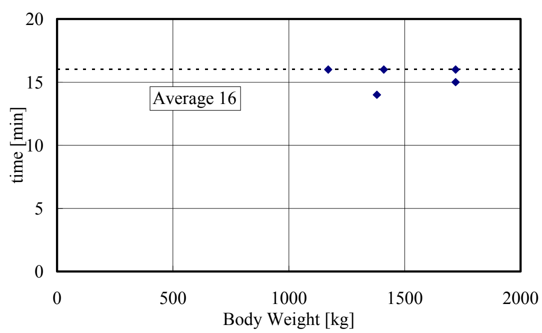


FIGURE 11. Time to Fire Spread from Front Seat to Engine Room

Summary of Fire Growth Behavior

For other fire spread routes, similar analysis was carried out. The results are summarized in Table 4.The correlation formula developed so far was applied to the car for indoor experiment 3. Burning period of individual parts were calculated and compared with experimental observation. As shown in Figure 12, prediction is satisfactory.

Table 4. Summary of Corralated Formula for Time to Fire Spread Between Major Parts

Parts	formula (*W* : body weight in kg)
FS → RS	0.0089*W*
FS → ER	16
RS → TR	0.0198*W*
FS → FRT,FLT	0.0114*W*
RS → RRT,RLT	0.015*W*
ER → FOB	3
TR → ROB	1

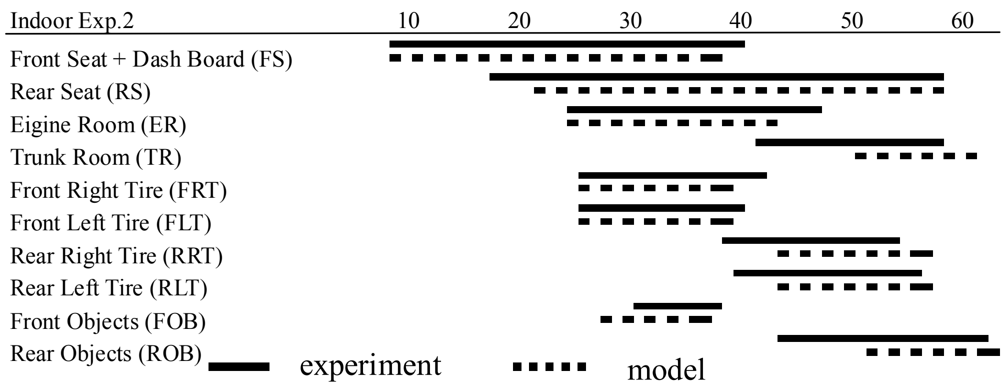


FIGURE 12. Comparison of Model with Indoor Experiment

Flame Height

Flame height of each part was correlated with body weight in the same way. For instance, flame height ejected from front window is shown in Figures 13 and 14. These data correspond with single flame when flames from no other part are merged together. Continuous flame height $h_{fg(c)}$, is shown in figure 13 as a function of non-dimensional time, which is zero at the start of burning, unity at the end of burning. Continuous flame height is about 1 meter high above reference height (bottom edge of front window) until 60% of burning duration. Intermittent flame height $h_{fg(f)}$ is shown in Figure 14. Flame tip was impinging on ceiling at 2,470 mm above floor.

Continuous flame heights are shown in Figure 15. They seem to have linear correlation with body weight. In Figure 16, maximum intermittent flame height was plotted against body weight. In all of the indoor experiments with ceiling (indoor exp. 1, 2 and 3, circled in figure 16), intermittent flame touched ceiling. In other experiments without ceiling, intermittent flame height happened to be the same. Thus the correlation is not very clear.

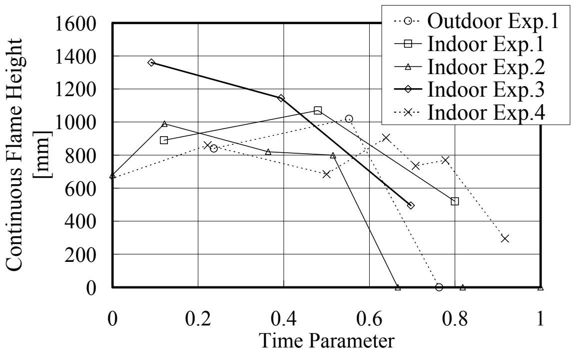


FIGURE 13. Continuous Flame Height ejected from front window above bottom edge of front windows

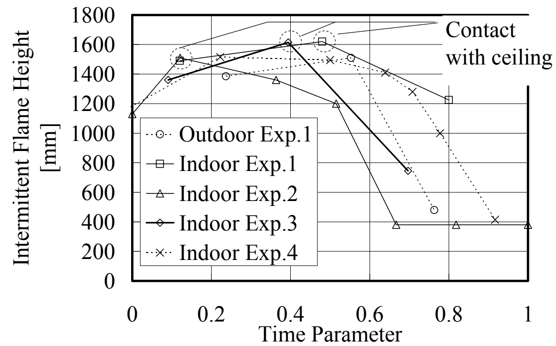


FIGURE 14. Intermittent flame height ejected from front window above bottom edge of front windows

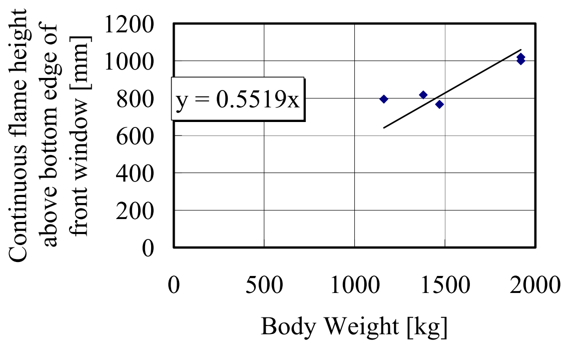


FIGURE 15. correlation between continuous flame height ejected from front window and body weight

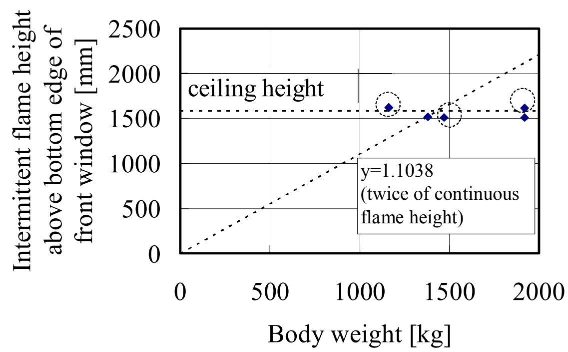


FIGURE 16. correlation between intermittent flame height ejected from front window and body weight(circle = experiment with ceiling)

Flame heights from other parts were analyzed in the same way. The results are shown in Table 5. Height of flame ejected from internal burning depends on body weight. On the other hand, flame height of external burning would not vary considerably with body weight.

Table 5. Flame Height from representative parts

	Continuous Flame Height [mm]	Intermittent Flame Height [mm]
h_{fg}	$0.5519W$	1580
h_{fg+fsg}	$0.5546W$	1700
h_{fsg}	440	600
h_{fsg+fg}	$0.5278W$	$1.05W$
h_{rsg}	$0.3602W$	$0.630W$
h_{er}	$0.3499W$	$0.526W$
h_{er+fob}	$0.7628W$	$1.16W$
h_{tr+rob}	$0.5765W$	$0.836W$
h_{ft}	620	870
h_{ft+er}	1170	2060
h_{rt}	590	940
h_{rt+rg}	1580	2620

h: flame height [mm], *W*: body weight [kg], *fg* : front glass, *rg* : rear glass, *fsg* : front side glass, *rsg* : rear side glass, *er* : engine room, *tr* : trunk room, *ft* : front tire, *rt* : rear tire, *fob*: front objects, *rob* : rear objects

Heat Release Rate

In the indoor experiments, heat release rate was measured. The results are summarized for initial growth and fully developed periods.

Induction Time and Fire Growth Rate

After the initial break of front window glass, fire grows rapidly. The heat release rate during growing period can be approximated by t^2-fires

$$Q = \alpha(t - t_o)^2 \tag{4}$$

where α is the fire growth rate [kW/s^2], t_0 is the induction time [s] which was taken as the time to glass breaking. The measured HRR curves in indoor experiments are shown in Figure 17. The average value of fire growth rate was 0.0095 kW/s^2 with standard deviation 0.0019. The average value of induction time was 336 [sec] with standard deviation of 116 [sec]

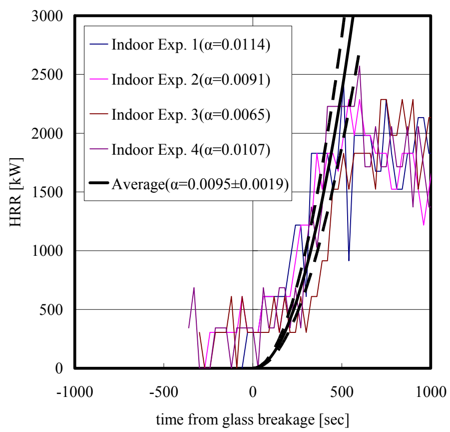


FIGURE 17. Heat Release Rate in Initial Growth Period

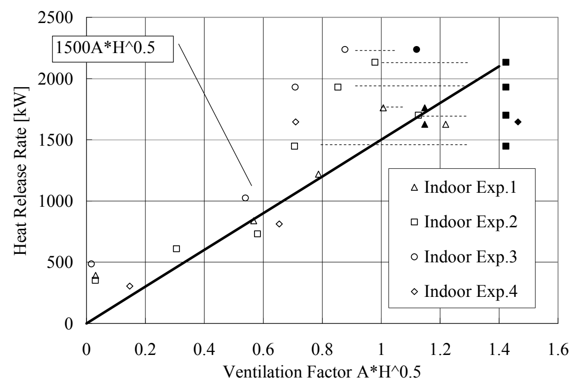


FIGURE 18. Ventilation Factor and Heat Release Rate

Heat Release Rate during Fully-developed stage

As was discussed in preceding sections, internal burning is ventilation- controlled. External burning is fuel-surface controlled. The total heat release rate would be given by the sum of heat release rates of internal and external burning. Thus the total burning was separated into three parts, namely cabin (internal burning), external burning of front parts (FRT, FLT, FOB) and external burning of rear parts (RRT, RLT, ROB).

As to internal burning, empirical formula

$$Q = 1500A\sqrt{H} \quad \text{[kW]} \tag{5}$$

was applied where $A\sqrt{H}$ is the ventilation factor [m$^{5/2}$]. Using the VTR record, ventilation factor was estimated to calculate heat release rate. Ventilation factor was calculated only for broken windows (shown by open symbols) and for effective airflow route including broken windows and bottom opening of engine room (shown by filled symbols). The results are summarized in Figure 18 in comparison with measured results shown in Figure 7. As is shown, equation (5) gives reasonable estimation.

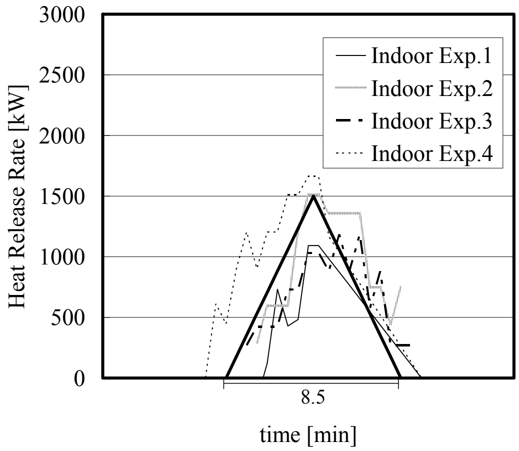


FIGURE 19. heat release rate of front external burning

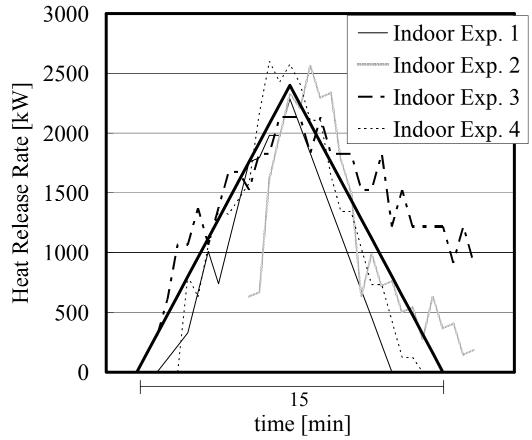


FIGURE 20. heat release rate of rear external burning

During external burning period, heat release rate curve has a sharp peak as shown in Figure 7. Peak

parts correspond with external burning. In Figures 19 and 20, heat release rate of front and rear external burning are plotted so that time to peak value in all the experiments would overlap. As to front external burning, heat release rate can be approximated by a triangle function whose duration is 8.5 minutes and peak value is 1,500 kW. As to rear external burning, duration is 15 minutes and peak value is 2,400 kW.

Total Heat Release

Measured total heat release is plotted against body weight in Figure 21. Total heat release by internal burning is proportional with body weight. On the other hands, the total (sum of internal and external burning) is not proportional.

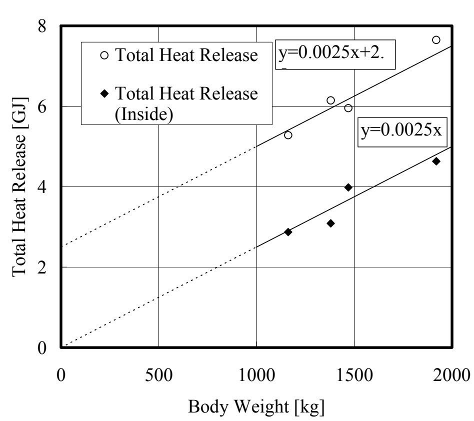


FIGURE 21. Total Heat Release measured in indoor experiments

CONCLUSION

Five burning experiments were carried out for conventional sedan type car in order to examine fire growth process, flame height, radiation heat flux and heat release rate. Analysis of experimental results led to three simple correlations of fire growth, flame height and heat release rate.

1) After cabin flashover, fire spread to front part and to rear part. Fire growth process was correlated with body weight.
2) Continuous and intermittent flame heights from major parts of car were correlated with body weight as well.
3) Heat release rate of cabin fire is approximated by t^2-fires followed by fully developed stage. Heat release rate by internal burning can be approximated by conventional ventilation-controlled formula. Peak heat release rate for external burning of front and rear parts were invariant with body weight.

REFERENCES

1) E. G. Butcher, G. H. Langdon-Thomas, G. K. Bedford, "Fire and Car Park Buildings", Fire Note 10, HMSO, U.K., July 1968
2) M. Shipp, M. Spearpoint, "Measurements of the Severity of Fires Involving Private Motor Vehicle", Fire And Materials, vol. 19, 143-151, 1995
3) J. Mangs, O. Keski-Rahkonen, "Characterization of the Fire Behaviour of a Burning Passanger Car", Fire Safety Journal, vol. 23, pp.17-35, 1994
4) B. Zhao, J. Kruppa, "Structural Behaviour of an Open Car Park under Real Fire Scenarios", Second International Workshop on Structures in Fire, Christchurch, March 2002