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## **Experimental studies on open type cabin fire**

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## **Abstract**

The “cabin” concept has been used widely for fire safety in big public transport terminals not fully protected by sprinkler nor smoke exhaust system in the Far East for the past 20 years. There, only the areas with a higher fire risk, such as retail shops, are protected. The big terminals are used to be crowded, and so there are concerns on whether the cabin design can provide adequate fire protection in such big halls, and whether the design will give problems in firefighting. Consequently, additional fire safety provisions such as long-throw sprinkler had been installed in areas with higher fire risk. Smoke exhaust system have to be added to the large hall.

In the new edition of fire safety provisions required for railway systems, the open type of cabin is specified. No in-depth study supported by systematic experiments on how the fire can be limited to 2 MW reported in the literature. On the other hand, preliminary experimental studies on cabin with sprinkler and smoke exhaust carried out indicated that there are many concerns.

In this paper, five tests on cabin fire carried out in a big burning hall at the State Key Laboratory of Fire Science, University of Science and Technology of China (USTC) will be taken out to demonstrate the problems associated with such open type cabins. Problems in big halls without fully covered by smoke exhaust system had been demonstrated clearly in an airport terminal fire in 1998. It took a long time for firefighters to locate the fire source in that small fire at the airport terminal. The fire safety must be upgraded by appropriate hardware engineering systems and software safety management to reduce the chance of having big fire, and facilitate firefighting.

## 1. Introduction

In the new edition of fire safety provisions required for railway systems released in 2013 [1], the open type of cabin is specified with concerns raised while implementing performance-based design [2,3]. In fact, the “cabin” concept has been used widely for fire safety in big public transport terminals without fully protected by sprinkler and smoke exhaust systems in the Far East for about 20 years [4,5]. Only the areas with a higher fire risk, such as retail shops, are protected and, the big terminals are used to be crowded. Any incidents might lead to uncontrolled evacuation as experienced in Lan Kwai Fong, Hong Kong [6], Kwai Yuan in Beijing [7], and others [8]. The smoke filling problem associated with fire in big hall had been clearly demonstrated in a small fire in the Hong Kong airport terminal before opening [9]. In fact, it took a long time for firefighters to locate the fire source. There are also concerns [10-22] on whether the cabin design can protect fires within 2 MW in such big halls not fully covered by sprinkler nor smoke control. Consequently, long-throw sprinkler had been installed in some areas [23] in some existing airport terminal, and smoke exhaust systems are specified to be installed in big halls for new development.

Very few experimental data are reported in the literature [4,5,15,24,25] on how the fire can be limited 2 MW. Preliminary studies [26-36] indicated that there are many problems in such cabin design. Some preliminary works were reported in Chinese literature without in-depth analysis. In this paper, five tests on cabin fire carried out in a big burning hall at the State Key Laboratory of Fire Science, University of Science and Technology of China (USTC) will be taken out to demonstrate the problems associated with such open type cabins.

It is necessary to carry out systematic experimental studies [22] on cabin with sprinkler and smoke exhaust operating as expected, say by limiting the fire load stored in each cabin, installing more effective fire extinguishing system, providing additional protection in the big halls such as long-throw sprinkler and smoke exhaust system. Appropriate fire safety management and tight fire inspection scheme must be implemented to reduce the chance of having big fires.

## 2. Earlier Experimental Study

To evaluate the performance of cabin fires with sprinkler and smoke exhaust systems in operation, a cabin model was constructed in an atrium of height 27 m. The cabin is of length 3 m, width 4 m and height 3 m as shown in Figs. 1a to c. A door of height up to 1.4 m was designed. The height can be varied to adjust the ventilation factor. A centrifugal water-cooling high temperature exhaust fan with adjustable flow rate was installed. A sprinkler system was installed with normal sprinkler head commonly used [37] to protect shops in an atrium. The nozzles and spray pattern discharged are shown in Fig. 2, with operating parameters listed in Table 1. The sprinkler operating curve is shown in Fig. 3.

Air temperature inside the cabin was measured by thermocouples inserted in the holes drilled on the northern cabin wall as shown in Figs. 4a and b. Nine holes (labeled as TC1 to TC9 in Fig. 4a) spaced uniformly were provided along the vertical line in two parts. As water discharged from the sprinkler nozzle acting on the thermocouples would affect the temperature measurement, thermocouples were shielded by steel plates as shown in Fig. 4c. Temperatures at the outside hall were measured by thermal resistors.

Carbon monoxide (CO) concentration inside the cabin was measured by a gas analyzer inserted in the center of the fan duct connected to the cabin. When the smoke exhaust fan operated, gas inside the cabin was extracted into the duct. A maximum reading of 5000 ppm was adjusted. Photograph of the CO analyzer is shown in Fig. 5.

The wood crib fires were set up as in Fig. 6a with key parameters listed in Table 2. The crib was ignited over a pool of size 0.25 m by 0.25 m with 0.2 kg of oil. Heat release rate of one wood crib of size 0.6 m by 0.6 m by 0.4 m was measured separately in an oxygen consumption calorimeter as shown in Fig. 6b. The wood crib broke down at 650 s with the heat release rate decreased. A steady heat release rate of 650 kW was observed at about 250 s. Four wood cribs were tested and labeled as C1 to C4 as in Fig. 1. Heat release rate of burning four cribs would be about 2.6 MW, when their separation distance was longer than 0.3 m.

Five full-scale burning tests [30-36] with smoke exhaust rates and sprinkler operating conditions shown in Table 3 were taken out for illustrating the fire hazards.

- Test T1: The smoke exhaust rate was 8000 m<sup>3</sup>/h, and the sprinkler pressure was 0.2 MPa. Four wood cribs were placed at the center.
- Test T2: The smoke exhaust rate was 1582 m<sup>3</sup>/h, and the sprinkler pressure was 0.2 MPa. Four wood cribs were placed at the center.
- Test T3: The smoke exhaust rate was 8000 m<sup>3</sup>/h, and the sprinkler pressure was 0.1 MPa. Four wood cribs were placed at the center.
- Test T4: The smoke exhaust rate was 1582 m<sup>3</sup>/h, and the sprinkler pressure was 0.1 MPa. Four wood cribs were placed at the center.
- Test T5: Without operating the smoke exhaust and sprinkler systems, all four wood cribs were placed at the center, known as a 'bare cabin' [17].

### 3. Observations

The following were observed in the five tests [30-36]:

- Test T1

After ignition, smoke spilled out from the cabin rapidly. Smoke exhaust fan was operated at 30 s, the smoke layer height rose with little smoke spilling out. The flame height of the two wood cribs near the fan is higher than that of the other two cribs. The fire grew rapidly, and spread to the edge of the wood crib at about 160 s.

Sprinkler was operated at 160 s and the flame height descended. The flame became not so bright, but the fire did not reduce in size. More smoke spilled out from the cabin. The smoke layer height fell to about 0.65 m with high smoke concentration. The cribs in the cabin were observed to be burning. Wood crib C4 broke down and C2 extinguished at 625 s. Wood crib C1 extinguished at 735 s and broke down at 790 s. All wood cribs extinguished at 840 s. Pictures inside the cabin after doing test T1 is shown in Fig. 7a.

Wood crib C2 did not break into smaller parts but almost burned out. Wood crib C3 burned out without breaking down.

- Test T2

The burning process was similar to Test T1 though the smoke exhaust fan was turned on upon ignition. As the exhaust rate was low, smoke spilled out from the cabin. Sprinkler

was operated at 206 s and more smoke spilled out. The burning process in the cabin could not be observed at 235 s as the smoke layer fell to about 0.25 m. Smoke concentration was the highest among the five tests.

The hall was also filled up rapidly with smoke. Smoke exhaust fan of the hall was operated at 580 s. The picture inside the cabin after test T2 is shown in Fig. 7b. All wood cribs did not break down, and most of them did not burn out.

- Test T3

The burning process was similar to Test T1 after ignition. Smoke exhaust fan was operated at 20 s. After that, smoke did not spill out of the cabin. The flame height of the two wood cribs near the fan is higher than that of the other two. Sprinkler was operated at 160 s and some smoke spilled out from the cabin. Smoke concentration was the lowest among the five tests. The burning process in the cabin could be observed clearly. The smoke layer height was about 0.9 m.

Wood crib C1 broke down at 490 s and extinguished at 690 s. Wood crib C2 broke down at 580 s and extinguished at 750 s. All wood cribs extinguished at 860 s.

The photograph inside the cabin after test T3 is shown in Fig. 7c. Wood crib C4 did not break down but almost burned out. Wood crib C3 burned out but did not break down.

- Test T4

The burning process was similar to Test T2 after ignition. Smoke exhaust fan was operated at 12 s with lower smoke exhaust rate. Smoke spilled out from the cabin. Sprinkler was operated at 145 s and more smoke spilled out. The smoke layer height descended to about 0.6 m. Smoke concentration was lower than Test T1 and T2, but higher than Test T3. The burning process in the cabin could be observed.

Picture of the cabin after test T4 is shown in Fig. 7d. Wood crib C1 broke down, wood cribs C2 and C4 almost burned out, but did not break down. Wood crib C3 mostly burned out, but did not break down.

- Test T5

Smoke spilled out from the cabin rapidly upon ignition. The fire grew up rapidly and the smoke layer height was about 0.9 m. Flame spread out from the door at 360 s. Observers could not stand in front of the door to observe the burning process due to strong heat radiation. It was not tenable to stay at even 5 m away from the door. Noise of cracking the flooring materials was heard at about 400 s. All wood cribs broke down at 560 s, and burned out at 700 s. The wood residue was still burning.

#### 4. Results on Temperatures

Air temperature measured inside the cabin and average smoke layer temperature are shown in Figs. 8 and 9.

For tests T1 and T2, air temperatures inside the cabin decreased suddenly upon operating the sprinkler system. Temperature in test T1 was quite steady. Air temperature in test T2 kept on decreasing until extinguishing the fire. The average smoke layer temperature in test T1 was higher than that in test T2 throughout the whole burning process.

In tests T3 and T4, air temperature decreased to a steady value but still quite high. The steady air temperature in T3 was about 330°C, higher than that in T4 of about 125°C. These indicated that air temperature inside the cabin would be affected by the smoke exhaust systems. Operating the smoke exhaust fan would draw in air to sustain combustion. Air temperature inside the cabin increased with increasing smoke exhaust rate.

Comparing air temperature in T1 with T3 under the same exhaust rate of 8000 m<sup>3</sup>/h, and comparing air temperature in T2 with T4 under the same flow rate of 1582 m<sup>3</sup>/h, increasing the sprinkler pressure would decrease the temperature inside the cabin.

As both smoke exhaust and sprinkler systems were not operated in test T5, air temperatures in T5 were the highest. The highest temperature was 860°C found near to the ceiling. The average smoke layer temperature increased to 600°C at 325 s but flashover did not occur. When

the average smoke layer temperature increased to 666°C at 400 s, air temperature increased rapidly. Corresponding to the noise of cracking the flooring materials heard at 400 s, flashover should have occurred. Therefore, fire suppression system such as sprinkler must be installed to protect the cabin.

Before operating the sprinkler, temperatures in tests T1, T3 and T4 were higher than that in T5. This suggested that operating the smoke exhaust fan would sustain combustion. Air temperatures inside the cabin increased with increasing smoke exhaust rate.

## 5. Results on CO Concentration

Concentration of CO measured inside the cabin for tests T1 to T4 are shown in Fig. 10.

CO concentrations measured in tests T1 and T2 were over the pre-set maximum value of 5000 ppm of the analyzer. CO concentration in T2 was higher than that in T1 with the same sprinkler pressure 0.2 MPa over some time. Similarly, CO concentration in T4 was higher than that in T3 with the same pressure 0.1 MPa. These indicated that CO concentration inside the cabin would be affected by the smoke exhaust system. Different smoke exhaust rates would give different ventilation conditions. The burning process would be affected. CO concentration inside the cabin decreased with increasing smoke exhaust rate.

In comparing CO concentration in T1 with T3 under the same exhaust rate of 8000 m<sup>3</sup>/h, and comparing CO concentration in T2 with T4 under the same exhaust rate 1582 m<sup>3</sup>/h, increasing the sprinkler pressure would increase the CO concentration inside the cabin. As observed, there were two peaks in the CO concentration curves in T1, T3 and T4. Only one peak was observed in T2. The first peak appeared after the sprinkler was operated, and the second peak appeared at the burning decay stage. These might suggest different fire suppressing effects. This point will be further explored and reported later.

## 6. Effect to the Hall

Smoke was observed to spill out from the cabin for all the five sets of tests. A stable layer was formed at the hall with lower smoke layer height for the cabin with sprinkler operating, due to the hot steam generated.

Average smoke layer temperatures measured in the outside hall are shown in Fig. 11. The highest smoke temperatures for the five tests were 20.7°C for T1, 20.7°C for T2, 22°C for T3, 24°C for T4 and 33.5°C for T5. Temperatures in the hall are very low due to the relatively small fire (2.6 MW) in a big hall of size 22.4 m by 12 m by 27 m.

Smoke layer height in the outside hall was measured with the N-percentage rule [38,39] with N taken to be 30 and visual observations, shown in Fig. 12.

- Test T1

The steady smoke layer height was about 4 m. The time for the smoke layer height to descend to 4 m after sprinkler operation was about 150 s. The rate of smoke filling up the hall was fast.

- Test T2

Smoke layer height started to descend at about 130 s before operating the sprinkler. Smoke layer height descended to 11 m with low smoke concentration. After the sprinkler was operated, the descending rate of smoke layer became slow, but smoke concentration became

very high. The time of smoke layer height descending to 4 m after sprinkler operation was about 200 s. It took 350 s to fall to 3 m after operating the sprinkler. Exhaust fan of the hall was operated at 580 s.

- Test T3

Similar to T1, smoke filled the hall after operating the sprinkler. The smoke layer height was about 5 m at about 250 s. Smoke concentration was very low.

- Test T4

Similar to T2, smoke layer height started to descend at about 140 s before the sprinkler was operated. The smoke layer fell to 22 m at the time when sprinkler was operated. The smoke concentration was low. After operating the sprinkler, smoke concentration increased but lower than that in tests T1 and T2. The smoke layer height was about 5 m. The time of smoke layer height descending to 5 m after operating the sprinkler was about 260 s. Smoke concentration was low.

- Test T5

Smoke layer height started to descend at about 80 s. The steady smoke layer height was even higher at about 7 m at about 360 s for the bare cabin.

## 7. Conclusions

The following are observed in the five preliminary tests with open cabin:

- It is obvious that smoke spread out to the hall from an open cabin in all five sets of tests.
- Temperature inside the bare cabin increased quickly upon burning the cribs. The ceiling temperature could be up to 860°C by burning four wood cribs of heat release rate 2.6 MW. Flashover occurred at 400 s. The average smoke layer temperature was 666°C, higher than the flashover criterion of 600°C in some standards. The cabin structure might be damaged by the high temperature. Flame and large quantity of hot smoke spilling out might be a threat to occupants staying at the outside hall.
- The operating sprinkler pressure is a key parameter. There was a critical operating pressure for the sprinkler system to control a fire.
- With the fire suppression system operated, temperature in the hall was low. Smoke concentration reduced when the smoke exhaust system in the cabin operated. Operating normal sprinkler will give a longer burning duration. More smoke was liberated. Although temperature in the hall was very low, the smoke concentration was very high. It is certainly a potential risk to life safety.
- It is doubtful whether normal operation conditions of sprinkler and smoke exhaust system

can control fires bigger than about 2 MW [24,25] in a cabin. Using a sprinkler pressure of 0.1 MPa and a smoke exhaust system of 40 ACH might not be effective in controlling the fire to 2 MW.

Note that terminals with cabin design are usually crowded with people. Passengers are allowed to carry luggage up to 25 kg even for economy class tickets. Appropriate fire suppression systems should be installed to control flashover cabin fires. Sprinkler system is only one of the active engineering systems commonly provided to give suppression effects. Other workable fire suppression systems with higher efficiency should be considered to put out the fire rapidly. Again, in-depth experimental studies must be carried out as raised by the principal author [2,3].

## 8. Additional Comments

The paper was published as a journal **study** [40]. With the practice of publisher, preprint is allowed to upload at a website. The **cabin** design looks good because the huge terminals need not fully covered by sprinkler nor smoke extraction. In response to the challenges encountered in the past 20 years, there are further studies on this topic because of safety concerns after some users put lots of combustibles outside the cabins, even for catering. Further, some fires occurred in such big terminals with smoke filled up the whole space quickly because no smoke extraction systems as in [41-71]. **This is clearly demonstrated in above with no or inadequate fire services installations.**

Additional fire services installations such as long throw sprinklers are installed [41,42,48,52]. Fire safety management [51,55,60-71] is a key part in providing safety, with more inspections to see combustibles put outside the cabins. Even the combustibles inside the shops were limited in some terminals. Note that higher punishment [55,60-67] to responsible persons on safety issues in the Hong Kong Special Administrative Regions (HKSAR) in early 2023. Enhancing safety culture [62-66,68] in retenting top management after big fires as in Beijing 2023 is a good practice for the HKSAR to learn, instead of just slight punishment with few thousand US dollars as in tower crane collapsed with causality. Nothing proceeded on collapse of a university green roofs [49,50]. Safety issues must be responsible by top management to execute effective fire safety management schemes. Recent serious incidence led to retention of responsible persons on falling down of external finishes in July 2023. Research on positive pressure ventilation (PPV) [53,56] must be explored on firefighting and rescue in atrium full of smoke. Anyway, HKSAR is moving towards a position of caring **labours** more on safety issues after smooth transition to mainland in 1997.

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JAFS\_CabinFSB07k

Record:

- A485UL22-1a (opened 27 July 2023, open from JAFS\_CabinFSB07g.doc)
- A485UL22-1b (opened 9 Aug 2023)
- A485UL22-1c (opened 11 Aug 2023)
- A485UL22-1d (opened 15 Aug 2023)
- A485UL22-1e (opened 17 Aug 2023)
- A485UL22-1f (opened 21 Aug 2023)
- A485UL22-1g (opened 22 Aug 2023)
- A485UL22-1h (opened 22 Aug 2023)

**Table 1: Sprinkler parameters**

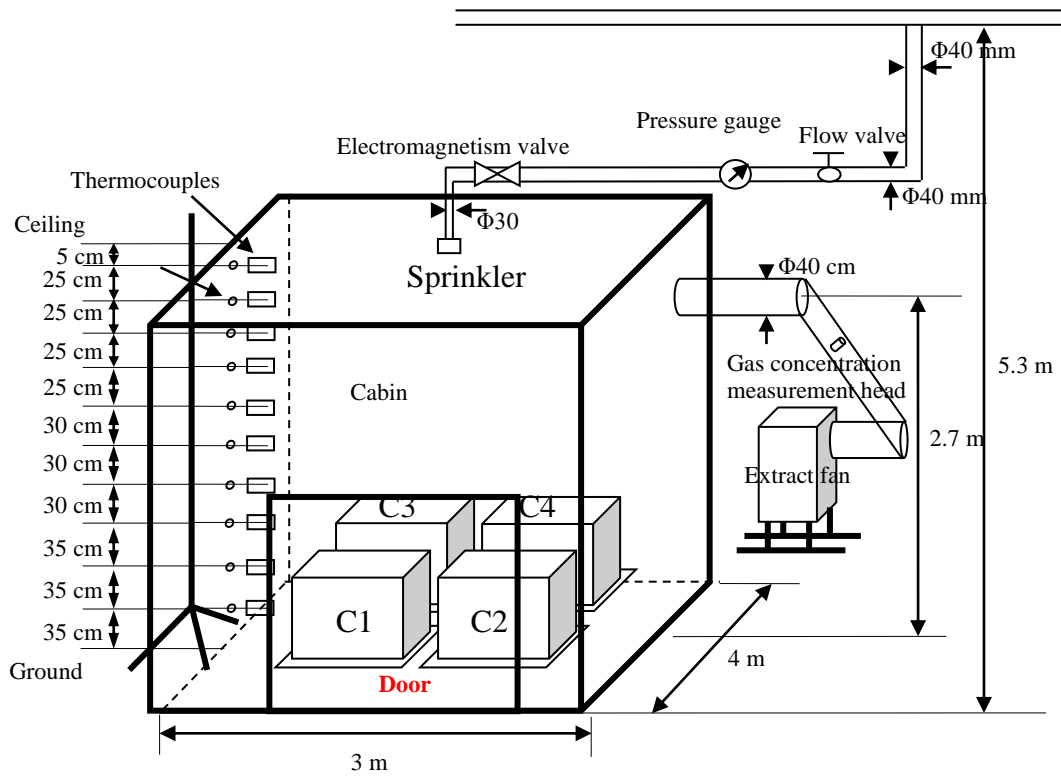
Sprinkler type	Pressure (MPa)	Flow rate (L/min)	Fog angle	Spray range (m)	Flow rate coefficient K	Screw thread (in)
A	0.1	80	/	/	80	R1/2
B	0.35	30	90°	7.4	16	R1/2

**Table 2: Wood crib fire**

Crib size	0.6 m × 0.6 m × 0.4 m
Stick size	0.6 m × 0.025 m × 0.025 m (section size)
Space ratio (porosity)	1:2
Number of layers	16
Number of sticks per layer	9

**Table 3: Testing conditions**

Test number	Ambient temperature (°C)	Number of wood cribs	Smoke exhaust system		Sprinkler	
			Flow rate (m <sup>3</sup> /h)	Operating time (s)	Operating pressure (Mpa)	Operating time (s)
T1	18	4	8000	30	0.2	160
T2	18	4	1582	0	0.2	206
T3	18	4	8000	20	0.1	160
T4	18	4	1582	12	0.1	145
T5	18	4	—	—	—	—



(a) Schematic



(b) Photograph: northwest

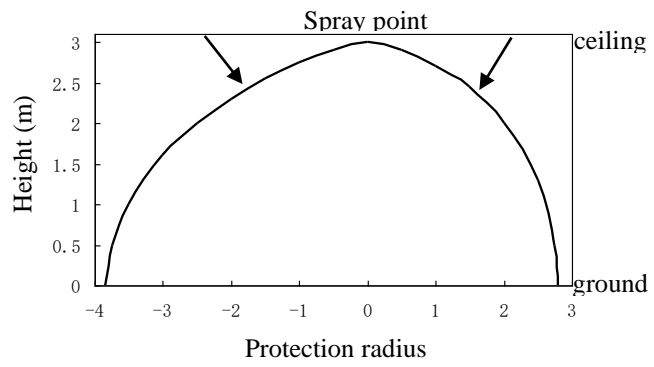


(c) Photograph: southwest

**Fig. 1: The full cabin**

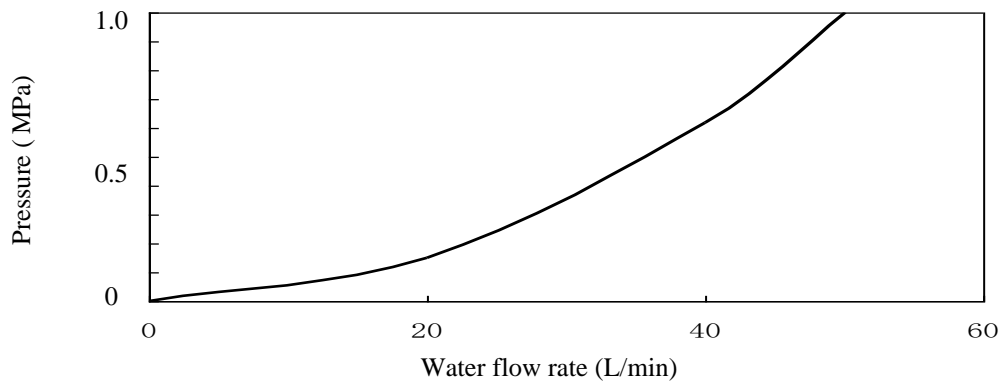


(a) Nozzle



(b) Spray pattern

**Fig. 2: Normal sprinkler head**



**Fig. 3: Sprinkler operating curve**

1	○	2.95 m
2	○	2.70 m
3	○	2.45 m
4	○	2.20 m
5	○	1.95
6	○	1.65 m
7	○	1.35
8	○	1.05 m
9	○	0.70
...	○	

(a) Location of thermocouples



(b) View



(c) Steel sheets

**Fig. 4: Thermocouples**

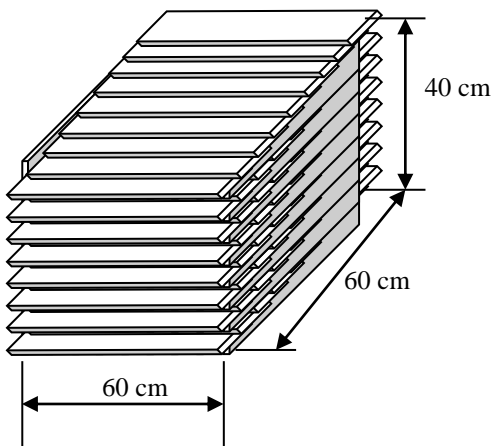


(a) Analyzer

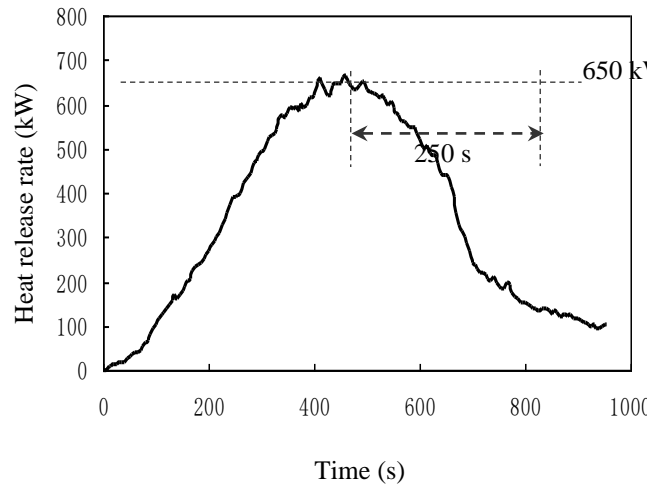


(b) Measurement head

**Fig. 5: CO analyzer**



(a) 1 crib



(b) Heat release rate

**Fig. 6: Wood crib fire**



(a) Test T1



(b) Test T2

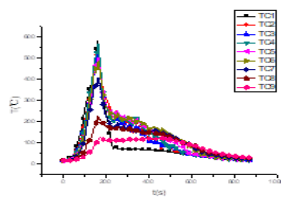


(c) Test T3

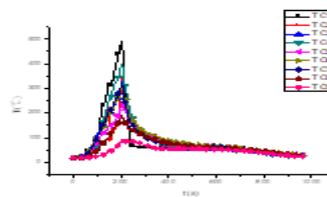


(d) Test T4

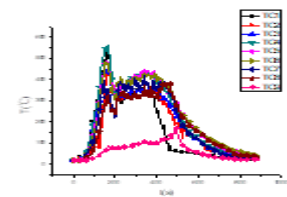
**Fig. 7: Pictures after tests**



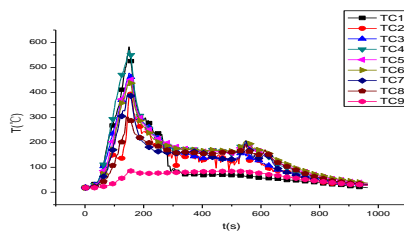
(a) Test T1



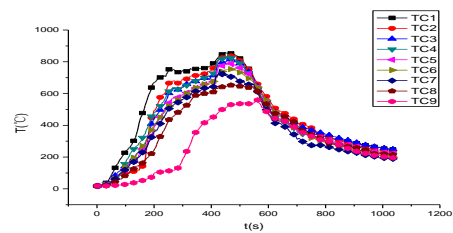
(b) Test T2



(c) Test T3

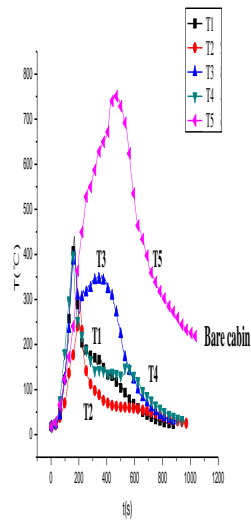


(d) Test T4

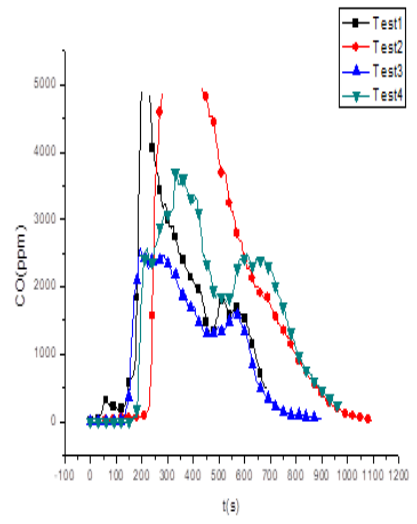


(e) Test T5

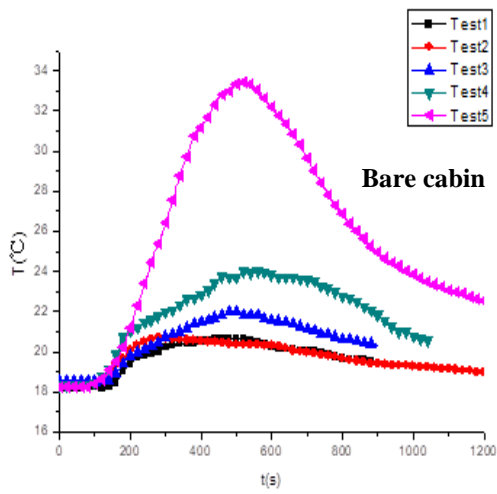
**Fig. 8: Temperature curves inside the cabin**



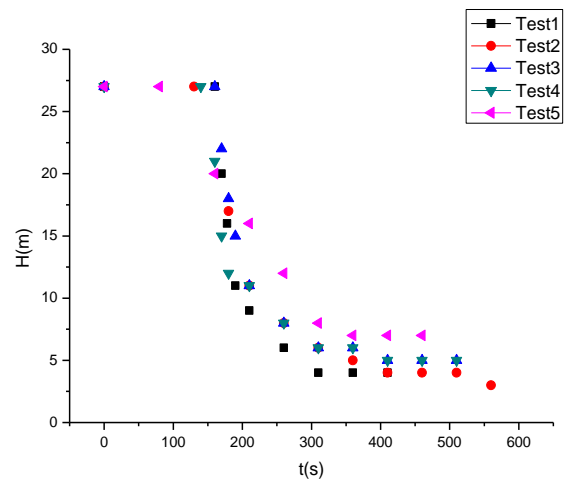
**Fig. 9: Average smoke layer temperature curves**



**Fig. 10: CO concentration curves inside the cabin**



**Fig. 11: Average smoke layer temperature in the outside hall**



**Fig. 12: Smoke layer height in the outside hall**

