An Exploratory Study on Decision to Main Control Room Abandonment due to Fire-Induced Loss of Habitability: Using a VR Nuclear Power Plant Main Control Room Simulator

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Abstract: In the fire probabilistic risk assessment (PRA) and the fire human reliability analysis (HRA) on nuclear power plants, the criteria related to the concentration of smoke or room temperature for main control room (MCR) abandonment due to loss of habitability (LOH) are provided by NUREG-6850. However, the criteria provided are extremely severe for the human body to remain the MCR and the instant at which operators might decide to abandon the MCR in the event of a fire is unclear. Additionally, because MCR fire events are extremely rare and cannot be simulated in MCRs, it is difficult for operators themself to image clearly about their own timing to decide to abandon during MCR fires, as well as their cognition and judgment associated with MCR fires. Virtual reality (VR) can be used to experience MCR fires, which might enable data collection on the timing of MCR abandonment, and the cognition and judgment associated with MCR fires. Therefore, this study aims to develop a virtual environment of an MCR fire using a VR nuclear power plant MCR simulator and acquire data on decision-making on MCR abandonment to improve fire HRA. Additionally, this paper focuses on the process of developing a VR environment for data collection.

1. INTRODUCTION

Two situations might result in main control room (MCR) abandonment in the event of a fire in nuclear power plants. The first is due to the loss of habitability (LOH), wherein the MCR becomes environmentally uninhabitable due to the heat and smoke. The second is due to the loss of control (LOC), which results in the loss of ability to prevent core damage from the MCR [1]. LOH has clear criteria related to smoke concentration or room temperature that prevent operators from effectively remaining in the MCR. The criteria are as follows [1][2]:

- The heat flux at 6 feet (1.83 m) above the floor exceeds 1kW/m^2 (relative short exposure) or the gas temperature exceeds 95 ˚C (200 ˚F) at the same point
- The smoke layer descends below 6 ft (1.83 m) from the floor, and the optical density of the smoke is greater than 3 m^{-1}

These criteria have been determined through fire modeling and are designed to represent conditions wherein it is physically impossible for the operators to remain in the MCR. Therefore, failure to abandon MCR caused by LOH is excluded from the probabilistic risk assessment (PRA) of fire events in nuclear power plants. In other words, it is assumed that MCR abandonment is always successful. Furthermore, the fire PRA and human reliability analysis (HRA) assume that it is not credible that the operators will remain in the MCR beyond the above criteria [1].

However, it is generally accepted that operators are reluctant to abandon the MCR [3]. In fact, a few cases have demonstrated that operators remained in the MCR even though a large amount of smoke had entered it [4]. For example, in Armenia (1982), the operators remained in the MCR even though dense smoke entered the room and made it uninhabitable. Additionally, in Beloyarsk (1978), the operators were severely affected by smoke inhalation because they remained in the MCR. Despite these severe circumstances, the operators performed appropriate actions in most cases.

However, the operators might evacuate the MCR before reaching the LOH criteria owing to its severity and the increase in the risk of smoke inhalation when it descends below the operators' eyes. The past cases [4] have occurred between the 1970s - the 1990s and it is expected that human life-centered decisions might be a possibility in the present times. In the case of early abandonment, the time margin for subsequent operations will be increased, which might affect HRA.

If data can be collected on what points operators make an abandonment decision in fire situations that could cause LOH and whether operators can properly assess the situation and make decisions during MCR fires, it may help to improve the fire HRA. However, MCR abandonment due to LOH is rare, with only one precedent (Narora, 1993). Although training is conducted on the procedures after the abandonment-decision-making occasionally, training on the decision to abandon the MCR is rarely conducted in Japan. Therefore, even if interviews with operators were conducted, it would be difficult for them to answer clearly about their own timing to decide to abandon the MCR during MCR fires, as well as their cognition and judgment associated with MCR fires. Furthermore, data cannot be collected using a training simulator because smoke is not generated in these simulators.

Virtual reality (VR) can enable the operators to experience MCR fires which might facilitate the collection of data on the timing of MCR abandonment. VR has been extensively used as a technique that can simulate real world situations regardless of the user's location. In industry, VR technology is widely used for various types of training such as skill acquisition [5], accident response [6][7], and evacuation during disasters [8][9]. Additionally, VR has been used for the simulation of evacuation behavior [10][11]. In the field of nuclear engineering, VR technology has been used for technical training for decommissioning [12][13][14] and ergonomic evaluation of control rooms [15][16][17]. In particular, Bergroth et al. [17] simulated a fire event in the MCR for the evaluation of MCR design. However, only a few studies have used VR to obtain data on the cognition and decision-making of operators in emergencies such as fires.

Therefore, this study aims to develop a virtual environment of an MCR fire using a VR nuclear power plant MCR simulator and collect data on decision-making on MCR abandonment to improve fire HRA. Additionally, this paper focuses on the process of developing a VR environment for data collection.

2. Development of a fundamental content

2.1. VR simulator system

A VR simulator system developed by Hitachi-GE Nuclear Energy Ltd., was used to simulate a fire event in MCR. The system consisted of an MCR of an advanced boiling water reactor (ABWR) in a virtual environment (Figure 1) and a simulator that simulated several emergency events such as alarms and parameters as in a real plant. Also, it could reflect operator's actions. The MCR in the virtual environment simulated a large display panel, operator's desk, shift manager's desk, and main control

Figure 1: VR Simulator System

boards with an operation console. Although it is not possible to approach the fire area described below, a part of the back panels was additionally simulated for confirmation of fire. The height of the virtual room and large display panel were 3.6 and 3.2 m, respectively.

2.2. Fire settings

It is unusual for a fire outside an MCR in a nuclear power plant to cause LOH [1]. Hence, this study assumed that the fire started in the MCR.

Additional settings such as ignition source and environmental conditions were obtained from the scenario described in Appendix A of NUREG-1934 [18]. However, the height of the MCR illustrated in NUREG-1934 [18] was 5.2 m with an open-grate ceiling, which is significantly different from that of the MCR in Japan. Therefore, the parameters related to the LOH criteria were reanalyzed using fire zone model *BRI2-CRIEPI* developed by Central Research Institute of Electric Power Industry (CRIEPI) [19] using the parameters described Table 1. Figure 2 depicts the schematic diagram of the model.

Table 1: Input Parameters for BRI2-CRIEPI

parameter	Value	Source
Peak Heat Release Rate (HRR)	702 kW	NUREG-1934 [18]
Time to reach peak HRR	12 min	NUREG-1934
Time for fully developed fire	8 min	NUREG-1934
Time for fire decay	19 min	NUREG-1934
Ignition source	A back panel (cabinet) in the MCR	NUREG-1934
Room height	3.6 m	VR plant simulator (section 2.1)
Room effective length	27.1 m	NUREG-1934
Room effective width	13.8 m	NUREG-1934
Structure of the room (location of fire source and operators)	refer NUREG-1934	NUREG-1934
Fire pan height	1 m *	-
Location of supply/return vents	Adjusted using the room height ratio (3.6 m/5.2 m)	NUREG-1934
Ventilation rate during fire	25 times/h	NUREG-1934

* The value adopted NUREG-1934 (2 m) would not allow the analysis

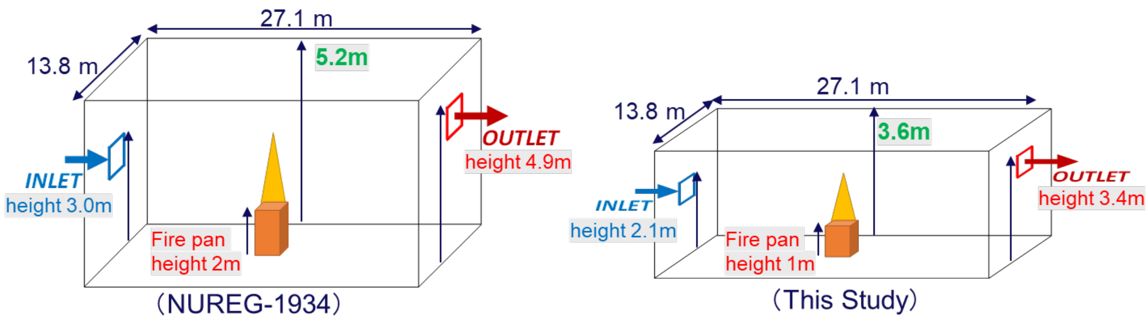

Figure 2: Schematic Diagram of the Model

Figure 3-5 exhibit the results of the analysis. These figures indicated that the visibility tenability criterion was exceeded at the operator position in approximately 13 min when the smoke purge system was not operational. The remaining criteria were not exceeded in this setting. These results were similar to that of the fire dynamics simulator (FDS) prediction in NUREG-1934 [18]. In order to make the operators decide to abandon in this virtual environment certainly, this study assumed that the smoke purge system remained inactive during the fire event.

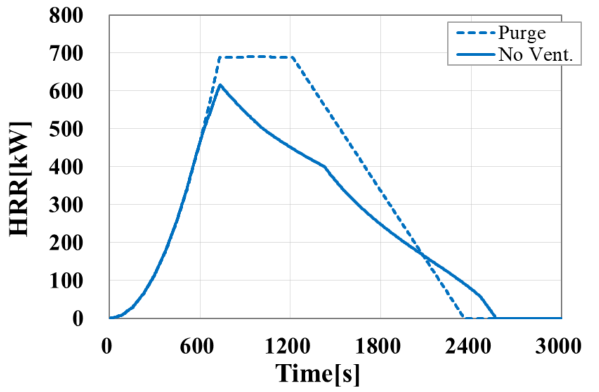

Figure 3: HRR

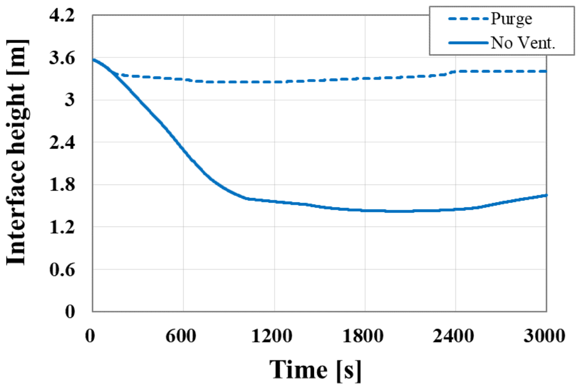

Figure 4: Height of Smoke

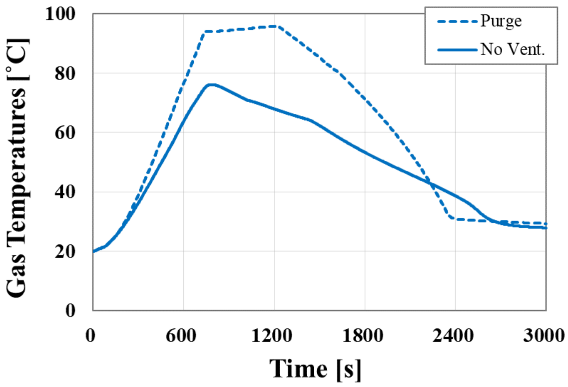

Figure 5: Gas Temperatures

3. Deciding plant response until MCR Abandonment

3.1. Interviews

The fundamental simulator content was developed in Section 2. However, events in addition to the activation of the fire alarm might occur when a fire occurs in the back panel. A few examples of MCR abandonment scenarios have been mentioned in literature [1] including past incidents [4]. However, these cases were mostly related to pressurized water reactors (PWR) without detailed scenario descriptions. Additionally, the procedures were unknown because they are foreign cases. Therefore, an interview survey was conducted for two shift managers at a power company to determine the chain of events that might occur in a nuclear power plant when a back panel fire occurs in the MCR. In addition, they were asked about the decisions and actions that they might adopt in the event of a fire as envisioned in this study to provide a reference for the development of the experimental scenario. The survey was conducted by sending the questionnaire and video recording of the fundamental content to the participants. Subsequently, the two participants were simultaneously interviewed online.

3.2. Creating a scenario

In the case of the interview described above, it was assumed that the equipment related to the panel was damaged when the fire occurred in the back panel (e.g., related alarms are activated simultaneously, displays turn light-out). However, multiple layers of protection were provided with each layer designed to provide the safety function without reliance on the different layers in ABWR plants [20]. Therefore, this study adopted a scenario that described the functional failure of a part of emergency core cooling system due to the fire. It was assumed that systems, such as the main steam system and the reactor containment vessel were not affected by the fire.

Additionally, the two interviewees pointed out that the smoke layer descended too early and MCR abandonment might occur immediately. Therefore, the scenario was changed wherein the smoke purge system was activated and it was assumed that the system failed due to an unknown reason during the fire progression.

4. CONCLUSION

The aim of this study was to collect data about the decision-making on MCR abandonment and the process of developing a VR environment for data collection was provided. Future experiments using this content will be conducted on shift managers in nuclear power plants posed with the possibility of abandoning MCRs. This study is expected to be applied for the improvement of HRA and the development of MCR fire procedure, and training for MCR abandonment in the case of MCR fires.

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