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CASE REPORT

ENGINEERING SCIENCES

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Using Fire Dynamics Simulator to Reconstruct a Hydroelectric Power Plant Fire Accident

ABSTRACT: The location of the hydroelectric power plant poses a high risk to occupants seeking to escape in a fire accident. Calculating the heat release rate of transformer oil as 11.5 MW/m^2, the fire at the Taiwan Dajia-River hydroelectric power plant was reconstructed using the fire dynamics simulator (FDS). The variations at the escape route of the fire hazard factors temperature, radiant heat, carbon monoxide, and oxygen were collected during the simulation to verify the causes of the serious casualties resulting from the fire. The simulated safe escape time when taking temperature changes into account is about 236 sec, 155 sec for radiant heat changes, 260 sec for carbon monoxide changes, and 235–248 sec for oxygen changes. These escape times are far less than the actual escape time of 302 sec. The simulation thus demonstrated the urgent need to improve escape options for people escaping a hydroelectric power plant fire.

KEYWORDS: forensic science, fire accident, heat release rate, hydroelectric power plant, fire dynamics simulator, fire hazard factors, escape time

Owing to global energy shortages, the development of environmentally friendly and sustainable substitute energy is actively proposed by a number of nations. Hydroelectric power has the benefit of little detrimental impact on the environment, and it also helps in flood prevention and provides reservoirs for a variety of benefits. However, hydroelectric power plants are commonly constructed in underground locations, which can greatly increase the potential fire risks and serve as a detriment to escaping from a fire.

To improve the fire safety of existing hydroelectric power plants and set a reference point for future ones, this study analyzed the fire at the Taiwan Dajia-River hydroelectric power plant, which involved six deaths and 26 injuries. Using a computer simulation, the characteristics of fire hazard especially at hydroelectric power plants were discussed. The information of this study can serve as a reference for fire escape and personnel's protection at hydroelectric power plants to reduce the fire casualties.

Fire Scene Observation

The worst fire case recorded at a hydroelectric power plant in Taiwan was selected to study. From the investigation of site, this study gleaned the locale information to complete a sectional drawing of the case, as shown in Fig. 1. The research team also conducted interviews with fire survivors. After all the collected information was processed, the fire dynamics simulator (FDS) version 4.05 computer-simulated program was used to reconstruct the fire scene. The result of computerized fire simulation was compared with the real fire scene to study the main cause of the deaths and injuries from this particular fire.

The aforementioned fire took place at the Taiwan Dajia-River hydroelectric power plant at around 4 PM on October 28, 1993. When it occurred, the hydroelectric power plant was running under testing mode before construction completion. It is suspected that improper operation caused the oil inside the transformer to start the fire. From there, the fire rapidly burned down the transformer room and spread to the surrounding areas. The fire spread so fast and furiously that it destroyed any escape path, resulting in serious casualties.

Simulation of Fire Space

After on-site investigations and interviews, it was discovered that the fire started in the transformer room. There was a transformer set which was constructed of flammable polyurethane and contained 38.1 m^3 of transformer oil. Next to the transformer room was a machine installation platform and the main egress lane. The machine installation platform was used to maintain and repair the generator set, while the main egress lane was accessed by employees and repair vehicles. The main egress lane connected with a 300-m-long cable tunnel to reach outside, as shown in Fig. 1.

When the fire started, the only escape route was through the machine installation platform to the main egress lane and cable tunnel. The ignition transformer room was not airtight, and there was a rolling steel door about 8 m wide, 5 m tall, and 1.2 mm thick between the transformer room and main egress lane, and two aluminum blinds each about 2.5 m wide and 1.5 m tall between transformer room and machine installation platform, as demonstrated in Fig. 2*d*. The rest of the transformer room surroundings were concrete walls about 20 cm in depth.

For computer simulation analysis, the heat release rate (HRR) calculation of combustible materials at a fire scene plays a very

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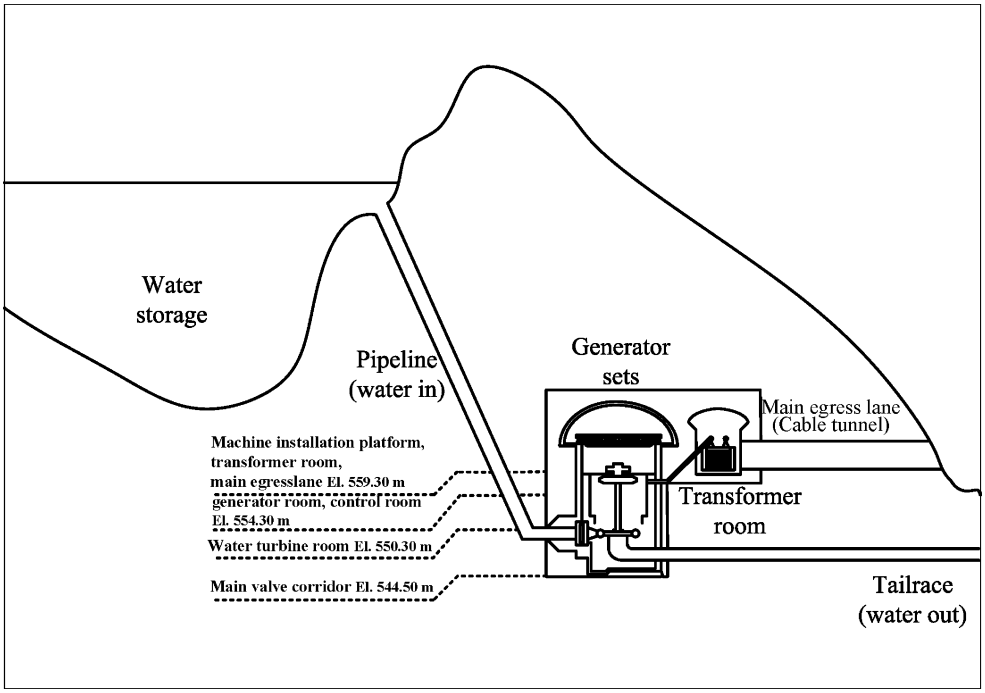

FIG. 1—*Sectional drawing of Taiwan Dajia-River hydroelectric power plant.*

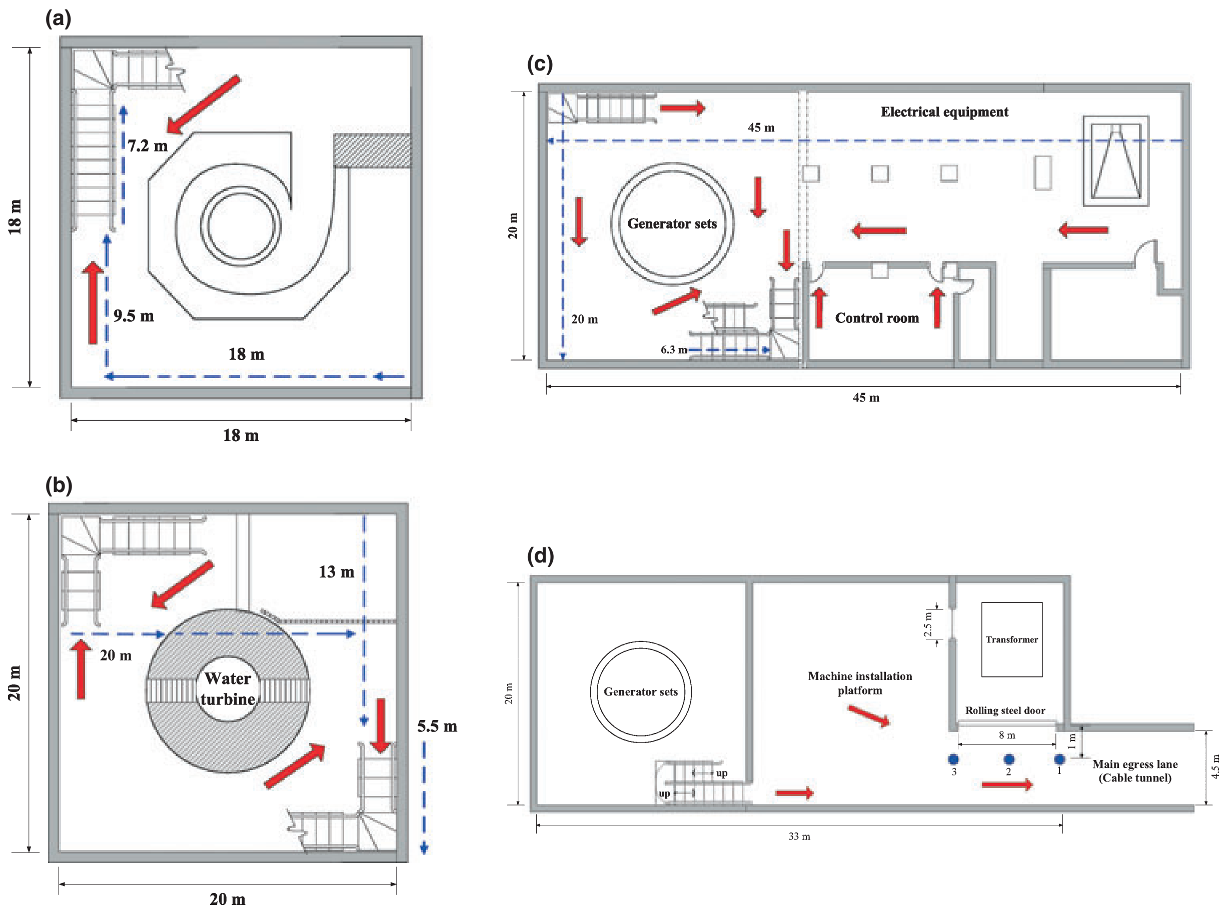

FIG. 2—*Section layout of the hydroelectric power plant. (Bold arrows indicate the escape route and dotted arrows indicate the travel distance.) (a) Main valve corridor (EL. 544.50 m); (b) water turbine room (EL. 550.30 m); (c) generator room and control room (EL. 554.30 m); and (d) machine installation platform, transformer room, and main egress lane, spots indicate the sensor location (EL. 559.30 m).*

important role as it affects the results of the overall simulation (1). For the case study, the fire initiation area was the transformer room and the combustible material was the transformer oil. The volume of transformer oil was 38.1 m^3, multiplied by its density (889.9 kg/m^3) (2), and the weight of transformer oil was almost 3.39×10^4 kg. Based on on-site investigation, two data were collected, the transformer area $A = 6.4\ m \times 3.0\ m = 19.2\ m^2$ and burning time $t = 7200$ sec. With the burning heat of transformer oil $\Delta H = 3920$ kJ/mol and its molecular weight MW = 84 (2), this study adopted the method used to calculate the HRR of gasoline in the research of Shen et al. (3), and the HRR is calculated as below:

$$\begin{aligned} Q(\mathrm{kW/m^2}) &= \Delta H(\mathrm{kJ/mol}) \times W/\mathrm{MW(mol)} \times 1/A(1/\mathrm{m^2}) \\ &\quad \times 1/t(1/\mathrm{sec}) \\ &= 3920(\mathrm{kW\,sec/mol}) \times 3.39 \times 10^4/84(\mathrm{mol}) \\ &\quad \times 1/19.2(1/\mathrm{m^2}) \times 1/7200(1/\mathrm{sec}) \\ &\approx 11{,}500(\mathrm{kW/m^2}) = 11.5(\mathrm{MW/m^2}) \end{aligned} \qquad (1)$$

Simulation Results and Analyses

The FDS computer simulation results have shown that the fire quickly spread after the ignition in the transformer room, as delineated in Fig. 3*a*. As the room temperature increased, the aluminum blind fractured about 15 sec after fire ignited, as shown in Fig. 3*b*. The flame and smoke then rapidly spread to the machine installation platform outside and extended to main egress lane used for fire escape, as shown in Fig. 3*c,d*. Not only did the broken window provide a path for the fire to reach outside the transformer room, but it also brought in additional air to fuel the fire. Figure 4*a–d* show that the curves move dramatically from 180 to 240 sec after fire began, which is believed to be related to the broken window.

To examine the escape risks in the main egress lane during the fire, this study set up three sensors: two at each side and the third one at the midpoint of the steel rolling door of transformer room at 1 m ahead of the door along the main egress lane, as depicted in Fig. 2*d*. The sensors were installed 1.8 m above the ground, which is the average height of a walking evacuee's nose and mouth according to the information by the Architecture and Building Research Institute (ABRI), Ministry of the Interior, Executive Yuan, Taiwan (4). The changes over time of temperature, radiant heat, carbon monoxide, and oxygen at each detection point were collected by the sensors (Fig. 4*a–d*). From Fig. 4*a*, it is shown that the main egress lane temperature reached 60°C in 180 sec after the ignition and rose to 120°C in 236 sec. The rising temperature would lower the evacuees' chance of escaping the fire safely (5). The research has showed that the radiant heat should not exceed 2.5 kW/m^2; otherwise, humans would not be able to tolerant the heat within 5 min and would incur injury (6). According to Fig. 4*b*, the radiant heat in the main egress lane already reached 2.5 kW/m^2 in 155 sec after

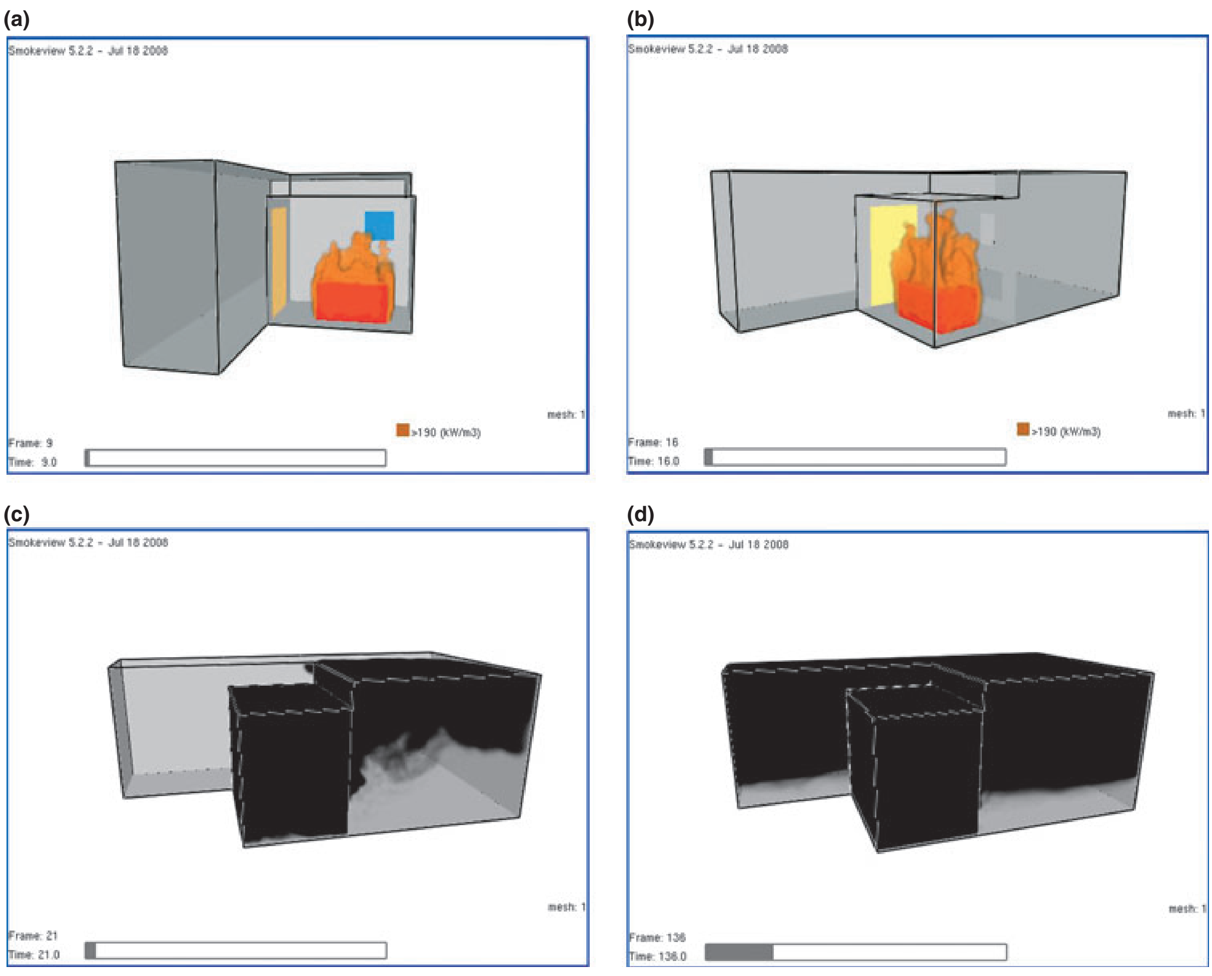

FIG. 3—*Fire and smoke spread profile of simulation; (a) 9 sec after fire ignited; (b) 15 sec after fire ignited, the aluminum blind fractured; (c) 21 sec after fire ignited; and (d) 136 sec after fire ignited.*

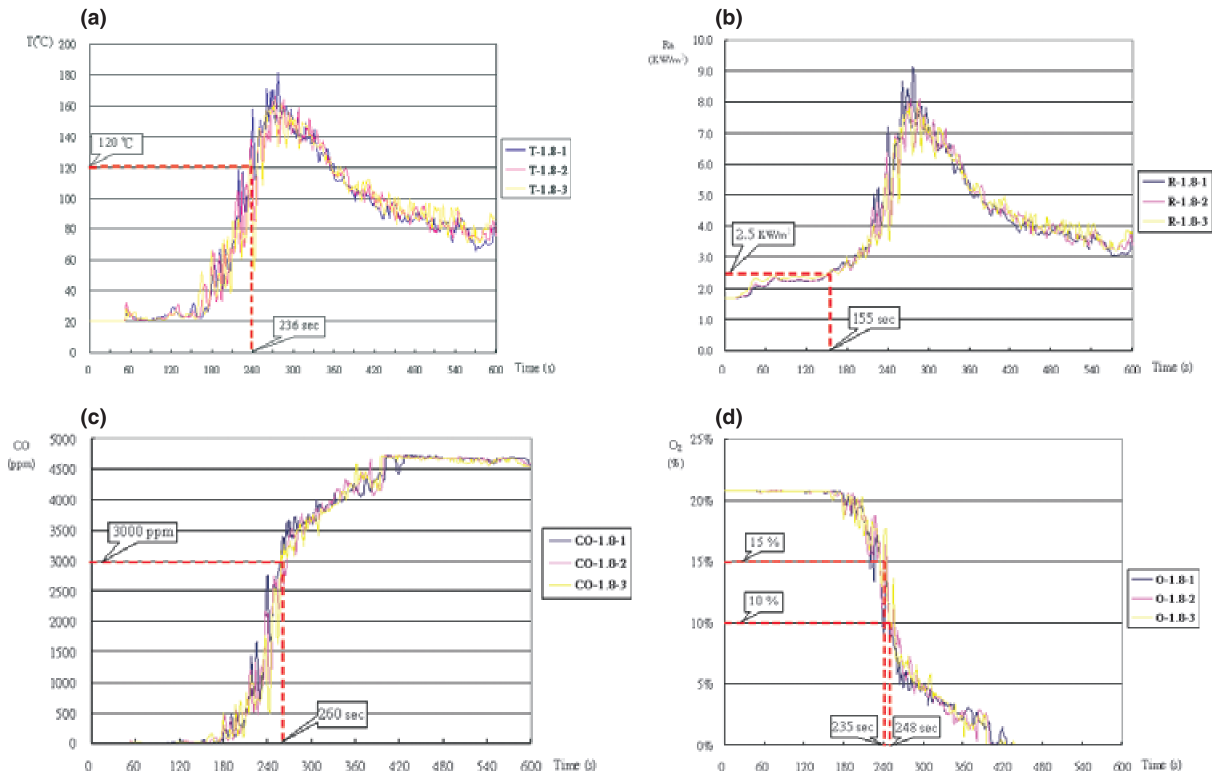

FIG. 4—*Variation of the fire hazard factors of simulation; (a) temperature; (b) radiant heat (c); carbon monoxide; and (d) oxygen.*

the fire started. By Fig. 4*c*, the density of carbon monoxide at the main egress lane reached 3000 ppm in 260 sec after the ignition, which exposes the possibility of choking and death from breathing in too much smoke during the fire escape (5). Moreover, evacuees are likely to make mistakes owing to fatigue when oxygen levels go from 14% down to 10% (5). Figure 4*d* shows that the oxygen level at the main egress lane was 15% in 235 sec after the fire started and then down to 10% in 248 sec after the fire began.

Calculation of Actual Escape Time

To distinguish the difficulty of fire escape for evacuees from the fire, the formulae developed by ABRI (4) were adapted to calculate the actual escape time of this fire.

By Fig. 1, inside the underground hydroelectric power plant, the main valve corridor was located at the deepest section, an elevation of 544.50 m above sea level. The water turbine room was located at the second deep section, an elevation of 550.30 m above sea level. Upper section included the generator room and control room, an elevation of 554.30 m above sea level. The nearest section to the ground was the machine installation platform, transformer room, and main egress lane, an elevation of 559.30 m above sea level. The floor layouts of each section are diagrammed in Fig. 2. In calculating the actual fire escape time, it was assumed that the evacuees stayed farther away from main egress lane at the main valve corridor and had to go through all the aforementioned floors to escape. Based on related formulae (4) by ABRI, the actual escape time that the personnel spent is calculated as following:

$$t_{\text{escape}} = t_{\text{start}} + t_{\text{travel}} + t_{\text{queue}} \tag{2}$$

where t_{escape} is escape finish time (min), includes three durations: t_{start}, the escape start time, the time between fire started and evacuees perception; t_{travel}, the escape travel time, the traveling time for evacuees from any location to exit point; and t_{queue}, the queue time, the time for all evacuees pass through the exit.

- Calculation of escape start time (t_{start})

$$t_{\text{start}} = \frac{\sqrt{\sum A_{\text{area}}}}{30} = \frac{\sqrt{A_1 + A_2 + A_3 + A_4}}{30} \tag{3}$$

where A_{area} is the total floor area (m^2), A_1 to A_4 is the floor area of each section, as depicted in Fig. 2*a–d*, the calculation is A_1 = 324 (m^2), A_2 = 400 (m^2), A_3 = 900 (m^2), and A_4 = 660 (m^2).

TABLE 1—*Calculations of escape travel time* (t_{travel}) for the investigated case.

Space	Situation	Travel Distance l_i (m)	Travel Speed v (m/min)*	Travel Time l_i/v (min)	Subtotal t_{ti} (min)
Main valve corridor	Stairs	7.2	35	0.206	0.559
	Nonstairs	18	78	0.231	
	Nonstairs	9.5	78	0.122	
Water turbine room	Stairs	5.5	35	0.157	0.58
	Nonstairs	20	78	0.256	
	Nonstairs	13	78	0.167	
Generator room	Stairs	6.3	35	0.18	1.013
	Nonstairs	45	78	0.577	
	Nonstairs	20	78	0.256	
Machine installation platform	Stairs	5.5	35	0.157	0.631
	Nonstairs	20	78	0.256	
	Nonstairs	17	78	0.218	

*v refers to the set travel speed of personnel at workplace by ABRI (8).

TABLE 2—*Calculations of queue time* (t_{queue}) for the investigated case.

Space	Occupant Density p (p/m^2)	Floor Area A_{area} (m^2)	Effective Flowing Coefficient N_{eff} (p/min/m)*	Effective Exit Width B_{eff} (m)	Subtotal t_{ti} (min)
Main valve corridor	0.04	324	90	1	0.144
Water turbine room	0.04	400	90	1	0.178
Generator room	0.04	900	90	1.5	0.267
Machine installation platform	0.04	660	90	4.5	0.065

*N_{eff} is the set value considering the capacity of main egress lane is enough for all evacuees (8).

Thus, $t_{start} = \frac{\sqrt{\sum A_{area}}}{30} = \frac{\sqrt{324+400+900+660}}{30} = 1.59\,(\text{min})$

- Calculation of escape travel time (t_{travel})

$$t_{travel} = \max\left(\sum \frac{l_i}{v}\right) = \sum_{i=1}^{4} t_{ti} = t_{t1} + t_{t2} + t_{t3} + t_{t4} = 0.559 + 0.58 + 1.013 + 0.631 = 2.783\,(\text{min}) \quad (4)$$

where l_i is the travel distance from any location to exit point (m), v is travel speed (m/min), which v is 35 m/min on stairs and 78 m/min on nonstairs (4). t_{t1} to t_{t4} is the travel time to exit point on each section. The calculation is detailed in Table 1.

- Calculation of queue time (t_{queue})

$$t_{queue} = \frac{\sum pA_{area}}{\sum N_{eff}B_{eff}} = \sum_{i=1}^{4} t_{qi} = t_{q1} + t_{q2} + t_{q3} + t_{q4} = 0.144 + 0.178 + 0.267 + 0.065 = 0.654\,(\text{min}) \quad (5)$$

where p is occupant density (p/m^2), acquired from the on-site investigation as 0.04 (p/m^2). A_{area} is total floor area (m^2), N_{eff} is effective flowing coefficient (p/min/m), acquired from the reference as 90 (p/min/m) (4), and B_{eff} is effective exit width (m). The calculation is given in Table 2.

- Actual escape time (t_{escape})

Using Eq. 2,

$t_{escape} = t_{start} + t_{travel} + t_{queue} = 1.59 + 2.783 + 0.654 = 5.027$ (min) = 302 (sec)

Verification on Real Fire Scene

As mentioned previously, the actual escape time of an evacuee is calculated to be about 5.03 min (302 sec). However, the computer simulation results from the detection point on the main egress lane reveal that the simulated safe escaping time is about 236 sec, taking into account changes in temperature, of 155 sec, changes in radiant heat, of 260 sec, changes in carbon monoxide, and about 235–248 sec for changes in oxygen level. These escape times are far under the actual escape time spent, 5.03 min (302 sec); thus, it was difficult for evacuees to escape after the fire began, which resulted in the tragic deaths of six and 26 injuries.

According to the fire investigation report, the fire area was located in a cave that is tens of meters under ground. The changing curve in Fig. 4*d* reveals the fire circumstance mentioned earlier. After the fire occurred, oxygen levels dropped quickly and the fire area went into an incomplete burning stage. Then, smoke rapidly spread over the fire area, as diagrammed in Fig. 3*d*.

Based on Fig. 4*a*–*d*, among all the fire hazards, radiant heat caused the most damage to fire escape. Figure 4*b* shows that less than 155 sec after fire started, radiant heat levels detected by the sensor at main egress lane would severely harm evacuees. The study results match what was found in the fire investigation that of 26 injuries, several people injured in the fire later died of severe burns.

At 400 sec after the fire occurred, oxygen levels dropped to almost zero, as shown in Fig. 4*d*. This matches the results from the fire investigation that five of six fire victims died from lack of oxygen.

Conclusions

The HRR of transformer oil used in hydroelectric power plants was calculated in this study to be as high as 11.5 (MW/m^2). Compared to a burning car, this rate is between a compact car and a van (7), which reveals how high the fire intensity was. Based on the computer simulation results, there were only 180–240 sec for evacuees to safely escape. However, to effectively generate power, the hydroelectric power plant generator is located as deep as tens or hundreds of meters underground. Therefore, when a fire occurs, especially in a transformer room next to the cable tunnel that is also used as main egress lane, the extremely high fire intensity would make it very difficult for evacuees to escape safely (8,9).

From the simulation results, the fractured aluminum blinds of the transformer room played a critical role in spread of flame and smoke. To avoid future similar fire tragedies, the openings in the transformer room should sustain 1+ hour of fire resistance and automatic sprinkler and fire smoke systems should be equipped as they are in the long tunnel or even provide more than two escape routes (10). Additionally, for protecting the trapped evacuees, personnel at the hydroelectric power plant should carry a breathing apparatus that provides oxygen effectively up to 60 min, and several emergency shelters should also be provided (11,12). It is expected that these suggestions will enhance the fire prevention and safety of both existing and future hydroelectric power plants to minimize the fire casualties.

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