Analysis on isolation condenser operation by Fukushima Daiichi Unit 1 operators

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Abstract: Fukushima Daiichi nuclear accident resulted in the core damage in three reactors and the release of considerable amount of radioactive material to the environment, not to mention significant social impact and anti-nuclear atmosphere all around the world. This paper provides a review of the findings related to shift operators' operation of the isolation condenser in Unit 1 to examine shift operators' response to the situation. Based on the review of the findings, a situation assessment model was developed to analyze shift operators' understanding on whether core cooling was successfully performed in Unit 1 through the operation of isolation condenser. It was found that lack of information could be one of the main causes for the failure in core cooling by the IC in Unit 1. It is also recommended that the differences in the mathematical model for the situation assessment and that of the real operator need to be further investigated.

Keyword: situation assessment; accident response; severe accident; Fukushima Daiichi accident

1 Introduction

Fukushima Daiichi nuclear accident resulted in the core damage in three reactors and the release of considerable amount of radioactive material to the environment, not to mention significant social impact and anti-nuclear atmosphere all around the world.

Whether human errors contributed to the progression of the accident or not has been controversial. The interim investigation report by Japanese government [1] indicated two specific examples of human errors, (1) misjudgment of operational situation of isolation condenser (IC) at Unit 1 and (2) poor handling of alternative water injection at Unit 3. This paper provides an analysis on the Unit 1 shift operators' understanding on the status of the core cooling by using IC.

Section 2 provides a review of the findings related to shift operators' operation of the IC in Unit 1 to examine shift operators' response to the situation. Section 3 provides an analysis on the shift operators' understanding on the operational status of IC by developing a mathematically-oriented situation assessment model for the shift operators. Section 4 provides the conclusion of this paper.

2 Summary of IC operation

In this section, the operation of IC in Unit 1 on March 11, 2011 is briefly summarized based on investigation reports and other literatures such as the Tokyo Electric Power Company and its Fukushima Nuclear Accident Analysis Report (TEPCO report) [2], the National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission (NAIIC report) [3].

Figure 1 shows the simplified system configuration of IC in Unit 1. When the Fukushima Daiichi nuclear power plants were hit by the Great East Japan Earthquake at 14:46, the reactor in Unit 1 shut down automatically and the reactor pressure and temperature were maintained by IC which started to operate at 14:52. The operation of IC was confirmed by not only the steam generation noise but also the decreasing trend of reactor pressure. The RPV pressure trend affected by the operation of IC is shown in Fig. 2. As the reactor pressure was rapidly decreasing, it was decided in the main control room (MCR) that the IC return piping containment isolation (CI) valves (MO-3A, MO-3B) were closed. In general, the reactor coolant

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cool-down rate is limited to be less than 100 ^{o}F/h (=55 ^{o}C/h) in emergency operating procedures (EOPs) to prevent pressurized thermal shock (PTS).

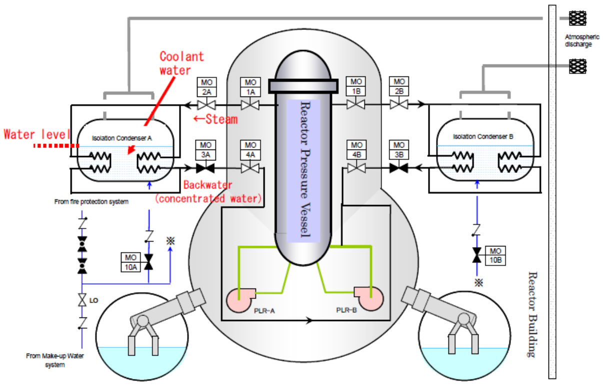

Fig. 1 System configuration of isolation condenser (Source: Tokyo Electric Power Company).

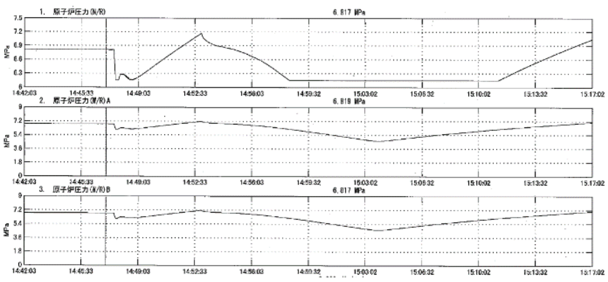

Fig. 2 RPV pressure affected by IC operation (Source: Tokyo Electric Power Company).

The two valves were closed at 15:03. As the reactor pressure rose after the closure of the two valves in IC, Subsystem A of IC was selected to limit the reactor pressure in the range between 6 and 7 MPa and therefore a return pipe CI valve (MO-3A) was manually opened and closed repeatedly to control the reactor pressure. After the reactor trip followed by the loss of offsite power (LOOP), the reactor in Unit 1 was stably operated towards cold shutdown by using the alternating current (AC) power supplied by two emergency diesel generators (EDGs) in Unit 1.

The tsunami hit the Fukushima Daiichi nuclear power plants twice, the first at 15:27 and the second at 15:35. The two EDGs in Unit 1 were tripped at 15:37, which caused the station blackout (SBO) condition at Unit 1. Due to the total loss of both AC power and direct current (DC) power, not only MCR lighting but also all instrument displays including those for ICs went out. Because the return pipe CI valve (MO-3A) was repeatedly opened and closed, the shift operators in the MCR could not remember the position of the valve. The positions of other valves could not be confirmed either.

The reactor water level indicator (wide range) was temporarily available between 16:42 to 17:00 and showed that the reactor water level is TAF (top of active fuel) + 2,500 mm and decreasing. Normally, the reactor water level is about TAF + 4370 mm. Such decrease and decreasing trend of reactor water level was the indication that the ICs were not functioning. To find out whether the ICs were functioning or not, the shift operators asked the emergency response center (ERC) whether steam was generating from the IC or not, and the ERC confirmed the steam generation, even though it was later found that the amount of steam was not significant. Shift operators in the MCR also headed to the reactor building (R/B) for field check at 16:55, to confirm IC shell side water level and to ensure an alternate reactor injection method using the diesel-driven fire pump (DDFP). The shift operators had to return without confirming IC shell side water level due to higher than normal radiation level in the R/B. The decreasing trend of reactor water level and the confirmation from the ERC that steam was generating from ICs were two conflicting evidences related to the operational status of ICs. It was unfortunate that the shift operators who left the MCR for field check could not confirm the IC shell side water level due to normal than higher radiation level because the information could provide shift operators in the MCR more accurate understanding on the operational status of IC.

While such response was carried out, the IC CI status indicator lamps were found to be lit, indicating that the supply pipe CI valve (MO-2A) and return pipe CI valve (MO-3A) of IC Subsystem A were in the closed state. Because the supply pipe CI valve (MO-2A) which was normally open was also closed, the shift operators believed that possibly all CI valves were closed due to the transmission of IC piping rupture signal which can also be generated by the loss of DC power source as a fail-safe feature. After deliberation, shift operators in the MCR managed to open CI valves (MO-1A, MO-4A) inside the primary containment vessel (PCV) and then IC return pipe CI valve (MO-3A) and supply pipe CI valve (MO-2A) at 18:18. The status lamps for the valves were confirmed to change from closed to open. Steam generation was confirmed by sight and sound. However, the steam generation halted after some time. The shift operators believed that steam generation halted because of isolation signal or lack of shell side cooling water. The shift operators closed the return pipe CI valve (MO-3A) at 18:25.

After establishing the configuration for the alternate water injection lines, it became certain that cooling water can be provided to the IC shell side. Shift operators activated DDFP at 20:50. The status display light for IC return pipe CI valve (MO-3A) was unstable and flickering at that time. Shift operators also attempted to provide make-up water to IC shell side using DDFP at 21:19. At that time, it was observed that the reactor water level was TAF + 200 mm and rising, which might be hard to be accepted by the shift operators. An explanation on why such erroneous indication on reactor water level was shown is provided in TEPCO report [2]. Shift operators entered R/B to check the IC shell side water level and reactor water level, but the field check was cancelled at 21:51 due to high radiation level. After connecting a small generator to dry well (D/W) pressure indicator and observed that D/W pressure was 600 kPa at 23:50. The rising radiation level and the very high D/W pressure were two more clues to the shift operators that the core cooling by the IC was not functioning.

3 Analytic model and results

To analyze Unit 1 shift operators' understanding on whether core cooling by IC was functioning or not, a situation assessment model was developed based on the one proposed by Kim and Seong [4]. Figure 3 shows the developed shift operators' situation assessment model in related to the core cooling by the operation of IC. The process of situation assessment was modeled with Bayesian inference. As shift operators receive information from the indicators in the MCR or other information sources, their belief on the status of core cooling was updated corresponding to the incoming information. The concept of ideal operator was also applied to the model and therefore the shift operators were assumed to be able to update their belief on whether core cooling was functioning or not upon receiving incoming information according to the mathematical relation of Bayes' theorem.

It should be noted that the situation assessment of real human operators cannot be as accurate as the mathematical relation. Bayesian inference provides only a rough approximation to the situation assessment of real NPP operators.

Seven information sources in Unit 1 during the initial response to the accident progression were considered, which were IC steam generation, IC tank level, RPV level, RPV pressure, D/W pressure, and the radiation in MCR. The relations between the status of core cooling and the indications from the information sources, which were considered as the mental model of the shift operators, were included in the model as node probability tables for the nodes corresponding to the information sources. The model also includes the shift operators' degree of trust on the information sources and the recognition of possible failures of information sources.

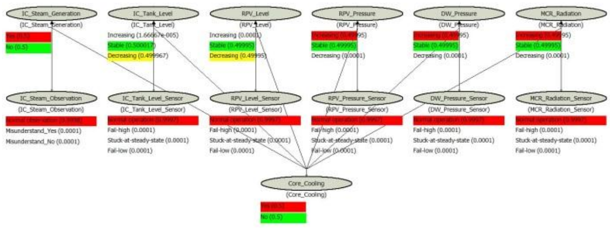

Fig. 3 Situation assessment model for core cooling in Unit 1.

According to the situation assessment model, the observation on the decrease in RPV water level could increase shift operators' belief that the core cooling was not functioning, while the confirmation from the ERC that steam was being generated from the IC could make it uncertain (two states with almost equal probabilities) of whether the core cooling was functioning or not. This uncertainty in the status of core cooling could be an important reason on why the shift supervisor dispatched operators inside the R/B to check the IC tank level, who returned without any information due to higher-than-normal radiation level inside the R/B. This inability to obtain information on the IC tank level maintained the uncertainty in the status of core cooling until further information was provided to the shift operators. It is speculated that if the steam generation from the IC could not have been confirmed or it had been confirmed that the IC tank level in the field did not change, priorities would have been given to the establishment of core cooling with IC at Unit 1.

The erroneous RPV water level in Unit 1 when the RPV water level indicator in MCR was restored at 21:19, about six hours after the total loss of AC and DC power, could significantly affect the situation assessment of shift operators. When the RPV water level was indicated as approximately TAF + 200 mm, in reality, core damage was already in progress. This indication could have made shift operators believe that the core cooling by the IC was functioning at that moment, although the increasing trend of RPV water level possibly made shift operators recognize that RPV water level indicator provided erroneous information. No matter how shift operators accepted the RPV water level indication at the moment, the erroneous RPV water level indication could affect the shift operators understanding on the status of core cooling by the IC.

As mentioned above, the change of real shift operators' belief might not be as drastic as the results of mathematical calculations. Such differences in the situation assessment of an ideal operator and a real operator need to be further investigated, like the one by Lee and Seong [5].

4 Conclusions

From the review of the findings, the lack of information is found to be one of the main causes for the failure in core cooling by the IC in Unit 1. It was also found that the shift operators continuously tried to find relevant information on the operational status of IC. Wrong information such as the erroneous RPV water level also imposed further difficulties in correctly understanding the operational status of the IC.

It was also found that shift operators' understanding on whether core cooling by IC operation was successful or not depending on the incoming information to the MCR could be modeled with a situation assessment model based on a Bayesian network. With the consideration of the limitations in the mathematical model, it is recommended to further investigate the differences between the situation assessment of ideal operators and the real operators.

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References

[1] Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company (established by the cabinet), Interim Report, 2011.

[2] Fukushima Nuclear Accidents Investigation Committee, Fukushima Nuclear Accidents Investigation Report, Tokyo Electric Power Company, Inc., 2012.

[3] The national Diet of Japan Fukushima nuclear accident independent investigation commission, The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission, The National Diet of Japan, 2012.

[4] KIM M. C., and SEONG P. H.: "An analytic model for situation assessment of nuclear power plant operators based on Bayesian inference," Reliability Engineering and System Safety, Vol. 91, No. 3, pp. 270-282, 2006.

[5] LEE H. C., and SEONG P. H.: "A computational model for evaluating the effects of attention, memory, and mental models on situation assessment of nuclear power plant operators," Reliability Engineering and System Safety, vol. 94, no. 11, pp. 1796-1805, 2009.