Risk-informed Emergency Response Training for Backdraft in Nuclear Power Plants

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Abstract: Research has been conducted for developing fire evacuation and response training programs for nuclear power plant (NPP) application. Among numerous fire scenarios that may occur in an NPP environment, three different points of origin for a fire were selected for the program based on a risk-informed approach: switchgear room, main control room, and safety injection pump room. Fire outcomes were predicted for these scenarios via numerical modeling and the results were incorporated into the newly developed fire evacuation and response training program for the APR1400, Korea’s next-generation NPP model. The switchgear room fire scenario was found to have the most potential for backdraft to occur during manual fire response following automatic gaseous fire suppression system activation. The emergency response manual does discuss this possible backdraft occurrence; however, the guidance to avoid injuries is qualitative, such as to be cautious of backdrafts and wait a sufficient amount of time after opening a door before entering the. In this study, backdraft phenomenon that may occur from a switchgear room fire was numerically examined using the recent version of the Fire Dynamics Simulator to develop an appropriate timeline to be implemented in the fire evacuation and response training program. Based on the findings, the following guidance is provided: (1) backdraft can only occur when the fire originates in the space near the door; (2) wait at least 10 minutes after opening the door before entering the room; (3) watch for rapid smoke production, as this may be an antecedent phenomenon of backdraft; and (4) when smoke production increases rapidly, leave the room as soon as possible to avoid being caught within the deflagrating flames from a backdraft.

Keywords: Nuclear power plant (NPP); Fire evacuation and response training; Backdraft

1. Introduction

Extended reality (XR) technologies such as augmented reality (AR), virtual reality (VR), and mixed reality (MR) have evolved rapidly over the past few decades. Currently, these technologies are being actively applied in various areas including entertainment, marketing, maintenance, and healthcare. They can provide users with various experiences by transferring massive amounts of information through different human sensory systems. Considering the potential strength in these technologies, research has been conducted to apply this tool to develop a fire evacuation and response training program for nuclear power plant (NPP) application. When XR technologies are applied to training programs for fire situations in an NPP, trainees may practice finding solutions and applying them competently in stressful, life-threatening environments without risking any lives. The newly developed XR training program is expected to have significant implications for enhancing the fire safety of NPPs when utilized properly.

The first step in developing a fire evacuation and response training program for NPP application is to select fire scenarios. XR technologies are typically expensive to implement; therefore, some of the various fire scenarios that may occur in the NPP environment must be prioritized as models in the training program. As the typical fire-protection philosophy for NPPs is risk-informed and performance-based, a similar approach was taken to select three fire scenarios for the training program. Statistical research conducted in the 1990s by the Electric Power Research Institute.
Institute in the United States found that the highest contributors to core damage frequency (CDF) were fires occurring in control and switchgear rooms[1]. In addition, fire ignition frequencies were found to be high for electrical cabinets, off-gas/H2 recombiner (BWR) and pumps, occurring in the $10^{-2}$ per year range[2]. For these reasons, switchgear room, main control room, and safety injection pump room fire scenarios were considered for program development.

Efforts have been made in creating the fire evacuation and response training program to computationally study changes that occur in the environment during fire situations. The fire dynamics within the room where the fire originated and nearby compartments impact the effectiveness of fire evacuation and response. Hence, numerical modeling was applied to predict the effects of smoke production and build-up within the room, heat generation, and impingement on people and objects. The modeling results provide information on tenability within the space, which is necessary to create fire training simulations similar to real-world situations in an XR-based program.

Three fire scenarios were studied using Fire Dynamics Simulator (FDS) version 6. Among the three cases, the modeling results from the switchgear room fire case demonstrated the potential for the backdraft phenomenon to occur during the manual fire response stage. The room consists of an automatic gaseous fire suppression system in a tightly closed compartment. After the gaseous fire suppression system has been activated, firefighters must enter the fire room to ensure the fire is out, and if not, further work to extinguish it manually. A backdraft, which is a catastrophic explosive event well-known to firefighters, is a rapidly developing flame spreading through the front of an enclosure that may even create a fireball that comes out of the opening after a sudden change in room ventilation. This phenomenon occurs when incomplete combustion products, carbon monoxide, and unburned fuels (e.g., hydrocarbons) accumulate within a compartment under fire conditions owing to limited ventilation. Usually, a sudden change in ventilation occurs when firefighters open a door or window to enter the compartment, which leads to the entrainment of fresh air into the room that then mixes with combustion products to allow for the onset of combustion. Explosions caused by backdrafts can result in serious burn injuries for firefighters, who are strongly cautioned to avoid exposure to such a situation in general. The emergency response manual also discussed the possibility of backdraft; however, the guidance to avoid injuries was qualitative, such as to be cautious of backdrafts and wait a sufficient amount of time to enter a room after opening the door. Best practices for avoiding backdraft exposure to protect the life and safety of firefighters needs to be taught through the fire evacuation and response training program. Therefore, the backdraft phenomenon, which may occur from a switchgear room fire, was further studied via computational means to develop the program’s training content.

2. Switchgear Room Fire Scenario and Backdraft

The fire evacuation and response training program was designed for the APR1400 model[3], which is a next-generation NPP developed by improving the OPR1000, Korea’s main NPP model. Developed in the early 2000s, the APR1400 model is a state-of-the-art NPP that has increased its power generation capacity from 1000 to 1400 MW and its continuous operation renewal period from 40 to 60 years. This model is considered to have strengths beyond the technological level of third-generation NPPs developed by advanced NPPs. The APR1400 model boasts the highest safety level worldwide, with a seismic response design to meet both the 0.3g seismic requirements in rock and soil conditions in accordance with the concept of a comprehensive site. In addition, introducing a four-way layout design method for auxiliary buildings enhanced the ability to cope with external shocks such as fires, floods, and earthquakes. This model is certified internationally and was exported to the United Arab Emirates in 2016.

A switchgear room with a height of 6m in the APR1400 model is shown in Figure 1. From the corridor, there is an entrance door, which is normally closed and leads to a small compartment with two rows of eight loop controllers (2.5m (H) x 0.8m (W) x 0.9m (D)). This compartment is connected to a larger compartment where a load center (2.4m (H) x 3m (W) x 2.1m (D)) and switchgear cabinet (2.5m (H) x 7.52m (W) x 2.7m (D)) are located. Based on fire test results, the maximum heat release rate observed from this equipment ranges up to 1 MW, with loop controllers providing the highest heat output[4]. The room is equipped with an automatic gaseous fire suppression system, and when a fire is detected, the delayed actuation of a total flooding cleaning agent system is released.
into the room. The compartment was designed to be airtight to maintain a certain concentration of inert fire-suppressing
gas inside the room when activated to extinguish fires. Any openings, including the HVAC duct system with fire
stopping, are closed to prevent fire agents from leaving the room. A clean agent fire suppression system usually
removes the oxygen in the compartment and maintains this condition to cool the fuels below its auto-ignition
temperature to extinguish the fire. In any area where fire is suppressed, the clean agent gas must sufficiently disperse
prior to the fuels cooling or the fire may reignite[5].

When a gaseous fire suppression system fails to extinguish an electrical room fire, whether due to poor system
design or an increase in fuel load, suddenly opening the door to the switchgear room while an oxygen-limited, vitiated
fire exists within the compartment may induce a backdraft[6,7]. Although, the likelihood this phenomenon will occur
is low as several conditions must be met, precautions are necessary to avoid unwanted fire injuries from a backdraft
when entering the switchgear room. Some of the preconditions necessary for a backdraft to occur are as follows:

- The unburned fuel concentration in the compartment must be sufficient prior to a sudden increase in ventilation
  increase.
- Fresh air entrainment and mixing, followed by a sudden increase in ventilation, must be adequately conducted.
- The air and fuel mixture concentration must be able to facilitate rapid flame spread.
- An ignition source providing sufficient energy to start the combustion reaction (e.g., hot surfaces) must exist
  and to meet with the air and fuel a gaseous combustible mixture.

![Switchgear room in the APR1400 model nuclear power plant.](image1)

Figure 1. Switchgear room in the APR1400 model nuclear power plant.
3. Fire Modeling Results and Discussion

3.1 Fire model and set-up

To study backdrafts in a switchgear room, gas-phase mixing, ignition (onset of combustion), and fire extinction are the key phenomena that must be addressed via numerical modeling. These requirements must be considered when selecting a numerical tool, and a computational fluid dynamics (CFD) simulation approach was used in this study. Among the various CFD models, numerical experiments were conducted using the FDS (version 6\cite{8,9}), which is an open-source code developed and maintained by the National Institute of Standards and Technology in the United States. This CFD model solves the Navier-Stokes equations appropriate for low-speed, thermally driven gaseous flows found in fire-related problems.

The gas-phase mixing was modeled using the large-eddy simulation (LES) approach derived from direct numerical simulation (DNS) calculations with a low-pass filter of width $\Delta = (\delta x \delta y \delta z)^{1/3}$ applied to the equations. The filter width is relatively large to capture all the small eddies in the gas phase flow; therefore, the sub-grid-scale (SGS) must be modeled, which is done by the turbulence model used in the model. The turbulence model provide means of estimating the SGS flux terms and the turbulent transport coefficients - turbulent viscosity, $\mu_t$. Currently, in FDS, various turbulent models are available; however, in this study, Deardorff’s model (default option) was applied, as this model has been shown to provide good agreement with a wide variety of full-scale fire experiments.

Gas-phase ignition was governed by assigning an auto-ignition temperature (AUTO_IGNITION_TEMPERATURE) to the model. This parameter was set to allow the model to prevent spurious reignition. For the combustion reaction to be ignited, gas-phase mixing between oxygen and fuel is required, and the gas-phase mixture temperature must be above the auto-ignition temperature. This value can be measured from small-scale experiments; however, when the grid size is greater than 10 cm, a lower value must be applied to account for the averaging effect of utilizing coarse grid cells. The combustion phenomenon was modeled as a single-step, using mixing-controlled combustion assuming that the chemistry is similar to that in the burning of methane. This approach is consistent with previous model calibration work conducted by Myilsamy et al.\cite{10}. The agreement between the experimental and simulated results of the backdraft phenomenon was good, even when this simple approach was applied to model combustion.

Gas-phase fire extinction was modeled in FDS by considering the gas-phase temperature and oxygen volume fraction. For higher temperatures, combustion is sustained for as long as oxygen is available; however, when the gas-phase temperature is lower, the limiting oxygen concentration required to sustain combustion reaction increases. The extinction model applied in this study (EXTINCTION 2) is shown in Figure 2. At temperatures above 1500 °C, all available oxygen is consumed in the combustion reaction when fuel coexists. At ambient temperatures, at least 14% oxygen concentration is required to burn the available fuel vapor in the gas phase.

![Figure 2. Extinction model (EXTINCTION 2) in FDS V6.](image-url)
3.2 Numerical experiments

The results of the numerical experiments are summarized in Table 1. Three tests were conducted using different grid resolutions (Tests 1 and 3) and surface temperatures at the fire origin (Tests 1 and 2). Commonly applied conditions are also summarized. These conditions were selected to provide the most favorable conditions for creating a backdraft situation from the switchgear room. The fire origin is the loop controller, as this had the highest potential heat release rate among the instruments in this compartment. In addition, other locations (i.e., load center and switchgear), are too far from the exit door, where fresh air can be entrained inside the compartment to cause a backdraft. When fresh air enters the room, buoyancy causes it to move towards the back of the compartment by creating a current near the floor. This causes the upper gas in the compartment to be filled with mostly fuel vapor, and the lower gas of the compartment to be filled with mostly fresh air. If the two gas layers do not mix properly, violent gas mixture burning (i.e., backdraft) will not occur. Both the load center and switchgear were found to be too far from the door, and by the time the air reached them, two distinctive gas layers (upper and lower)formed and no backdraft occurred. This was confirmed through a preliminary numerical modeling exercise. The heat release rate was set to 1 MW, the loop controller’s maximum output, and the fire scenario assumed that the gaseous fire suppression failed and the fire is still vigorously producing pyrolysates in the gas phase owing to the high energy input. The time of door open was set to 130 s after the loop controller reached maximum fuel production. The auto-ignition temperature of the gas-phase combustion was set to a lower value of 100 °C to account for the resolution effect on the modeling. Typically, the autoignition temperature of hydrocarbon fuels ranges between 200-600 °C[11], and the ignition phenomenon occurs within the boundary layer at the interface between the gas phase and the hot surface. The boundary layer exists within a few millimeters of the interface, whereas the grid resolution applied in this study was two orders of magnitude greater. Accounting for this effect, the volume-averaged temperature increase of a grid cell when the boundary layer within it is above the auto-ignition temperature is below 10 °C. Therefore, setting the autoignition temperature of the gas-phase combustion to 100 °C is an order of magnitude higher than the actual temperature. However, this value was selected to conduct a conservative analysis because applying a higher value would result in a longer time until backdraft occurs.

Table 1. Numerical Experiment Test Matrix

<table>
<thead>
<tr>
<th>Test</th>
<th>Grid Size (mm)</th>
<th>Surface Temperature at Fire Origin (°C)</th>
<th>Common</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>500</td>
<td>• Fire Origin: Loop Controller</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>1000</td>
<td>• Heat Release Rate: 1 MW</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>500</td>
<td>• Time of Door Open: 130 s • Auto-Ignition Temperature: 100 °C</td>
</tr>
</tbody>
</table>

The test results are presented in Table 2, and show that, in all cases, an explosive fireball exiting the door followed by a sharp pressure increase occurred 5-8 min after the door was opened. The estimated maximum pressure peak ranges up to $10^4$ Pa, which can cause severe injury to the firefighters entering the room (e.g., eardrum damage). Tests 1 and 3 model the same case with different grid resolutions; however, the estimated pressure increase differed by two orders of magnitude. This can be explained by considering the quantity of fuel and oxygen mixture within a grid cell at the time of burning (i.e., when combustion is turned on) based on the extinction model. The extinction model checks the grid-volume-averaged values of the oxygen volume concentration and gas-phase temperature. When a larger grid volume is used for the calculation, the burning in a grid cell will take longer, as averaging over a larger volume will take more time for changes in the oxygen volume concentration and gas-phase temperature to be noticed in the model output. Therefore, the difference in grid volume caused the quantity of the fuel and oxygen mixture in the grid cell at the time of burning to be larger in the larger grid resolution case (Test 1) than in the finer grid resolution case (Test 3). This resulted in a higher pressure increase in Test 1 than in Test 3, as more fuel was instantly consumed in the combustion reaction. The difference in time of flame out the door and time
of maximum pressure increase in Tests 1 and 3 was less than 1 min, and the estimations from Test 1 (coarser grid resolution) were more conservative than those from Test 3. Therefore, in this study, the coarser grid case was considered to present reasonable calculation outputs compared with the finer grid case.

Table 2. Experiment Results Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>Time of Flame Out the Door (s)</th>
<th>Time of ∆Pmax (s)</th>
<th>∆Pmax (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>568</td>
<td>574</td>
<td>1800</td>
</tr>
<tr>
<td>2</td>
<td>402</td>
<td>526</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>532</td>
<td>532</td>
<td>20</td>
</tr>
</tbody>
</table>

The simulation results of the fireball exiting the opened door in Tests 1 and 2 are shown in Figure 3. Compared to that in Test 1, the fireball in Test 2 exited the opened door approximately 3 min. earlier. This divergence resulted from the surface temperature conditions applied in the simulations. In Test 1, surface temperature of the fire origin was set to 500 °C, whereas in Test 2, it was set to 1000 °C, which allows for quicker heating of the gas phase near the fire origin in Test 2, eventually causing earlier ignition of the gas-phase fuel-air mixture. The earlier ignition in Test 2 compared to Test 1 resulted in a lower concentration of fuel in the gas phase, as less time was provided for fuel generation. A lower fuel concentration in the gas phase causes the explosive flame to spread and become weaker, followed by ignition. Hence, unlike the large, strong fireball that filled up the corridor space in Test 1, smaller and weaker flames, rather than a fireball, were observed in Test 2.

Figure 3. Simulated fireball existing the door: Flame and smoke outputs from test 1 (top) and test 2 (bottom). A stronger and larger fireball exits the door in test 1 than in test 2.
The simulated oxygen volume fractions in the compartment directly prior to the flame exiting the door from Tests 1 and 2 are shown in Figure 4. In both cases, prior to the fireball/flame exiting the door followed by ignition, the oxygen concentration near the fire origin (hot surface) becomes closer to the ambient concentration. After the door is opened at $t = 130$ s, relatively heavier fresh air enters the compartment, creating a current near the floor. Ignition can occur when the oxygen concentration and gas-phase temperature are both sufficiently high to override the extinction and auto-ignition models in FDS (see Section 3.1). As the oxygen concentration exceeds 14% by volume and the fuel-air gas-phase mixture temperature becomes greater than 100 °C, the set auto-ignition temperature, owing to heat transfer from the hot surface of the fire origin, ignition is turned on in FDS, allowing for rapid combustion in all the cells that meet the preconditions. Notably, as the ignition was turned on and the flame appeared, rapid smoke production was observed.
To assess the effect of grid resolution on the simulation results, Test 3 was performed, which was a reproduction of Test 1 but with a finer grid. The simulated fireball exiting the open door and the oxygen volume fraction in the compartment just before the flame exits are shown in Figure 5. These results indicate that the simulated backdraft phenomenon is consistent with that of Test 1. Step 1: fuel generation without burning due to low gas-phase temperature and lack of oxygen in the compartment; Step 2: fresh air entrainment with respect to door opening and flow current develops near the floor; and Step 3: the fuel-air gas mixture is reignited as the gas-phase temperature exceeds the auto-ignition temperature and the oxygen volume concentration exceeds 14%, followed by a fireball exiting the open door. When a coarser grid was applied (Test 1 case), the delays in Step 3 resulted in a large and stronger fireball, owing to the larger volume in each grid cell. In this study, a backdraft fire scenario was investigated numerically to develop an appropriate timeline to be implemented in a fire evacuation and response training program. Therefore, considering that the coarser grid cases (Tests 1 and 2) provide more conservative simulation results (i.e., timeline and fireball magnitude) compared to the finer grid case (Test 3), the coarser grid case results were adopted to develop the fire evacuation and response training program.

Figure 5. Simulated fireball exiting the door: Flame and smoke outputs from test 3 (top) and oxygen volume fraction in the compartment directly prior to the flame exiting the door (bottom). The finer grid case shows earlier onset of burning and a weaker fireball exiting the door.
3.3 Best practices for the emergency response training program

Backdraft explosions can cause serious burn injuries to firefighters, and the exposure of firefighters to such situations must be avoided. The emergency response manual refers to the possible occurrence of a backdraft from a switchgear room protected by a gaseous fire suppression system; however, the existing guidance to avoid injuries from backdrafts is qualitative (i.e., be cautious of backdrafts and enter the room once a sufficient amount of time has passed after opening the door). By employing the simulation results, a more quantitative guide to avoiding backdrafts from switchgear room fires in NPPs using the APR1400 model can be implemented in the fire evacuation and response training program as follows:

(1) Backdrafts can only occur when the fire originates in the space near the door.
(2) Prior to entering the room, wait at least 10 minutes after opening the door.
(3) Watch for rapid smoke production as this may be an antecedent phenomenon of a backdraft.
(4) When smoke production increases rapidly, leave the room as soon as possible to avoid being caught in the deflagrating flames from the backdraft.

4. Conclusion and Future Works

To understand the potential strength of XR technologies (e.g., AR, VR, and MR), this study utilized XR as a tool to develop a fire evacuation and response training program for NPP application. As the first step, three fire scenarios were selected based on a risk-informed, performance-based approach, which is consistent with the typical fire protection philosophy for NPPs (i.e., switchgear, main control, and safety injection pump room fires). To develop the fire evacuation and response training program, numerical modeling was conducted using FDS (version 6) to predict the effects of smoke production and build-up within a room, heat generation, and impingement on people and objects. The modeling results provide information on tenability within a space, which is necessary to create fire-training scenarios similar to real-world situations in the XR-based program. Among the three cases, the modeling results from the switchgear room fire demonstrated the most potential for backdrafts to occur during the manual fire response stage. A backdraft is a rapidly developing flame that spreads through the front of an enclosure, and
occurs when limited ventilation causes incomplete combustion products, carbon monoxide, and unburned fuels (e.g., hydrocarbons) to accumulate within a compartment under fire conditions. When firefighters open a door or a window to enter the compartment, this can lead to entrainment of fresh air into the room and that then mixes with combustion products, allowing for the onset of rapid combustion. An explosion from a backdraft can cause firefighter to receive serious burn injuries; therefore, this phenomenon was further studied to develop best practices for avoiding exposure to backdrafts to be taught in a fire evacuation and response training program.

A switchgear room fire resulting in a backdraft was studied via computational modeling. With the APR1400 model of NPPs, backdrafts may occur from a switchgear room fire when a gaseous fire suppression system fails to extinguish an electrical room fire and other conditions related to gas-phase mixing of fuel and oxygen, ignition (onset of combustion), and fire extinction are met. The preliminary modeling exercise confirmed that, among the three items in the compartment (i.e., loop controller, load center, and switchgear), only a fire originating from the loop controller can induce backdraft from this room. This is because the other components are too far away from the exit door, which is the only opening that can provide ventilation to the room. Considering that the statistical maximum heat release rate from a loop controller is 1 MW, this was simulated in a switchgear room under vitiated condition followed by a door opening suddenly. Then, the time the flame exited the door and the magnitude of pressure increase due to the backdraft were estimated.

Based on the simulated results, guidelines for firefighters to avoid being caught in a backdraft when entering the switchgear room in an APR1400 model NPP are provided. First, backdraft can only occur when the fire originates in the space near the door. Second, prior to entering the room, wait at least 10 minutes after opening the door. Third, watch for rapid smoke production as this may be an antecedent phenomenon of a backdraft. Fourth, when smoke production increases rapidly, leave the room as soon as possible to avoid being caught within the deflagrating flames from a backdraft. The results will be implemented in the adopted XR fire evacuation and response training program to allow trainees to prepare for a possible backdraft and practice these guidelines to avoid unwanted exposure to backdrafts, thereby protecting the life and safety of firefighters.

Author Contributions


Conflicts of Interest

Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. Declare conflicts of interest or state "The authors declare no conflict of interest."

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