Human Performance to a Fire in the Main Control Room of Nuclear Power Plants Leading to Loss of Habitability: Using a Virtual Environment

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Abstract: In the human reliability analysis (HRA) of the fire probabilistic risk assessment of nuclear power plants, NUREG/CR-6850 provides criteria for the concentration of smoke (visibility) or room temperature causing main control room (MCR) abandonment due to loss of habitability (LOH). However, because MCR fire events are extremely rare and cannot be simulated in conventional MCR simulators, it is difficult to collect data on cognitive processes during MCR fires, including the actual timing of MCR abandonment. This study aimed to collect such data through experiments using a virtual reality (VR) nuclear power plant MCR simulator with an MCR fire. Eleven operators at the sub-shift manager level and above participated in and responded to accidents in the VR environment. The results showed that more than half of them decided to abandon MCR once visibility became insufficient owing to smoke, but the abandonment was performed earlier than the LOH visibility criteria provided by NUREG/CR-6850 in all cases. Furthermore, there were large individual differences in the overall response to the MCR fire, and half of them were concerned with the time of abandonment. The data obtained from this experiment can be utilized to create interview items and extract performance shaping factors for the qualitative HRA of MCR fires.

Keywords: Main Control Room Abandonment, Loss of Habitability, Fire Human Reliability Analysis, Virtual Reality

1. INTRODUCTION

The main control room (MCR) of a nuclear power plant contains the control and instrumentation circuits of all redundant trains for almost all plant systems; therefore, small fires within control panels in an MCR may be risk-significant [1]. Additionally, because plant operators are stationed in the MCR, if a fire occurs in the MCR, it is assumed that the fire would affect the operators, leading to a major plant safety problem. Therefore, evaluating MCR abandonment conditions may be necessary [1]. In a fire probabilistic risk assessment (PRA), a fire in an MCR is assessed separately from other fire scenarios [1].

Two situations can result in MCR abandonment in the event of a fire. The first is the loss of habitability (LOH), wherein the MCR becomes environmentally uninhabitable owing to heat and smoke. The second is loss of control, which results in the loss of the ability to prevent core damage from the MCR [2]. The 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 [2]:

- The heat flux at 6 feet (1.83 m) above the floor exceeds 1 kW/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 were determined through fire modeling and were designed to represent conditions where it is physically impossible for operators to remain in the MCR. Therefore, the failure to abandon the MCR caused by LOH is excluded from the fire PRA in nuclear power plants. In other words, it is assumed that the MCR abandonment is always successful.

However, it is generally accepted that operators are reluctant to abandon 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]. However, because the aforementioned criteria are too severe for the human body, there is a possibility that abandonment will be carried out well before the criteria. In the case of early abandonment, the time margin for subsequent operations will be increased, which might affect the fire human reliability analysis (HRA). In addition, 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, because an MCR fire is a rare event and is impossible to replicate by training simulators, it is difficult to collect data on operators' cognition and behaviors until MCR abandonment using interviews with operators.

To solve this problem, this study aims to reproduce an MCR fire situation leading to LOH using virtual reality (VR) technology and collect data on the operators' perception and behavior in the situation. In the previous PSAM16, we primarily reported on the process of developing a virtual environment for data collection [5]. This paper reports the results of an experimental study using the virtual environment.

2. METHODS

2.1. Setting up an MCR fire situation [5]

A VR simulator system developed by Hitachi-GE Nuclear Energy, Ltd. was used to simulate a fire event in the MCR [6]. The system consisted of the MCR of an advanced boiling water reactor (ABWR) in a virtual environment, and a simulator that simulated several emergency events, such as alarms and parameters, as in a real plant. In this study, the ignition source was a back panel in the MCR, following the MCR fire scenario described in NUREG-1934, Appendix A [7]. Based on the interviews with experts, the specific ignition source was an engineered safety feature (ESF) panel that controlled the emergency core cooling system. To simulate the spread of smoke in a VR environment, the height of the smoke layer was set to change in four levels based on the progress of the fire.

2.2. Procedure

2.2.1. Participants

Eleven ABWR plant operators from five companies at the sub-shift manager level and above participated in this study. All participants were men with a mean age of 49.3 years. Their average years of experience as sub-shift managers and above were 4.8 years. This study was approved by the Research Ethics Review Committee of the Nuclear Risk Research Center of the Central Research Institute of Electric Power Industry (O2022002). All the participants provided informed consent.

2.2.2. Scenarios

The three scenarios described below were created and implemented for all participants. Each scenario included the time of the events and the assumed performance of each operator (i.e., instructions for operations, responses to those instructions, etc., so-called "scripts"). In these scenarios, there were eight operators in the MCR: the shift manager, sub-shift manager, reactor operator, turbine operator, and four auxiliary equipment operators. The participants played the role of the sub-shift manager and responded to the plant (instructing operators on operations). They also made important decisions, such as MCR abandonment, and proposed them to the shift manager. Shift managers typically make judgments and decisions on critical matters. However, in actual fire situations, they are busier in dealing with external responses than with the plant. Then, this study focused on sub-shift managers.

The role of the shift manager was played by a collaborator within the company to which each participant belonged, whereas the roles of the other operators were shared by the two experimenters. These scenarios were only shared by the experimenters and collaborators.

1) Control scenario
Only a total loss of feedwater occurred at the beginning of the event, and no fires occurred. This scenario was intended to familiarize the participants with the experimental environment. The reactor core isolation cooling system (RCIC) indicator was turned off for 2 min after activation. This scenario was terminated when the participants noticed that the indicator went off, indicating that they would activate the high-pressure core flooder system (HPCF) (B) or take other measures.

2) Fire scenario
A fire occurred at the location indicated in Section 2.1 during normal operation. This scenario was used to collect data on the timing of the reactor scram, which could not be confirmed in the abandonment scenario

described below. No events other than the fire occurred, and the scenario was terminated when the participant instructed the reactor scram. If the initial fire suppression was initiated according to the participant's instructions, the scenario was set up such that it would fail after 5 min.

3) Abandonment scenario
The events listed in Table 1 were generated in this scenario. Table 1 also lists the instructions provided by the participants to the operators. In this scenario, a total loss of feedwater event occurred as in 1) and a fire occurred as in 2); however, to promote reliable abandonment, the scenario was set up such that the smoke exhaust in the MCR was insufficient owing to an unidentified malfunction. The smoke layer was lowered step-by-step at the time shown in Table 1 so that the apparent height of the smoke layer on the simulator conformed to the height of the smoke layer at the time of the fire in the MCR analyzed in a previous report [5]. This scenario was terminated when the participants instructed all operators to evacuate from the MCR. For reference, images of the inside of the MCR are shown in Figure 1 depending on the smoke exhaust conditions.

Table 1. The contents of abandonment scenario

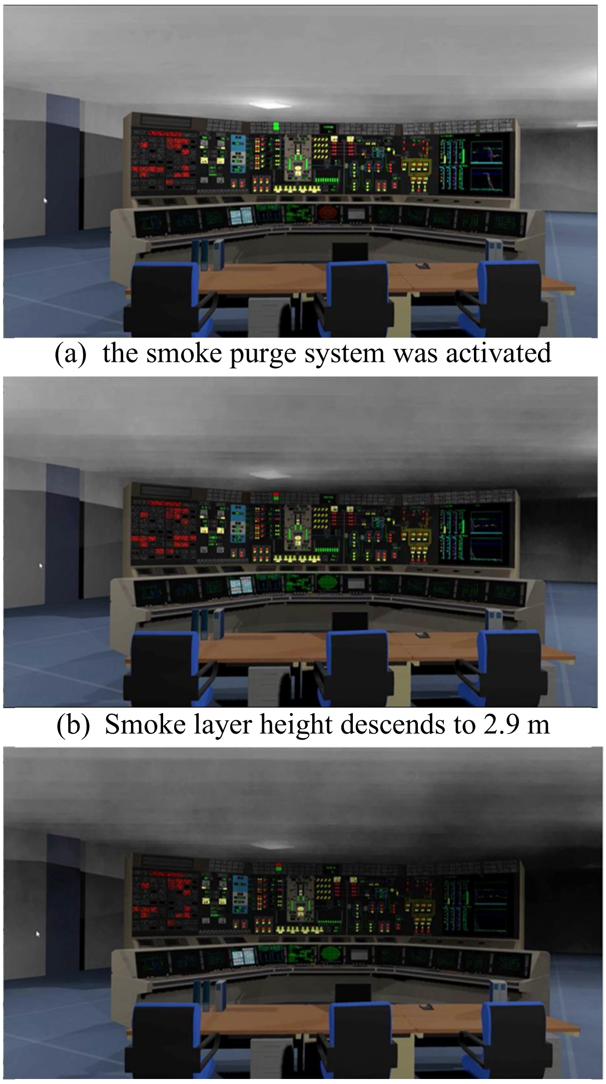
Event No.	Time of events	Contents of events	Assumed performance by the participants
1	Scenario begins	Occurrence of total loss of feedwater	Instruction of reactor scram
2		Failure of RCIC startup	Instruction of HPCF (B) startup
3	2 min after HPCF (B) startup	Occurrence of fire	Instruction to the followings: identify the fire ignition check the plant parameters check safety system equipment for ESF panel category 2 check smoke purge system prepare for initial fire suppression
4	3 min after preparation for initial fire suppression	Auxiliary equipment operators begin fire suppression	-
5	5 min after event No.4	Failure of initial fire suppression	-
6	2 min after event No.5	Occurrence of injury to people	Instruction to rescue injured people
7	The same time as event No.6	HPCF (B) indicator goes off	Instruction to check HPCF (B) and startup HPCF (C)
8	Directly after the rescue instruction	Failure of smoke purge system (Smoke layer height descends to 2.9 m from the floor)	Instruction of MCR abandonment
9	5 min after event No.8	Severe insufficient smoke exhaust (Smoke layer height descends to 2.3 m from the floor)	
10	3 min after event No.9	Smoke layer height descends to LOH criteria (1.8 m from the floor)	

2.2.3. Experimental procedures

The experiment was conducted in the office of each participant. After being briefed on the experiment and providing consent to participate in the study, the participants were fitted with a head-mounted display (HMD) (HP Reverb) and responded to the plant as a sub-shift manager with three scenarios in the order of 1) to 3), as described in Section 2.2.2. At the end of each scenario, the participants removed their HMDs and responded to psychological indices, as described in Section 2.3.2. Following the completion of all scenarios, the participants were interviewed about the experiment.

Although only the participants could experience the virtual environment at a time, they were told that the other operators mentioned in Section 2.2.2 were also stationed in the MCR. The two experimenters and one collaborator from the participants' company responded to the instructions given by the participants in accordance with the scenario; when the participants gave an instruction that was not included in the scenario, they responded flexibly so as not to change the flow of the scenario. The occurrence of each event and the corresponding operations instructed by the participants were controlled by the experimenter's personal computer.

To prevent VR sickness, participants were not allowed to move around in the virtual environment. A speaker placed in front of the participants produced various warning sounds that were generated by the plant. Additionally, a screen set up in front of the room enabled the experimenters to view the images experienced by the participants. Furthermore, two video cameras were placed with the participants' permission to measure their responses to the scenarios.



(a) the smoke purge system was activated

(b) Smoke layer height descends to 2.9 m

(c) Smoke layer height descends to 2.3 m

Figure 1. Smoke exhaust condition of the MCR [9]

2.3. Measurement indices

2.3.1. Performance indicators[1]

To confirm the performance in each scenario, the participants' utterances were captured verbatim using video recordings. Among the participants' utterances, those belonging to instructions to the operator to operate or confirm, briefings or announcements to the operators, and requests or offers to the shift manager were extracted as performances and classified according to their similar content. In addition, the time at which a performance was uttered was extracted for performances uttered by more than half of the participants.

2.3.2. Psychological indicators

To measure the transient tension, anxiety, and agitation resulting from a fire, 14 items from the Phasic Stress Scale [8], including the five factors "Languor," "Comfort," "Anxiety/Uneasiness," "Tension," and "Overall Stress Level," were used as psychological indices. Additionally, participants were asked about "experiencing hesitation in judgment" and "degree of difficulty" during plant operation. At the end of each scenario, the participants had to assess their mood using a visual analog scale by marking a point on the number line between "not at all" (0 point, left end) and "very much" (100 points, right end). The length of the line from the left end to the mark was measured. After each item was rated, it was scored against the average rating of items belonging to each factor [8].

3. RESULTS

3.1. MCR abandonment

3.1.1. Time for MCR abandonment

In the abandonment scenario, all the participants gave the instruction to evacuate from MCR (Table 2). In the fire scenario, one participant ordered some operators to evacuate to the Remote Shutdown System (RSS) before the reactor scram.

Although MCR abandonment was instructed at an average of 700.5 s after the onset of the fire (Table 2), the final evacuation, including the participants themselves, was instructed at an average 802.8 s after the onset of fire (SD 189.9, minimum 515 s, maximum 1112 s) because some participants instructed evacuation in a

[1] Although only utterances such as instructions and announcements were observed, this report defined this as "performance".

dispersed manner. The earliest instruction for evacuation was 145 s after the onset of the fire, which was a method of preemptively evacuating some operators to the RSS without waiting for the failure of initial fire suppression. In addition, there was one case in which the initial fire suppression was not performed, and all other cases except for these two were instructed to abandon the MCR after the initial fire suppression failed. The mean time from the initial fire suppression failure to final evacuation was 228.1 s (SD, 148.1; minimum, 5 s; maximum, 457 s).

Table 2. Time of utterance of each performance under the abandonment condition (after fire) [9]

Contents	Number of participants	Time (s)	SD	Minimum time (s)	Maximum time (s)
Instruction to check the fire alarm panel immediately after a fire alarm goes off	9	24.2	13.2	15	53
Instruction to identify the fire ignition	6	60.8	21.1	40	80
Instruction to prepare for initial fire suppression	9	86.1	46.9	45	175
Instruction to check the plant parameters※1	7	193.3	79.7	80	316
Instruction to check the smoke purge system or smoke exhaut※1	7	215.9	189.9	42	568
Instruction to check the safety system equipment for ESF panel category 2	6	242.7	181.4	46	551
Instruction to open main steam isolation valve	2	302.5	304.8	87	518
Briefing on possibility of MCR abandonment※1	10	334.9	323.4	60	880
Instruction to implement pressure reduction using turbine bypass valve	6	336.7	193.8	139	598
Instruction to check initial fire suppression status※1	6	100.8※3	89.4	2	269
Instruction to control reactor water level※1	9	391.8	167.1	115	646
Instruction to start suppression chamber cooling	2	350.0	116.0	268	432
Briefing on reactor operation strategies (water supply methods, etc.)	6	400.8	206.3	115	595
Instruction to rescue injured people	8	22.4※4	10.3	16	47
Reaction to HPCF (B) indicator light off	3	57.0※5	54.0	10	116
Instruction of startup HPCF (C)※2	3	129.0※5	51.5	77	180
Instruction of MCR abandonment※1	11	700.5	241.3	145	980

※1 The earliest time was used for multiple utterances.
※2 Excluding cases which HPCF (C) started before the HPCF (B) indicator light off.
※3 Time from the beginning of initial fire suppression.
※4 Time from the report about occurrence of injury to people.
※5 Time from HPCF (B) indicator light off.

3.1.2. Strategies of evacuation

Two types of evacuation strategies were observed: 1) all operators evacuated at once, and 2) some operators evacuated first. The three participants chose the latter evacuation strategy, but the details, such as the timing of the evacuation and the personnel to be evacuated first, differed.

3.1.3. The timing of MCR abandonment judgment

Figure 2 shows the timing of instructions for MCR abandonment based on the content of the utterances. The most common timing was "insufficient smoke exhaust," followed by "failure of initial fire suppression." In the post-experiment interviews, the reasons for the final decision to abandon MCR were mainly divided into "failure of initial fire suppression" and "(amount and/or color of) smoke." Based on this interview, we extracted each participant's utterances immediately after the failure of the initial fire suppression. It was found that participants who chose failure of initial fire suppression provided instructions on their evacuation immediately after the failure of initial fire suppression. The mean time between the failure of initial fire suppression and the instruction for MCR abandonment was 96.5 s (SD 167.8, minimum 5 s, maximum 348 s). However, many participants

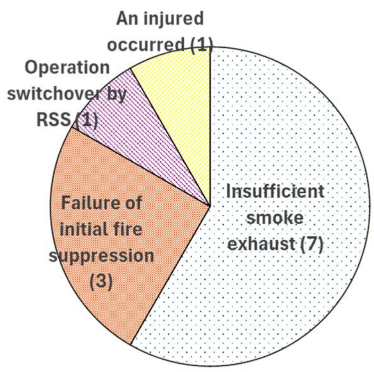


Figure 2. Timing of MCR abandonment decision [9]

who chose insufficient smoke exhaust gave instructions about various measures to be taken after the failure of the initial fire suppression. The mean time between the failure of initial fire suppression and the instruction for MCR abandonment was 201.0 s (SD 23.8, minimum 180 s, maximum 235 s). The above results showed that participants who chose failure of initial fire suppression as the reason for the MCR abandonment decision gave instructions about their evacuation 104.5 s earlier on average than those who chose smoke as the reason for the MCR abandonment decision.

Similarly, by extracting the utterances of participants who remained until the insufficient smoke exhaust, it was found that each participant referred to worsening of the smoke situation. The average time from the insufficient smoke exhaust to the instruction of MCR abandonment (in the case of distributed evacuation, the instruction closest to the occurrence of the insufficient smoke exhaust) was 82.9 s (SD 37.1, minimum 45 s, maximum 162 s). In addition, two participants remained until after the recognition of insufficient smoke exhaust, both of whom chose dispersed evacuation and wore self-air masks. However, none of the participants remained in the MCR until LOH criteria were met.

As shown in Table 2, 10 out of 11 participants had a briefing with operators and shared the possibility of MCR abandonment at an average time of 334.9 s after the onset of fire: six participants before the initial fire suppression, one during it, and three after its failure. This indicated that the possibility of MCR abandonment was recognized early after the onset of the fire. In the interviews, most participants answered that they started thinking about it “immediately after the onset of the fire.”

3.1.4 Participants’ comments regarding MCR abandonment

The following were the comments obtained from the participants regarding the abandonment scenario:
(1) Quality of MCR abandonment response
When asked whether they were able to respond well to the MCR abandonment, four participants answered “yes,” while the others answered “no” (four participants) or “undecided” (three participants). Comments from the participants were as follows:
- I could have decided earlier (three participants).
- I should have informed a little more in advance because the operators had to evacuate in a flurry. I also wanted to check the preparation and operation for going to the RSS in the procedure manual.
- I forgot to check who had entered the MCR area.
- I was too fixated on whether the initial fire suppression was possible.

(2) Hesitation about abandonment of MCR
Although comments such as “I made a quick decision based on the knowledge that I should move to the RSS when the MCR was not available” were obtained, approximately half of the participants commented on their hesitation to evacuate. The following was a summary of the comments:
- I waited for the shift manager to tell me that it was time to evacuate.
- There was hesitation in judging whether to leave the MCR.
- I wanted to evacuate immediately, but there was a procedure manual that says, “If it is difficult to operate from the MCR, use RSS....” I kept checking the fire suppression situation and reactor parameters to determine if this was a “difficult” situation.
- I always wondered where and how to decide to evacuate.

3.2. Reactor scram

3.2.1. The timing of reactor scram

In the fire scenario, all but one participant instructed reactor scram. Participants who did not instruct reactor scram were terminated in the middle of the experiment because it was expected to end up in the same manner as the subsequent abandonment scenario.

Reactor scram was indicated on average of 430.8 s after fire onset. However, the shortest and longest times for the instruction of scrams were 88 and 880 s after the fire, respectively, with a difference of more than 13 min. The utterances of each participant regarding the timing of the scram instructions were then extracted. They were divided into two groups: before and after the failure of initial fire suppression, as shown in Figure 3.

When the reactor scram was instructed before the failure of the initial fire suppression, the mean time from fire occurrence was 173.6 s (SD 72.1), and when the reactor scram was instructed after it, the mean time from fire occurrence was 688.0 s (SD 111.7). As the mean time from fire occurrence to failure of the initial fire suppression was 633.3 s, the reactor scram was initiated approximately 1 min after the failure of the initial fire suppression was reported.

The following were the reasons for determining the reactor scram from their utterances and interviews (including multiple answers).
(1) Participants who were instructed before failure of the initial fire suppression
- Because it was the MCR fire (four participants)
- Because smoke was visible (three participants)
- Shutting down the reactor before the fire spreads makes it easier to manage the situation afterwards

(2) Participants who provided instructions after failure of the initial fire suppression
- Because the fire could not be extinguished (four participants)
- Because the smoke did not seem to subside
- Fear of losing control
- Because supporters had not yet arrived
- Fear of fire spreading to other areas
- Could not make a decision immediately

Based on the above, participants who instructed the reactor scram before failure of the initial fire suppression were more likely to give the reason that “the MCR was on fire,” while participants who instructed the reactor scram after it were more likely to give the reason that “the initial fire suppression failed.”

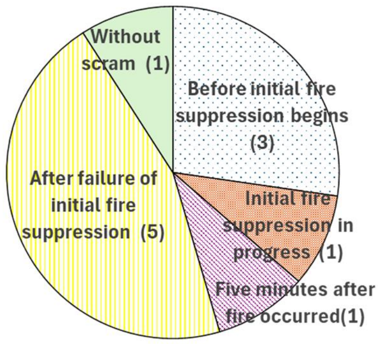


Figure 3. Timing of reactor scram decision [9]

3.2.2. Participants’ comment about reactor scram

Based on the interviews, approximately half were hesitant about the reactor scram as well as the MCR abandonment decision. The details of this process were described below.
- I was hesitant to scram the reactor because although the smoke was coming to the center of the room, there was no alarm.
- It took time to judge whether the fire could be extinguished immediately, and the decision on reactor scram was made later.
- I wanted a document that would serve as a standard for scram judgment because the reason for judgment of reactor scram would be required.
- I wondered if I could shut the reactor down by my own judgment.
- I was always hesitant to make a reactor scram.
- I wondered if I should make a reactor scram decision when smoke was generated.

3.3. Overall response to a MCR fire

This section describes the overall responses of each participant from the occurrence of a fire to MCR abandonment.

Table 3 outlines the responses of each participant from the occurrence of fire to MCR abandonment, including the presence or absence of instructions about smoke exhaust, initial fire suppression, preliminary confirmation of the systems related to the fire location, strategies of water injection and reactor depressurization at MCR abandonment, and evacuation. Table 3 indicated that no participant implemented exactly the same response; namely, there were large individual differences in the overall response from the onset of the fire to abandonment. Only one participant (No. 1) responded similarly to the abandonment scenario created by the researcher.

Table 3. Overview of responses from the onset of fire to MCR abandonment [9]

Participant No.	Instruction of smoke exhaust	Instruction of initial fire suppression	Confirmation of systems related to the location of the fire	Means of water injection	Depressurization method	Timing of abandonment decision	Strategies of abandon ment
1	○	○	○○	C train	SRV	Smoke	All
2	-	○	○○	Water truck	TBV	Smoke	All
3	-	○	○	C train	TBV	Smoke	Distribute
4	○	○	-	B & C train	-	Smoke	Distribute
5	○	○	○	B train	-	Smoke	All
6	-	○	-	C train	TBV	Smoke	All
7	○	-	○○	C train	TBV	Smoke	All
8	Confirma-tion only	○	-	B train	SRV	Suppression Failure	All
9	○	○	-	B train	TBV	Smoke	Distribute
10	○	○	-	B & C train	TBV	Suppression Failure	All
11	-	○	○	C train	-	Suppression Failure	All

※○...Response, -...No response, ○○...Stopping the systems were taken
※B and/or C trains represent trains of water injection systems
※Water truck was ordered because the participant considered ECCS would be unusable for all systems
※SRV means safety relief valve, TBV means Turbine bypass valve
※Smoke means insufficient smoke exhaust, and suppression failure means the failure of initial fire suppression

3.4. Psychological indices

As there were outliers and normality was not satisfied for the psychological indices, Friedman tests were conducted among the three scenarios for each factor.

The results showed that "Comfort" ($p<.01$), "Anxiety/Uneasiness" ($p<.01$), "Overall Stress Level" ($p<.01$), "Tension" ($p<.05$), and "degree of difficulty" ($p<.001$) were significant. "Languor" and "experiencing hesitation in judgment" was significant. To determine the differences among the significant factors, the Bonferroni method was used for multiple comparisons to adjust for the level of significance. As a result of multiple comparisons, differences were found between the control and abandonment scenarios for "Comfort," "Anxiety/Uneasiness," "Overall Stress Level," and "degree of difficulty." The Overall Stress Level" was also significantly different between the control and fire scenarios. In addition, "Anxiety/Uneasiness" and "degree of difficulty" tended to be significant between the control and fire scenarios, while "Tension" tended to be significant between the control and abandonment scenarios.

The results indicate that psychological "Comfort" was lower and "Anxiety/Uneasiness," "Overall Stress Level," and "degree of difficulty" were higher in the abandonment scenario than in the control scenario. The fire scenario also had a higher "Overall Stress Level" than the control scenario.

Similarly, in a post-experiment interview on whether the participants felt stressed or threatened by the fire, 9 participants answered "yes" and 2 participants answered "no." Approximately 90% of participants felt stressed or threatened by the fire environment presented in this experiment.

3.5 Existence and content of manuals and training

The following were the results regarding the existence or nonexistence of manuals and training on MCR fires from the interviews.

3.5.1. Manuals for MCR fires

Five participants indicated that their nuclear power plant had a manual for MCR fires. However, no clear answers were obtained about the contents, such as "it only described the power sources that should be turned off," "I have little understanding of it," and "it was said that the priority was fire suppression."

3.5.2. Trainings for MCR fires

All participants answered that they did not have any experience in training for MCR fires.

3.5.3. Criteria for MCR abandonment

All participants answered that they did not have any clear criteria for MCR abandonment in the case of LOH.

4. DISCUSSION

The results of psychological indices and interviews indicated that many participants responded to each event with anxiety, even though the environment was quite different from that of a real plant. This suggests that the above results regarding the timing of MCR abandonment and reactor scrams, the related cognition and judgment, and the overall plant response to an MCR fire are reliable to some extent. Conversely, although approximately half of the participants had a manual about MCR fires, no clear answer was obtained regarding its content, because they do not usually use it. Additionally, all participants answered that they did not have any experience of training for MCR fire and had no clear criteria for MCR abandonment in the case of LOH.

In fact, fires that would affect the operations in the MCR are unlikely to occur because of the use of flame-retardant cables, the introduction of very early fire detection systems for panel fires, and the installation of fire shutters and partition walls between the MCR and the back panel at some power companies. However, some utilities in Japan are currently preparing a procedure manual for MCR fires. Additionally, only a few trainings on MCR fires have been conducted to date. We believe that the results of this experiment may help in the development of a procedure manual and design of new training programs. Furthermore, this study enabled us to obtain not only the criteria for the decision to abandon the MCR by the operators, but also the time required for the decision to abandon it, the method of evacuation, and other details that could not be answered in detail in the interview survey during the HRA qualitative analysis. In the future, if the issues in this study, as described below, can be resolved, a fire HRA that more closely reflects reality can be expected.

The issues in this study were the reality of the fire and the differences between actual plant responses. In the interviews, several participants highlighted a lack of senses other than the visual perception associated with fire, such as smell and heat. When similar experiments are conducted in the future, considering the presentation of fires will be necessary.

Note that the data in this experiment were obtained in an environment that is quite different from that of an actual plant. For example, the participants could not refer to manuals, they could not directly confirm changes in water levels, there was no one in front of them to provide instructions, and the structure of the MCR was different from that of their own. These factors make the response more difficult than that in normal plants. This VR simulator system allows only one person to experience the system simultaneously. In real operations, other operators may have spontaneously checked the plant parameters and provided information to the sub-shift manager. Furthermore, because the shift manager makes the actual decision to abandon the MCR, the sub-shift manager does not have to make a decision alone. The interview results showed that several participants commented that it was difficult to make a decision alone, and it can be inferred that the stress differed from that in an actual fire.

As this experiment was conducted in a setting where no support team, such as a self-defense fire brigade, arrived and because the fire was in a single unit, it is assumed that more people would come in and out of the MCR in a real fire. Although more people coming and going would increase the number of people who can engage in firefighting activities and the number of eyes monitoring the plant, other problems, such as communication errors, could occur. However, although the number of people in the MCR was set to eight in this experiment, the actual number was much smaller, and it may be more realistic to deal with a situation with a smaller number of people.

When conducting similar experiments in the future, it will be necessary to construct a system in which several people can respond simultaneously, and investigate the plant response of a team. Additionally, a system that allows manuals to be viewed in a virtual environment is required. We would also like to investigate the influence of each performance shaping factors on the fire response, such as the differences in the number of responders.

5. CONCLUSION

In this study, an experimental investigation was conducted to collect data on cognitive processes during MCR fires, including the actual timing of MCR abandonment, using VR. The following findings were obtained for the scenarios in this study:

1) The timing of the reactor scram was polarized either before or after the failure of the initial fire suppression, with the former deciding on an average of approximately 3 min after the onset of the fire. By contrast, the latter group decided within approximately one minute of the failure of the initial fire suppression.
2) The reasons for the reactor scram decision were mostly twofold: it was a MCR fire or the initial fire suppression had failed.
3) The average time for MCR abandonment was approximately 13 min after the onset of the fire (approximately four min after the failure of the initial fire suppression).
4) The timing of the instruction on MCR abandonment was mainly based on either failure of the initial fire suppression or insufficient smoke exhaust, although the possibility of MCR abandonment was considered at the same time as the onset of the fire.
5) Regarding insufficient smoke exhaust, no participant remained in the MCR without a self-air mask when the smoke layer descending below 2.9 m from the floor.
6) There were cases of dispersed evacuation.
7) Approximately half the participants were worried about the decision to abandon the MCR and/or reactor scram.
8) The response from the onset of fire to abandonment differed among individuals, even if they had the same utilities.

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References

[1] U.S. Nuclear Regulatory Commission and EPRI. *"EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Volume 2: Detailed Methodology"*, NUREG/CR-6850, EPRI 1011989, (2005).

[2] U.S. Nuclear Regulatory Commission and the Electric Power Research Institute (EPRI). *"EPRI/NRC-RES Fire Human Reliability Analysis Guidelines – Qualitative Analysis for Main Control Room Abandonment Scenarios – Final Report"*, NUREG-1921 Supplement 1, EPRI 3002009215, (2020).

[3] U.S. Nuclear Regulatory Commission and EPRI. *"EPRI/NRC-RES Fire Human Reliability Analysis Guidelines – Quantification Guidance for Main Control Room Abandonment Scenarios – Final Report"*, NUREG-1921 Supplement 2, EPRI 3002013023, (2019).

[4] U.S. Nuclear Regulatory Commission and Sandia National Laboratories, *"Risk Methods Insights Gained from Fire Incidents"*, NUREG/CR-6738, SAND2001-1676P, (2001).

[5] Hirose A., et al. *"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"*, Probabilistic Safety Assessment and Management PSAM 16, A-50, (2022).

[6] Hitachi-GE Nuclear Energy, Ltd. Web. *"Nuclear Power Plant Simulator"*, https://www.hitachi-hgne.co.jp/en/activities/abwr_construction/simulator/index.html, Accessed 13 May 2024.

[7] U.S. Nuclear Regulatory Commission and EPRI, *"Nuclear Power Plant Fire Modeling Analysis Guidelines (NPP FIRE MAG) -Final Report"*, NUREG-1934, EPRI 1023259, (2012).

[8] Research Institute of Human Engineering for Quality Life (HQL) HQL database site: the human senses database for work environment diagnosis. https://www.hql.jp/database/cat/etc/workdb1998, (1998). Accessed 25 Dec. 2023. (in Japanese)

[9] Hirose A., et al. *"A Study on the action to a Fire in Main Control Room of NPPs Leading to Loss of Habitability -Collection of knowledge on the cognition and behaviors of operators using VR-"*, CRIEPI Report, NR22012, (2023). (in Japanese)