# EFFECT OF FIRE SIZE ON SUPPRESSION CHARACTERISTICS OF HALON REPLACEMENT TOTAL-FLOODING SYSTEMS

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## ABSTRACT

The effect of fire size on the toxic gas formation, the oxygen depletion, and the pressure fluctuation in a fire compartment during suppression by total-flooding fire extinguishing systems was investigated. Suppression experiments were conducted against various sizes of heptane fires (30 kW to 420 kW) in a 60 $m^3$ test room. The suppressants tested were three inert agents, IG-100 (100% N,), IG-541 (52% N„ 40% Ar, 8% CO,), IG-55 (50% N„ 50% Ar), and two fluorinated agents, HFC-23 (CHF,) and HFC-227ea ($CF_3CHFCF_3$). The species analyzed were CO, CO„ HF, $CF_2O$, NO„ and O,. The Fourier transform infrared spectroscopic method was used to monitor the concentrations of HF and $CF_2O$. The maximum CO, CO„ HF, $CF_2O$, and the minimum O, concentrations all showed linear correlation with the fire size. The concentrations of HF and $CF_2O$ significantly exceeded the IDLH (Immediately Dangerous to Life or Health concentration) even for the minimum size of the test fires with the HFCs. While the CO concentrations never exceeded the IDLH during suppression by the inert agents and HFC-23, suppression of a 230 kW fire by HFC-227ea caused CO production over IDLH. The concentration of CO, exceeds the IDLH when IG-541 is applied to the fires greater than 150 kW. The minimum O, concentrations after the suppression of 420 kW fires by the inert agents reached 8.8%, which was significantly lower than the design concentrations of over 12%. Remarkable over- and underpressurization in the compartment were observed during several experiments, even though a venting was provided. These pressure changes due to the agents' discharge were also strongly dependent on the fue size. The total-flooding systems can cause destruction of the compartments and/or significantly dangerous levels of the fluorinated compounds when fires are above critical sizes.

## INTRODUCTION

In response to the production ban of the halon fire suppressants, two research committees were organized by the National Research Institute of Fire and Disaster (NRIFD) in Japan in FY 1993 and 1994, in order to determine the evaluation methods of the toxicity and the fire suppression effectiveness of halon replacement. Based on the recommendations made by the committees, the Fire Protection Equipment and Safety Center of Japan (FESC) started the evaluation of halon replacement total-flooding systems in 1995. It has been pointed out that the toxicity of the combustion products from the fluorinated agents (HFC) must be a serious issue. However, the safety standards on toxic combustion products has been unsettled during the past six years, due to the difficulty in evaluating the toxicity of combustion products relative to the risk caused by a fire itself.

In FY 1999, the Japan Fire Equipment Inspection Institute organized a new research committee and investigated the effect of fire size on the toxicity of combustion products generated during suppression by the halon replacement agents. Total-flooding suppression tests were performed, in which the concentrations of the toxic gases, the oxygen depletion, and the pressure fluctuation in the test room were measured as a function of the size of the heptane pan fire. This paper reports major findings obtained through these experiments.

## EXPERIMENTAL METHODOLOGY

Figure 1 shows the schematic illustration of the experimental setup. The 60 m' test room was constructed in the sprinkler test building of the Japan Fire Equipment Inspection Institute. The building is equipped with a device for exhausting gases at the top. The test room, built of wood, had two wooden doors and two polycarbonate windows. The ceiling and the walls were made of plywood, which was lined with plaster ($CaSO_4 \bullet 2H_2O$) panels, and further partly with steel sheets. Outside the test room, the corner

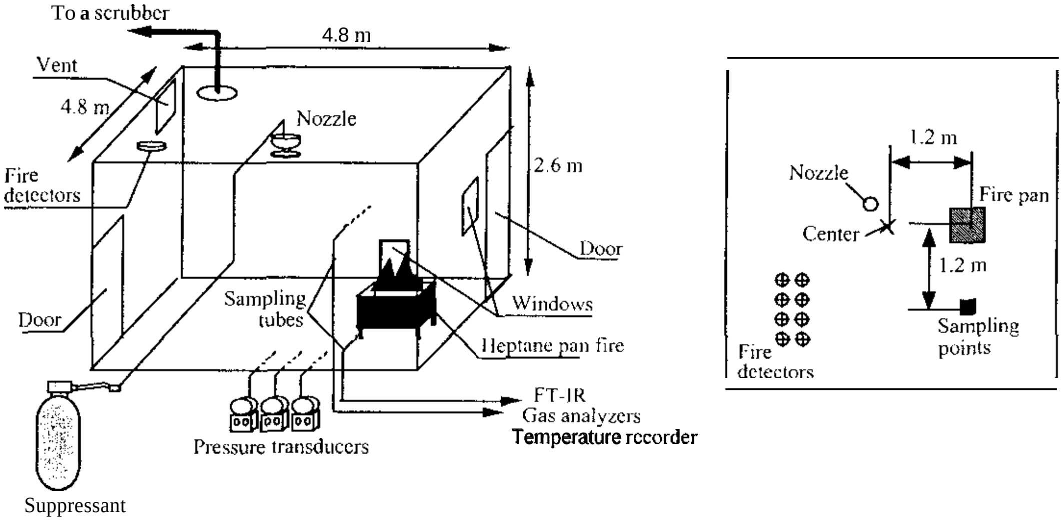

Figure I. Schematic illustration of the experimental setup.

pillars were reinforced with rafters that were fixed on the floor of the building, and a steel beam was laid over the ceiling of the test room for additional reinforcement. All joints were sealed to make the room airtight. A 300 mm square vent for pressure relief was located on a wall near the ceiling. At the ceiling, an exhaust duct connected the test room with a gas scrubbing system.

Suppressants used in the present study are three inert agents, IG-100 (100% $N_2$), IG-541 (52% $N_2$, 40% **Ar,** 8% $CO_2$), and IG-55 (50% $N_2$, 50% Ar), and two fluorinated agents, HFC-23 ($CHF_3$) and HFC-227ea ($CF_3CHFCF_3$). These five agents include every agent approved by the FESC as a halon replacement by the end of FY2000. The design concentrations of the agents, the discharge time, and the extinguishment time data are listed in Table 1.

TABLE 1. DESIGN CONCENTRATION, DISCHARGE TIME, AND EXTINGUISHMENT TIME.

| Agent | Design Concentration (%) | Discharge Time Max. / Min. (sec) | Extinguishment Time **Max.** / Min. (sec) |
|---|---|---|---|
| IG-IO0 | 40.3 | 55 / 57 | **24** / 83 |
| IG-541 | 37.5 | 55 / 58 | 181137 |
| IG-55 | 37.9 | 98 / 105 | 29 1562 |
| HFC-227ea | 7.7 | 10 / 11 | 10 / 14 |
| HFC-23 | 14.9 | 10 / 11 | 5 / 8 |

**A** fire source was selected from four different sizes (0.05 $m^2$, 0.1 $m^2$, 0.2 $m^2$, and 0.3 $m^2$) of n-heptane square pans and a wood crib made of 52 Japanese cedar sticks of 30 by 40 by 900 mm piled in 6 layers. The fire source was placed 1.2 m away from the center of the room (Figure 1). The heat release rates of n-heptane fires were measured prior to the suppression experiments and were found to be 30 kW, 89 kW, 230 kW, and 420 kW for 0.05 $m^2$, 0.1 $m^2$, 0.2 $m^2$, and 0.3 m’ pans, respectively. The heat release rates of the wood crib fire at the agent discharge, measured simultaneously with the suppression experiments, were found to vary between 212 and 287 kW for the inert agents and between 101 and 137 kW for the fluorinated agents due to the shorter preburn time.

The species analyzed were CO, $CO_2$, HF, $CF_2O$, NO, (NO and NO,), and $O_2$. Gas samples were taken at two locations, both 1.2 m away from the center of the fire source (Figure 1). The upper sampling port was placed 0.5 m below the ceiling; the lower port was placed 0.5 m above the floor. The Fourier transform infrared spectroscopic (FT-IR) method was used to monitor the concentrations of HF and $CF_2O$.

Two sets of MIDAC IGA-2000 FT-IR spectrometers were placed adjacent to the test room. The gas cells had a path length of 10 cm and optical windows made of ZnSe. To verify the FT-IR measurement, the lower sample was collected in the buffer solution and analyzed with an ion chromatograph. CO and CO, were monitored with infrared gas analyzers (Horiba VIA-510), while $O_2$ was measured with a paramagnetic O, analyzer (Shimadzu POT-101) and a zirconia-method O, analyzer (Shimadzu CGT-7000). NO. was measured with chemi-luminescence analyzers (Shimadzu NOA-8000).

A load cell was used to measure the mass of the agents discharged. For the liquefied agents, the discharge time was also measured with the load cell, while the pressure transducer was used to measure the discharge time for the inert agents. In the present study, the discharge time is defined as the time required to discharge 90% of the total agent discharged.

To determine the fire extinguishment time, three thermocouples were placed over the heptane pan and five thermocouples were placed on the wood crib. Temperatures in the test room were also measured using five thermocouples: two at the sampling locations, one 0.1 m below the ceiling over the fire source, one near the detectors, and the rest on the steel sheet at the ceiling over the fire source.

Differential capacitance-type pressure transducers (Tsukasa Sokken SPX-D) with three different ranges (0-100 mm $H_2O$, 0-200 mm $H_2O$, and 0-2000 mm $H_2O$) were used for the room pressure measurements. The pressure at 0.1 m above the floor, 0.05 m inside the wall, and approximately 3 m away from the fire source was introduced into the higher-pressure side of the pressure transducers of 0-200 mm $H_2O$ and 0-2000 mm $H_2O$, and the lower-pressure side of the 0-100 mm $H_2O$ transducer. This allows measurement of both over- and under-pressurization simultaneously. The direct current signals from the pressure transducers were converted into voltage signals by amplifiers and recorded at intervals of 1/16 or 1/8 sec.

The heptane fires were preburned for 60 sec before the agent discharge. During the first 50 sec of the preburn time, the doors were kept opened to prevent oxygen depletion. The doors were then closed and the agent was discharged into the test room 10 sec after closing the doors. The wood crib fires were preburned for the experiments with the inert agents (for 275 sec) and the fluorinated agents (for 190 sec). The doors were first opened and then closed 10 sec before the discharge. The measurements of the temperatures and the gas concentrations were continued for 30 min. When the measurements were completed, the gas scrubbing system was turned on and continued the operation for more than 2 hrs, to remove the combustion products from the test room.

## RESULTS *AND* DISCUSSION

### PRODUCTION OF TOXIC GASES *AND* OXYGEN DEPLETION

Prior to the suppression experiments, a free-burning test of each fire source was conducted for reference. The doors were first opened during the period equal to that in the suppression experiments and then closed. The measurements of the temperatures and the gas concentrations were continued without agent discharge. Figure 2 shows the variation in the concentrations of CO, CO,, O,, and NO, during the free-burning test of the wood crib and plots the mean values of the measurements at the upper and the lower sampling locations. It is seen that the O, concentration decreases rapidly after the doors are closed at 265 sec. Initial increases in CO, and NO, were replaced by a significant increase in CO. The fire intensity was reduced when the O, concentration reached approximately 13%, resulting in concentrations of CO, CO,, and NO, that all decreased gradually. The 0.1 and 0.2 $m^2$ heptane pan fires were completely self-extinguished 25.5 and 12 min after closing the doors, respectively, due to the $O_2$ depletion.

Maximum CO, CO,, and HF concentrations and the minimum O, concentrations observed during the suppression experiments are shown in Figure 3 as a function of the fire size. In Figures 3a, b, and d, IDLHs [1] for the corresponding gases are also shown for comparison. The concentrations of NO, are

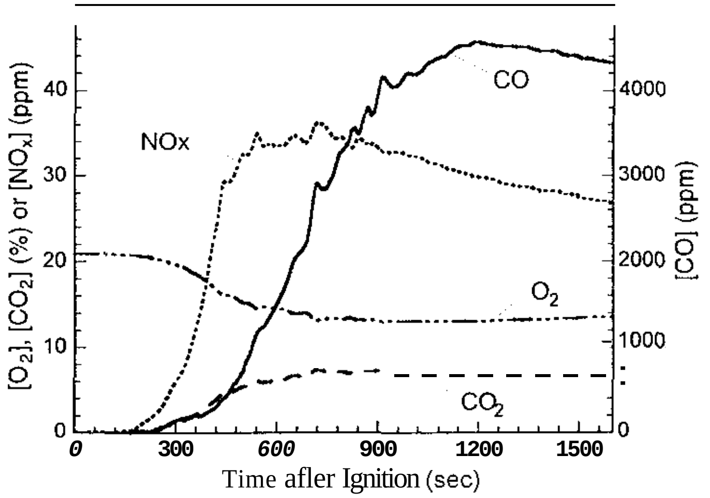

Figure 2. Variation in the concentrations of CO, CO,, $O_2$, and NO, during the free-burning test of the wood crib.

not plotted because they never exceeded even half of the IDLH value (20 ppm) for all the suppression experiments. It is seen in Figures 3a and b that the maximum CO and CO, concentrations during suppression by any agent are lower than that for the free-burning tests. It has been suggested that the inert agents can enhance the production of CO due to the significant **O,** depletion [2]. Although the present study showed that the discharge of the inert agents causes an instant promotion of the CO production, the maximum CO concentrations were found to be lower than the IDLH of 1200ppm.

For the heptane fires, the maximum CO, CO,, HF, $CF_2O$ and the minimum **O,** Concentrations all showed linear correlation with the fire size. The results clearly show that the fire size at the time of agent discharge is of critical importance to ensure safety of the halon replacement total-flooding systems. In Figure 3a, HFC-227ea shows the most significant increase in the maximum CO concentration with an increase in the heptane fire size among the agents. The suppression of the 230 kW heptane fire by HFC-227ea caused CO production over IDLH. The remarkable CO production during suppression by HFC-227ea was also observed by **Su** and Kim [3]. The magnitude of the increase in the maximum CO, concentration in Figure 3b shows an insignificant difference between the agents. For IG-541, however, the concentration of CO, exceeds the IDLH when the fire size is greater than 1SO kW as the agent itself contains CO,. The **O,** depletion by the inert agents was found to be more serious than the production of CO and CO,. The minimum **O,** concentrations after the suppression of 420 kW fires by the inert agents reached 8.8%, which was significantly lower than the design concentrations of over 12%.

**As** seen in Figure 3d, the concentration of HF significantly exceeded the IDLH of 30 ppm even for the minimum size of the test fires when the HFCs were discharged. The maximum $CF_2O$ concentrations were found to be always within 10 and 20% of the maximum HF concentrations, which is in good agreement with the results reported by Williams et al. [4]. The total F ([HF] +2[$CF_2O$]) concentrations measured by the ion chromatograph were within 60 and 90% of the FT-IR measurements. The discrepancies may be attributed to the losses during the sampling and the transfer processes before the injection into the ion chromatograph.

The 5-min average HF concentration data measured by the FT-IR in the present work were compared with literature data [5-8] in Figure **4,** as a function of fire size to room volume ratio. The production of HF is dependent on the type and the discharge concentration of the agents, the discharge time, and thetype of the fuel [5-9]. To eliminate the influence of these variables, only data obtained for liquid hydrocarbon fires using fluorinated hydrocarbons (HFC) or perfluorocarbons (PFC) with the design concentrations of the cup-burner flame extinguishing concentrations multiplied by 1.2 and the discharge time of approximately 10 sec are included in Figure 4. It is seen that the present results are in good agreement with those of Su et al. [5], while the earlier data [6-8] are all lower than the present data at

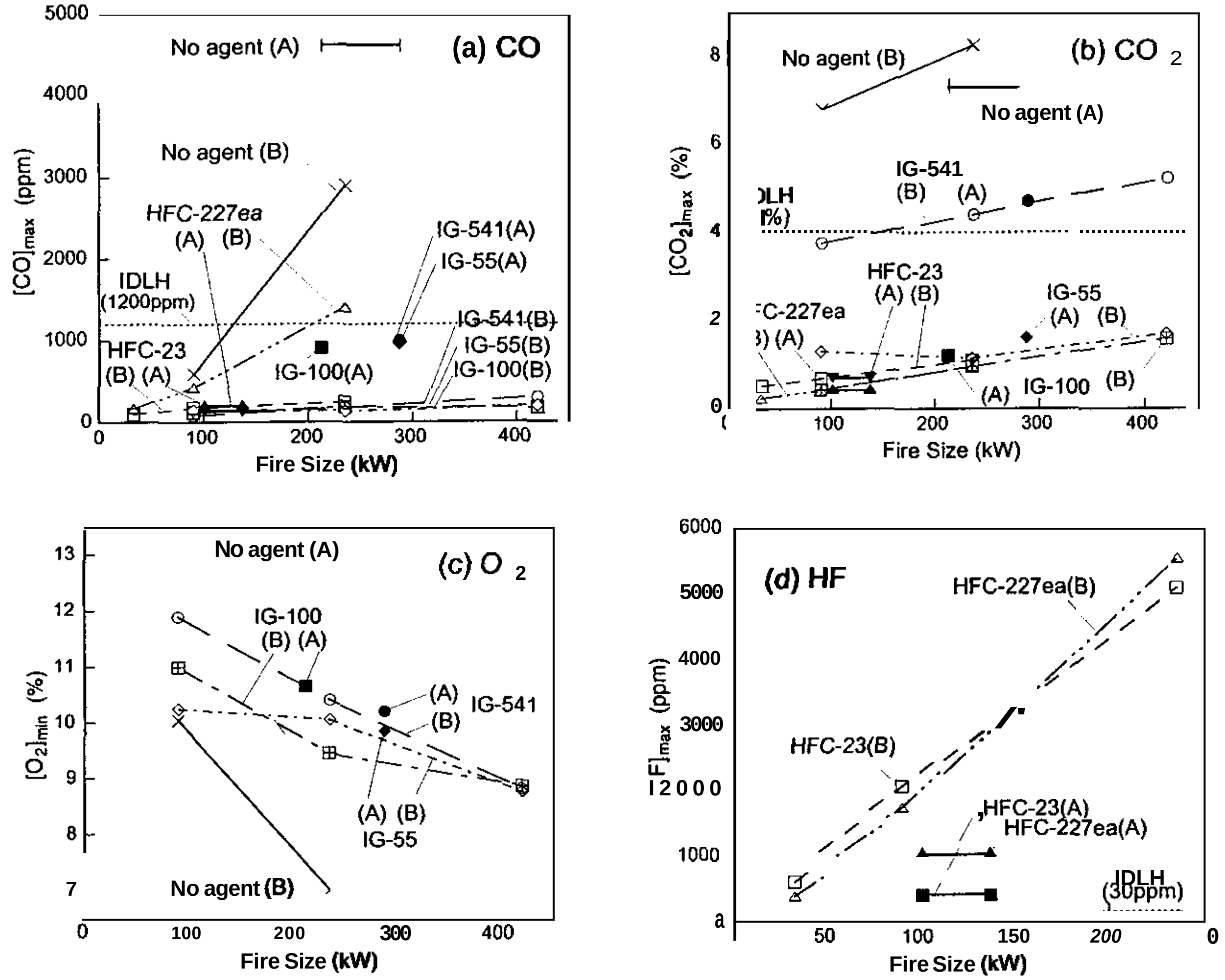

Figure 3. Variation in the maximum CO, CO,, HF, and the minimum O, concentrations during the suppression experiments, as a function of the fire size. (A) and (B) denote the wood crib fire and the heptane pan fire, respectively. The mean values of the measurements at the upper and the lower sampling locations are plotted. Data for the free-burning tests are also plotted, as a function of the corresponding fire size at the time of agent discharge in the suppression experiments.

larger fire size to room volume ratios. The difference may be attributed in part to the decay speed of the HF concentration. In the present study, the decay was found to be slightly less significant for larger fire size to room volume ratios, which is in contrast to the observations by Peatross and Forssell [8], who found that the HF concentration decays more quickly for larger fire size to room volume ratios. Their results can be attributed to the difference in wall material and wall surface area between the test rooms, while the influence of these parameters is eliminated in the present study.

The present results in Figure 4 show an approximately linear relationship between the HF concentration and the fire size to room volume ratio. On the other hand, the production of HF by the decomposition of **HFCs** is known to be approximately 7 times greater than that from Halon 1301. Recognizing that fires grow in proportion to the square of time, fire detection systems must he designed to detect fires more than 2.6 times faster than that for the Halon 1301 total-flooding systems, to ensure safety of the HFC systems equal to that of the Halon 1301 systems.

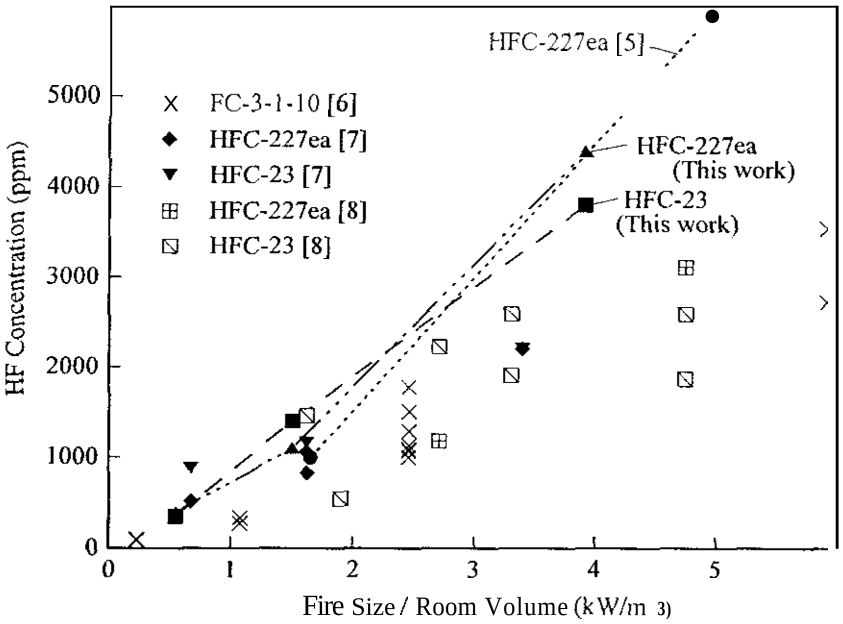

Figure 4. Average HF concentration vs. fire size to room volume ratio.

## RISK ASSESSMENT USING TOXICITY INDEX

To compare between potential risks associated with different toxic gases, a universal measure of toxicity is required. For this purpose we introduce a toxicity index, which was tentatively defined as

$$TI = Max\{[X]/\mathrm{IDLH}_X\} \tag{1}$$

Here *TI*, **X,** and [X} denote the toxicity index, a species name in the test room, and the concentration of the species **X,** respectively. That is, *TI* is the normalized concentration of the species that possesses the largest relative concentration to the IDLH in the test room.

In Figure 5, variations in the toxicity index during the suppression of the wood crib fire by various agents are compared with that for the free-burning test. The results show that the *TI,* after the suppression by the inert agents, is approximately one fourth of the maximum *TI* for the free-burning test, while the maximum *TI* during the suppression by HFC-227ea is 10 times greater. We should note that the wood crib fire gave the largest ***TI* for** the inert agent and the free-burning tests among all the fire sources employed in the present study, while it gave the smallest *TI* for the HFCs. Thus the difference in *TI* between the inert agents and the HFCs is more significant for the heptane fires.

Using the present results in Figure 4, the 5-min average Tl for the suppression of heptane fires by HFCs can be related to the fire size to room volume ratio as follows:

$$TI_{\mathrm{HFC}} = 36 \times Q(\mathrm{kW})/V(\mathrm{m}^3) \tag{2}$$

Here *Q* and *V* denote the fire size and the room volume, respectively. **Eq.** (2) shows that the HF concentration reaches at least 14 times greater than the IDLH even with modern fire detection systems that can detect fires in the range 0.4 to 0.7 kW/m$^3$ [9]. The maximum *TI* for the suppression of heptane fires by IG-100 is found to be approximately 0.17% of $TI_{\mathrm{HFC}}$, that is:

$$\mathrm{TI}_{,,} = 0.06 \times Q(\mathrm{kW})/V(\mathrm{m}^3) \tag{3}$$

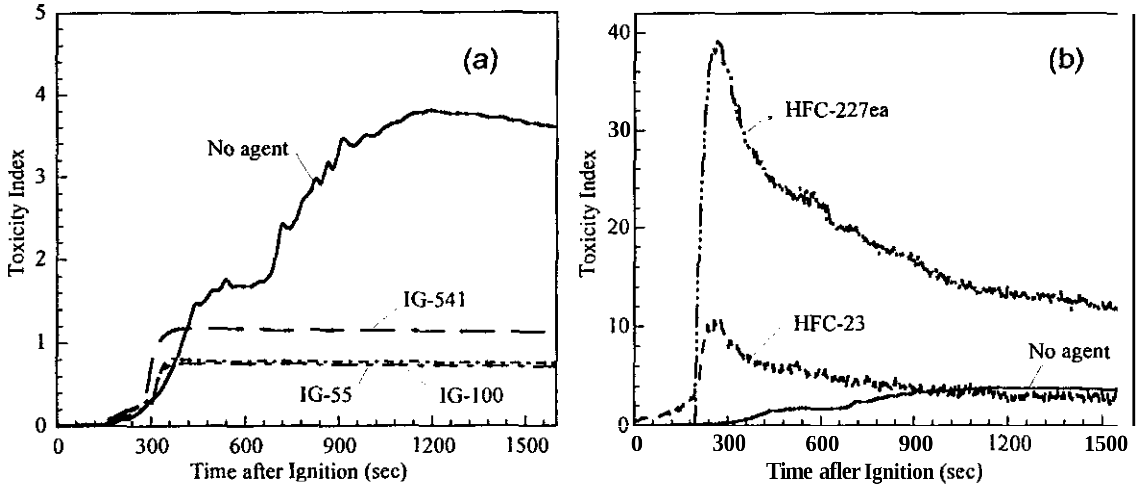

Figure 5. Variation in the toxicity index during the suppression by (a) the inert agents, (b) the HFCs, or the free-burning tests for the wood crib fire. Fire size at the time of agent discharge was 212-287 kW for the inert agents and 101-137 kW for the HFCs.

In the event that the agent discharge is delayed or the suppression results in failure, the large coefficient in Eq. (2) must bring an extremely dangerous condition, which may cause difficulty in firefighting and rescue work. A maximum permissible coefficient of TI should be considered in the course of establishing the safety standards on halon replacement agents.

## OVER- AND UNDER-PRESSURIZATION OF COMPARTMENT

Figure 6a shows the variation in the maximum room pressure observed during the suppression of the heptane pan fires, as a function of the fire size. Although results for IG-100 are not plotted because of incomplete measurement, they are estimated to be between the data for **IG-541** and **IG-55.** It is seen in Figure 6a that the maximum pressure increases with an increase in the fire size for all the agents. During the free-burning tests with the doors closed, the pressure relief vent was opening slightly and the room pressure was kept at a constant value of approximately 20 mm $H_2O$ regardless of the fire size. On the other hand, when the agents were discharged, the room pressure was raised before the vent opened completely. When HFC-23 was discharged against the 0.2 $m^2$ heptane pan fire, significant over-pressurization broke a spike and generated a crack between the ceiling and a wall. These results indicate that the maximum room pressure estimated using the following equation based on the Bernoulli's theorem is not always valid.

$$p = \frac{\rho(L_{max}/A)^2}{2} \tag{4}$$

Here $p$, $\rho$, $L_{max}$ and $A$ denote the room pressure, the density of air, the maximum discharge rate of agent, and the area of the pressure relief vent, respectively.

Figure 7 shows variation in the room pressure during the suppression by various agents. During the suppression of the heptane fires, the room pressure does not decay monotonously after reaching the peak but shows complicated variation of repeating rise and fall, as seen in Figure 7a. It is also seen in Figure 7a that the negative pressure is observed after the extinguishment at 60 sec. The magnitude of the negative pressure was also found to increase with an increase in the fire size for all the inert agents and for HFC-23. Figure 7b shows the room pressure variation during the suppression of the 0.2 $m^2$ heptane pan fire by HFC-23. The over-pressurization reached near 300 mm $H_2O$, which was followed by a rapid drop causing remarkable under-pressurization. When the room pressure reached approximately -60 mm $H_2O$ a

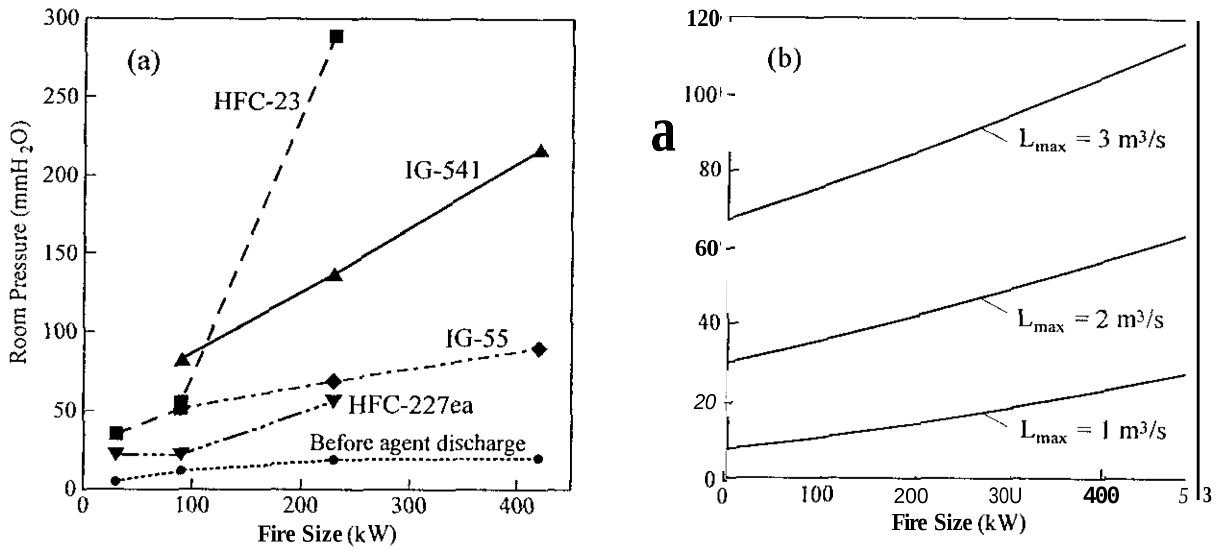

Figure 6. Variation in (a) the measured maximum room pressure during the suppression of the heptane pan fires and (b) the room pressure estimated by employing the chemical equilibrium calculation with various agent discharge rate, as a function of the fire size

door latch came off and the door was opened completely. The discharge of HFC-23 against smaller sizes of heptane fire did not result in such a drastic variation in pressure.

Figure 7c shows the room pressure variation during the suppression of the 0.05 and 0.2 $m^2$ heptane pan fires by HFC-227ea. In contrast to the pressure variation with HFC-23, the over-pressurization during the suppression by HFC-227ea was preceded by noticeable under-pressurization. The magnitude of this initial under-pressurization due to the discharge of HFC-227ea was found to be more significant for smaller fire sizes. The difference in the initial pressure variation between HFC-23 and HFC-227ea can be attributed to the vapor pressures of these agents. The initial under-pressurization similar to the results in Figure 7c was also observed for FC-3-1-10 [10].

Figure 7d shows the room pressure variation during the suppression of the wood crib fire by IC-541. It is seen that the pressure is decreased monotonously after reaching the peak, which is in contrast to the results of Figure 7a. The peak over-pressurization during the suppression of the wood crib fire was always smaller than that for the heptane pan fire of the equal heat release rate. The results imply that the room pressure variation is dependent on the type of fuel as well as the type of agent.

The strong dependence of the maximum room pressure on the fire size shown in Figure 6a clearly reveals that the over-pressurization during suppression is caused not only by the agent discharge but also by the expansion of gases due to the combustion. Thus it is necessary to add a term for the gas expansion into Eq. (4) to estimate the maximum room pressure properly. In the present study, the chemical equilibrium calculation was employed to estimate the gas expansion term. Complete combustion of n-heptane with air of 25 °C under the adiabatic condition results in the gas volume approximately **8.2** times as much as that unburned. Then the gas expansion rate $U$ is obtained as a function of the heat release rate of heptane fire. Figure 6b shows the maximum room pressure estimated using the following equation,

$$p = \frac{\rho[(L_{\max} + U)/A]^2}{2} \qquad (5)$$

Eq. (5) was derived on the assumption that $U$ is independent of the agent discharge. The maximum agent discharge rate $L_{\max}$ was found to be within the range of 0.7 to 2.4 m³/sec in the present study, where the

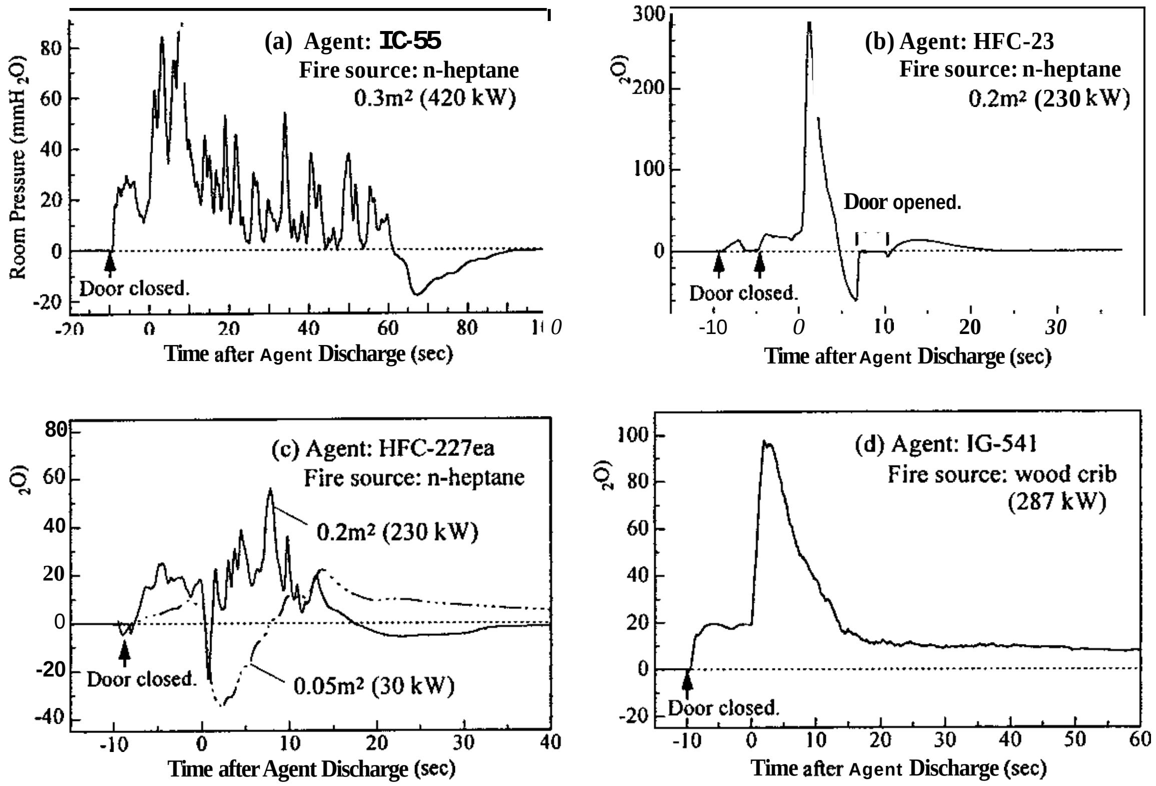

Figure 7. Variation in the room pressure during suppression by the halon replacement agents

maximum room pressure $p$ estimated using Eq. (5) never exceeds 100 mm $H_2O$ within the fire size range employed, as seen in Figure 6b. The significant discrepancy between the results of Figures 6a and b implies that the agent discharge enhances the fire intensity; i.e., $U$ must be a function of $L_{max}$. Deflagration induced by the discharge of halon replacement agent was recently reported [11]. Recognizing these results, application of the total-flooding systems to volatile liquid fuel fires has a potential risk of compartment destruction due to the rapid mixing of unburned vapor with air.

## CONCLUSIONS

The effect of fire size on the toxic gas formation, the oxygen concentration, and the pressure variation in a fire compartment during suppression by total-flooding fire extinguishing systems was investigated experimentally. The maximum CO, $CO_2$, HF, $CF_2O$, and the minimum $O_2$ concentrations all showed linear correlation with the fire size. The concentrations of HF and $CF_2O$ significantly exceeded the IDLH even for the minimum size of the test fire with the HFCs, while the CO concentrations never exceeded the IDLH during suppression by the inert agents. A maximum permissible level of the toxicity of combustion products should be considered to establish the safety standards on halon replacement agents. Remarkable over- and under-pressurization in the compartment, strongly dependent on the fire size, were observed during the suppression. The results show that the current venting design is not sufficient to prevent the over- and/or under-pressurization during suppression of larger fires.

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