Development of Margin Assessment Methodology of Decay Heat Removal Function Against External Hazards
− Project Overview and Preliminary Risk Assessment Against Snow −

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Abstract: This paper describes mainly preliminary risk assessment against snow in addition to the project overview. The snow hazard indexes are the annual maximum snow depth and the annual maximum daily snowfall depth. Snow hazard curves for the two indexes were developed using 50-year weather data at a typical sodium-cooled fast reactor site in Japan. Snow hazard categories were obtained from a combination of the daily snowfall depth (snowfall speed) and snowfall duration that can be calculated by dividing the snow depth by the snowfall speed. For each snow hazard category, accident sequences were evaluated by producing event trees that consist of several headings representing the loss of the decay heat removal. Snow removal operation and manual operation of the air cooler dampers were introduced into the event trees as the accident managements. In this paper, a snow risk assessment showed less than 10^{-6}/reactor-year of core damage frequency. A dominant snow hazard category was a combination of 1−2 m/day of snowfall speed and 0.75−1.0 day of snowfall duration. Sensitivity analyses indicated important human actions, which were improvement of the speed of snow removal and awareness of snow removal necessity.

Keywords: PRA, External Hazard, Sodium-Cooled Fast Reactor.

1. INTRODUCTION

External hazard risk is increasingly being recognized as important for nuclear power plant safety after the Fukushima Daiichi nuclear power station accident. To improve the nuclear plant safety, risk assessment methodologies are necessary against various external hazards, although a probabilistic risk assessment (PRA) methodology against earthquake has been developed as a priority because of the importance of consequences by the earthquake. The Atomic Energy Society of Japan published a seismic PRA standard [1] in 2007 and a tsunami PRA standard [2] in 2012 which was vigorously developed as an important issue after the Fukushima Daiichi accident caused by the tsunami. Except for the two external hazards, there are no PRA standards against various external hazards in Japan. An alternative methodology different from the PRA was developed in Europe after the accident for complementary safety assessments, so called stress tests [3]. The stress test methodology is useful to show a margin to core damage against earthquakes and floods. Since challenging tasks in external PRA methodologies are quantitative external hazard evaluation, the stress test methodology would be useful and effective to suggest safety measures and accident managements that extend margins to core damage against external hazards. To improve the plant safety against various external hazards, it is necessary to develop risk assessment methodologies, such as the PRA or stress test methodology.

A four-year research project has started since 2012 to develop a margin assessment methodology of decay heat removal function against external hazards. In this project, only the decay heat removal function was taken into account assuming no loss of reactor shutdown function because the reactor trip was successful in the Fukushima Daiichi accident. Although this accident lessons suggested the importance of a spent fuel pool, this study focuses on event sequences resulting in core damage as a first step. The developed methodology is applied mainly to sodium-cooled fast reactors (SFRs), while it would be applicable basically to light water reactors (LWRs). A typical SFR heat sink is air, which is different from a heat sink in LWRs. Therefore, it is important external hazards that influence to air coolers (ACs) which are located at high elevation. This project addresses extreme weathers (snow, tornado, wind and rainfall), volcanic eruption and forest fire as representative external hazards. In this study, the external hazard evaluation, the event sequence and the margin assessment methodologies are developed for each external hazard.

This paper describes the project overview, followed by a presentation mainly of preliminary risk assessment methodology against extreme snow which is one of outcomes from this project in Japanese fiscal year 2012.

2. PROJECT OVERVIEW

2.1. Scope of External Hazards

The external hazards are roughly categorized into three groups: underground, ground-surface, and above-ground hazards. One of the representative underground hazards is earthquake which would have a structural impact on the nuclear power plant. Since significant boundary/component failures might lead to core damage, seismic design with an appropriate design margin to component failure has been preferentially implemented. The ground-surface hazards consist of tsunami (sea), flood (river), etc. The tsunami in the Fukushima Daiichi site in Japan and the flood in the Blayais site in France [4] have given full recognition to the significance of their hazard potential. From this background, nuclear regulatory authorities in many countries strongly require some actions and/or measures against their external hazards. This study aims mainly at a contribution to the risk assessment and safety improvement of the typical SFR in Japan. As shown in Fig. 1, the scope of external hazards in this study is above-ground hazards which might influence the decay heat removal system of the SFR. Air is usually taken not only into the decay heat removal system but also ventilation and air-conditioning system, emergency power supply system, etc. It should be noted that the PRAs against earthquakes and tsunami would be performed separately based on the regulatory requirement for the typical SFR in a similar way to risk assessments in LWRs.

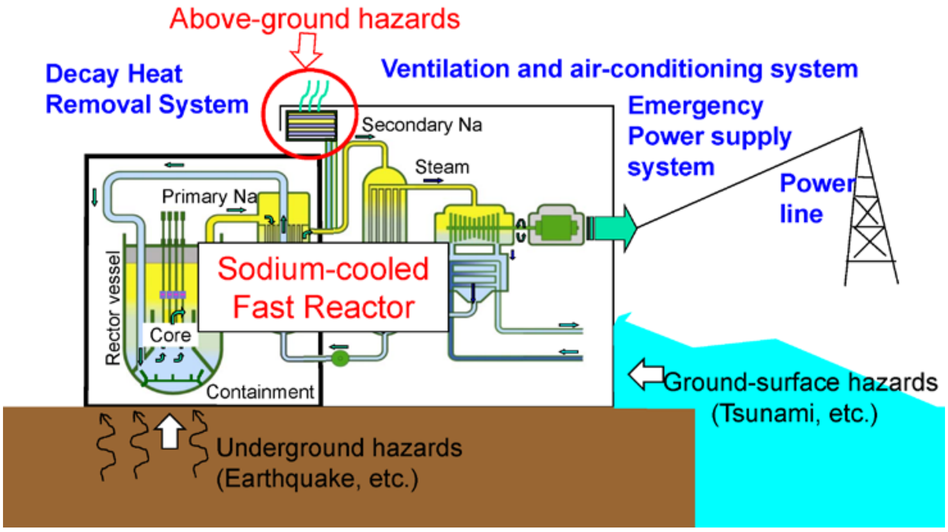


Figure 1: Scope of external hazards in this project

2.2. Selection of Representative External Hazards

In this section, a screening process is described to select the representative external hazards in this project: extreme weather, volcanic eruption and forest fire. At first, all foreseeable external hazards shall be exhaustively identified, including the potential for human-induced events directly or indirectly affect the safety of the nuclear power plant. There are a wide variety of external events by referring the International Atomic Energy Agency (IAEA) reports and so on [5–8]. Figure 2 shows the screening process for the typical SFR site in this study. As an initial step, a wide variety of external events are screened out in terms of site conditions, impact on plant, progression speed, envelop and frequency, in a similar manner to the NUREG/CR-4550 report [9–10]. For example, a drought can be precluded because it is less significant in Japan since nuclear plants are usually located near sea coast. In the second screening process, the external hazards are selected on a basis of the scope of this project, which are performed in view of natural hazards and above-ground hazards. Similar hazards are merged; e.g., hail can be enveloped by tornado-induced missiles. Through this screening process, this project selected extreme weathers (snow, tornado, wind and rainfall), volcanic phenomena and forest fire as representative external hazards.

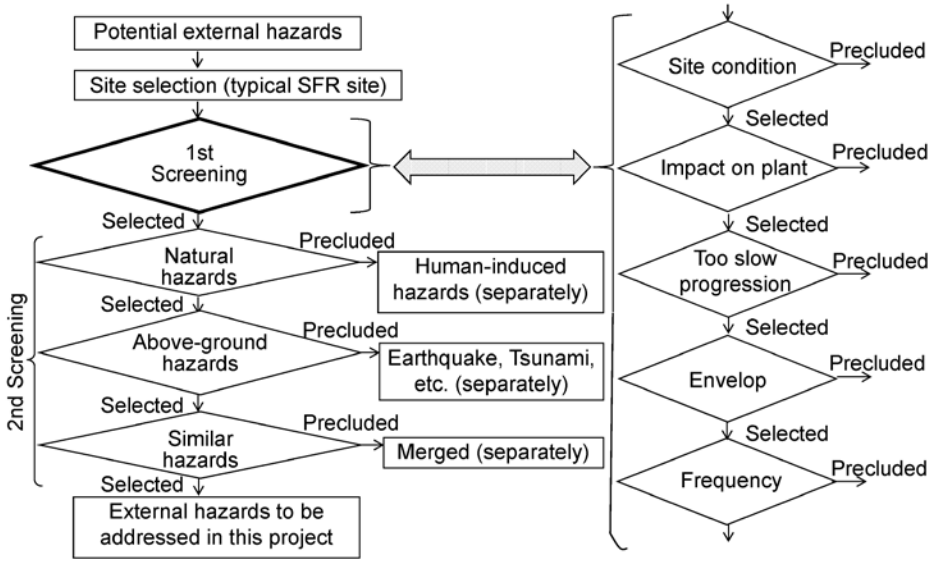


Figure 2: Screening process to select representative external hazards

2.3. Concept of Assessment Methodology

In general, an external hazard evaluation has a large uncertainty to quantify an occurrence frequency. Based on such background, the term "likelihood" is used in this paper. As with the stress test, an advantage of margin assessment is un-necessity of quantitative external hazard evaluation. Only an index is necessary to specify hazard intensity; e.g. peak ground acceleration in seismic margin assessment. On the contrary, the PRA requires a hazard curve that creates a relation between the likelihood and the hazard intensity. Since the event sequence evaluation is needed both for the margin assessment and PRA, a difference between them is quantification of external hazards. As illustrated in Fig. 3, both the margin assessment and PRA methodologies are developed because this project makes an attempt to develop the external hazard curve. The PRA would indicate a core damage frequency (CDF), whereas the margin assessment would show the extension of a margin to the core damage by introducing several measures including accident management.

The snow PRA methodology has been developed in the first year. Next, the PRA methodologies against tornado and wind in the second year, and against rainfall and volcanic eruption in the third year are scheduled to be developed. Finally, the PRA methodology development against forest fire and combination events is planned.

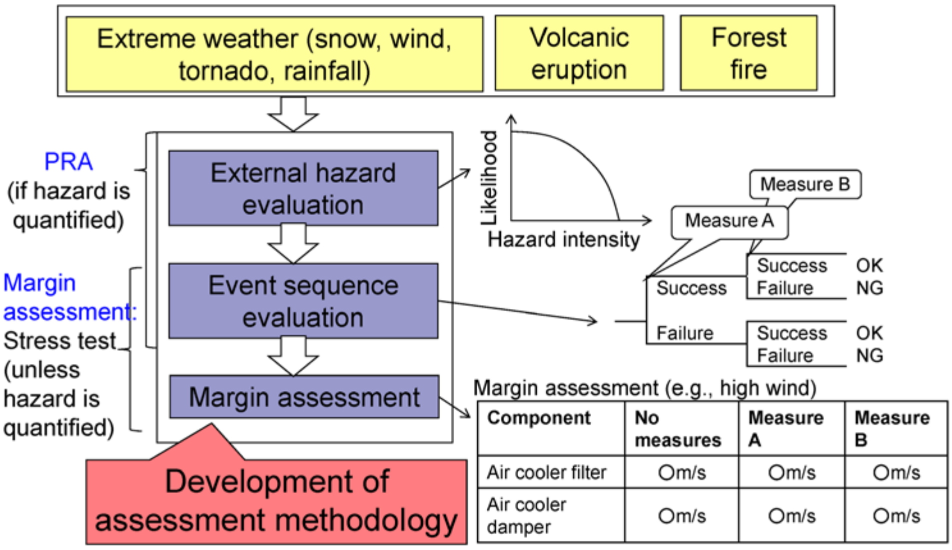


Figure 3: Concept of assessment methodology

3. SNOW PRA METHODOLOGY

3.1. Snow Depth Leading to Component Failure

Initiating events can be identified because components would be failed by a certain large level of earthquake and/or tsunami in a very short time without personnel actions. On the other hand, the personnel (except the one in the control room) can remove snow which is accumulated very slowly as not to have a serious impact on the plant. Therefore, the snow removal can be expected in the snow PRA. In this study, the initiating events were simplified and the event sequence was evaluated considering the time dependence, for which snow hazard category was used as mentioned in Section 3.2.

In this study, no snow removal capability for higher than six meters of snow depth was assumed for conservativeness and simplification, as explained in Section 3.2. Emergency power supply function would be lost by filter clogging at the air inlet of the emergency diesel generator room. In addition, the emergency diesel generator (EDG) could be failed by heating in the EDG room in case that the snow clogs the air inlets of ventilation and air-conditioning system. Thus, it was assumed that the loss of EDG power supply function enveloped the loss of the ventilation and air-conditioning system. The main decay heat removal system is an auxiliary cooling system (ACS) consisting of three loops in the typical SFR. This ACS is normally operated in a forced circulation mode with pony motors, but a natural circulation mode in this system is also available even in station blackout. Moreover, a maintenance cooling system (MCS) in the forced circulation mode with one loop using an electromagnetic pump is also available even if the decay heat removal capability by the ACS is lost. To put it all together, important components of the decay heat removal function that are affected by the extreme snow are representatively regarded as the ACS, MCS and EDG power supply system.

In fact, the heights are different between the air inlet and outlet of each important component. Since the snow would be melted due to hot exhausted air at the outlet, their important components are actually available for the decay heat removal if air is taken into the inlet. To conservatively evaluate in this study, however, the important components were assumed to be failed when the snow reached a lower elevation between the inlet and outlet. In this paper, the snow depths leading to the failure of the important components are specified as follows: 1.5 m for ACS, 2.0 m for MCS and 1.2 m for EDG.

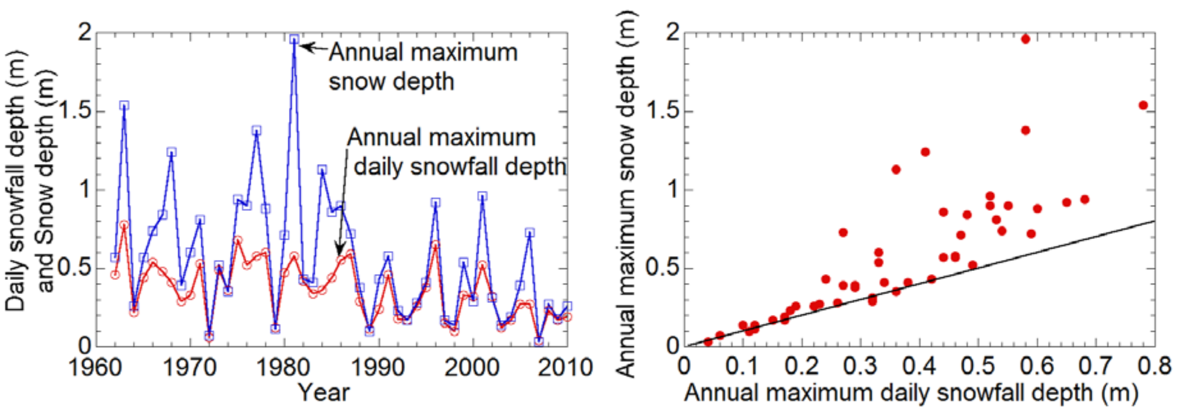
The loss of the decay heat removal function is roughly divided into two types: its functional failure and the structural failure of the system. The failure of the important components stated above is categorized to the functional failure which is caused by isolating air ventilation due to snow. The structural failure could arise from a heavy snow load exceeding the proof strength of a building or component. A reactor auxiliary building can withstand higher than ten meters of snow depth in the typical SFR in Japan. Other components also keep their integrity in a view of structural strength under a deeper snow condition, compared to the functional failure. Therefore, only the functional failure is addressed in this study.

In this paper, the lowest height leading to the failure of the important components is 1.2 m, at lower than which in turn no core damage sequence appears in the snow PRA. Sometimes, offsite power is lost at several ten centimeters of snow depth by disconnecting the power line. Therefore, the loss of offsite power can be regarded as an initiating event in the snow PRA.

3.2. Snow Hazard Category

3.2.1. Historical Records of Snow

In Japan, snow data is recorded at representative local offices of the Japan Meteorological Agency (JMA). Near the typical SFR site, a local weather observatory measures and collects various weather data including snow at the Japan Sea side central area in Japan. This study used snow data of 50-year from 1961 to 2010 based on the JMA database [11]. Historical records are plotted in terms of the annual maximum snow depth and the annual maximum daily snowfall depth in Fig. 4. At maximum, the annual maximum snow depth and the annual maximum daily snowfall depth are 1.96 m and 0.78 m/day, respectively. The snow depth has tended to decrease since 1980. As shown in Fig. 4 (b), the heavier the daily snowfall is, the deeper the snow depth is. Scattering, however, is large in deeper regions. In other words, duration of heavy daily snowfall is not always continuously long, so that a snowfall duration is important in the hazard evaluation.



(a) Historical records of snow **(b) Correlation of daily snowfall and snow depth**

Figure 4: Annual maximum data of daily snowfall depth and snow depth

3.2.2. Snow Hazard Evaluation Methodology

In this study, a snow hazard evaluation methodology was developed as described in Fig. 5 based on a probabilistic precipitation estimation methodology proposed by the JMA [12]. A basic concept of this methodology is a generalized estimation way. This is characterized by obtaining appropriate probability distribution through the conformance and stability evaluations.

The annual maximum data of the snow depth and daily snowfall depth was collected in Fig. 4. At first, using these data, the annual exceedance probability can be evaluated by plotting position formula: Weibull, Hazen and Cunnane for general use. Of the three formula, it is said that the Cunnane is the best suitable and applicable to all probability distributions. Next, the parameters of Gumbel or Weibull cumulative probability distributions are determined by a least square method. Using the annual exceedance probability, the snow hazard curves can be obtained after checking the conformance and stability evaluations.

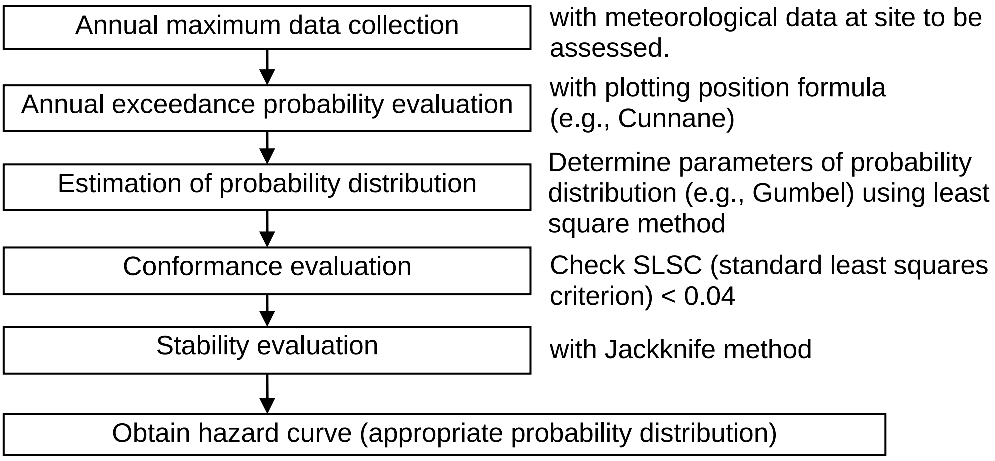


Figure 5: Snow Hazard Evaluation Methodology

3.2.3. Snow Hazard Category for PRA

Based on the snow hazard evaluation methodology in Section 3.2.2, the snow hazard curves were obtained in terms of the annual maximum snow depth and the annual maximum daily snowfall depth, as presented in Fig. 6. Given that the snowfall is time dependent, the snowfall speed (daily snowfall depth) and snowfall duration are important in the PRA for the personnel snow removal action. Using them, we have categorized the snow hazard to evaluate event sequences with the time dependence of snowfall. The snow hazard categories are obtained as a combination of the snowfall speed and snowfall duration that is defined as the snow depth divided by the snowfall speed.

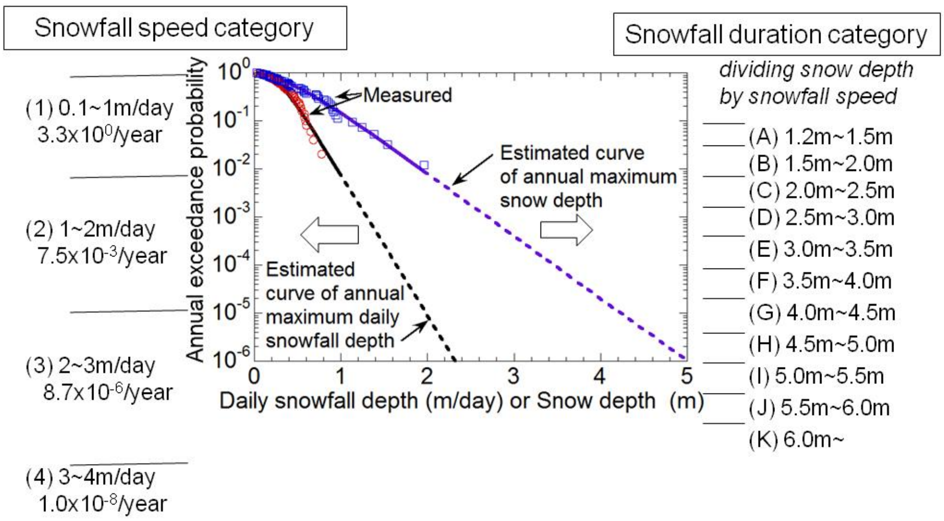


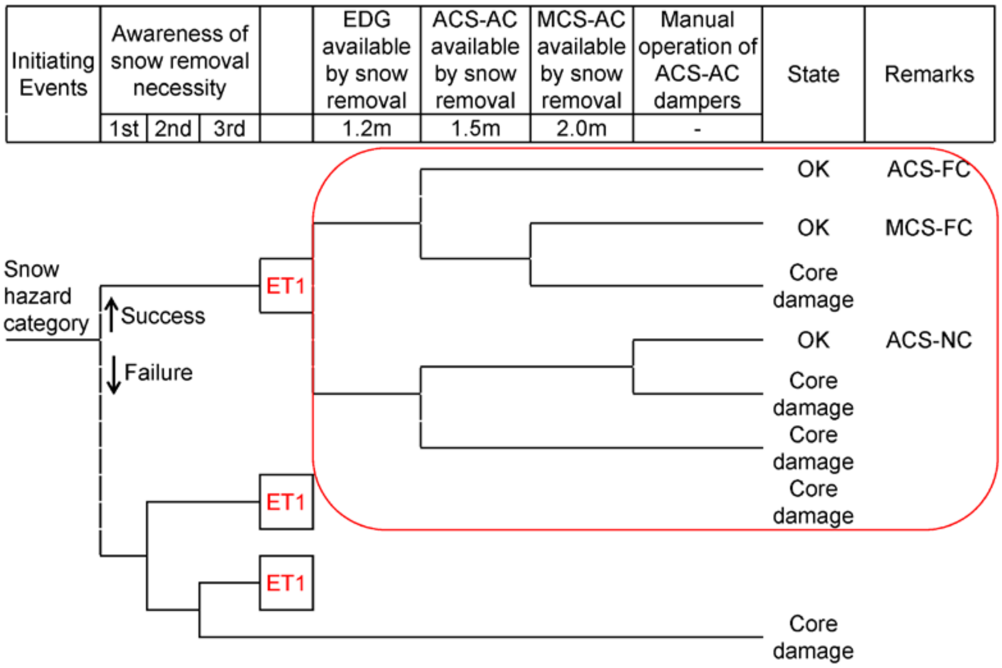
Figure 6: Snow Hazard Category

The snowfall speed lower than 0.1 m/day was precluded in this study because it was expected very low failure probability of snow removal, which needed 12 days to reach 1.2 m that could affect the plant. The present PRA also precluded the snowfall duration corresponding to the snow depth lower than 1.2 m because of no core damage. The snow hazard categories were represented as 44 combinations of four snowfall speed and eleven snowfall duration categories. The snow hazard category higher than 4 m/day of snowfall speed was regarded as the core damage because the annual exceedance probability was estimated less than 10^{-11}/year. For conservativeness, the present PRA used the maximum value in each snowfall speed category; e.g., 1 m/day in the category of 0.1−1 m/day.

The snowfall duration can be calculated by dividing the snow depth by the snowfall speed. For example, the snowfall duration category for 1.2–1.5 m becomes 0.4 day (9.6 hrs) − 0.5 day (12 hrs) of snowfall in case of 3 m/day. In this paper, the snowfall duration category corresponding to higher than 6 m of snow depth was also assumed as the core damage because the probability was estimated less than 10^{-7}/year by the snow depth curve. It should be noted that the CDF assessed in this paper is not lower than 1.7×10^{-7}/year, corresponding to the snow hazard category of a combination of the snowfall speed of 0.1–1 m/day and the snowfall duration corresponding to higher than 6 m.

3.3. Event Tree

As described in Section 3.1, air ventilation channels shall be secured for the important components in this PRA: EDG, ACS and MCS. The natural circulation decay heat removal is expected in the SFR, so that manual operation of the ACS-AC dampers is required in a total blackout situation (the loss of direct current powered equipment). They became headings of an event tree developed in the present PRA (see Fig. 7). Although personnel are usually aware of snowfall as much as necessary snow removal by weather forecast, it was assumed in this study that the awareness of snow removal was required when snowfall started. If there is no awareness of snow removal necessity, the event sequence would results in core damage. Several opportunities were actually expected for the awareness, but the present PRA assumed three chances for the awareness of snow removal necessity. This was incorporated into the first heading in the event tree.



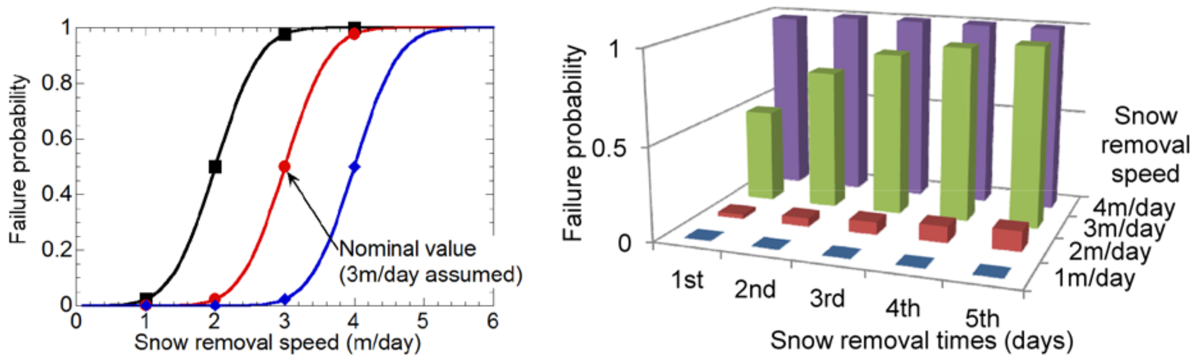
NB) EDG: Emergency Diesel Generator, ACS: Auxiliary Cooling System, MCS: Maintenance Cooling System, AC; Air Cooler, FC: Forced Circulation, NC: Natural Circulation

Figure 7: Main Event Tree for Snow PRA

3.4. Failure Probability for Each Heading

Based on NUREG/CR-1278 [13], the failure probability of the awareness of snow removal necessity was obtained 8.5×10^{-4}/demand using a human error probability with 60 minutes of grace period assuming a multiplier (one share) of an optimum stress level, step-by-step task, and skilled personnel.

Vulnerability against the snow hazard was focused in the present snow PRA, and thus we neglected component random failures involved usually in an internal-event PRA. The filter clogging of the air ventilation channels in EDG, ACS and MCS was assumed to depend only on the failure of snow removal task. Figure 8 shows snow removal failure probability model developed in this study. Its failure probability was modeled assuming a normal distribution with 1σ of 0.5 m/day. The average value of nominal snow removal speed was assumed 3 m/day in this paper. The present PRA assumed that the frequency of snow removal task increased according to the snowfall duration. For example, the snow removal times (days) were assumed five in the case of 5.0–5.5 m depth and 1 m/day (5.0–5.5 days) and once in the case of 5.0–5.5 m depth and 4 m/day (1.3–1.4 days). Figure 8 (b) indicates the increase of failure probability in many chances of snow removal (longer snowfall duration).



(a) Failure probability per day **(b) Failure probability considering snow removal times (days) with 3 m/day of nominal speed of snow removal**

Figure 8: Assumed Snow Removal Failure Probability

In manual operation of the AC dampers, sodium temperature measurement is necessary to prevent sodium freezing due to excessive cooling by keeping the damper opening. The reactor coolant temperature usually decreases to about 250°C in three days and then approaches to about 200°C in several days under the natural circulation heat removal condition with three loop ACSs. In the present PRA, the snowfall duration was considered six days at longest. Within six days, sodium freezing in the ACS can be neglected judging from the sodium temperature decrease history mentioned above. In the present PRA, therefore, the sodium temperature measurement was not necessary, and the failure of the natural circulation cooling was assumed to be dependent on the manual operation failure of the AC damper opening. Based on NUREG/CR-1278 [13], the human error probability was specified in regard to the opening operation of two dampers in one loop AC. The manual operation failure probability was estimated 2.4×10^{-4}/demand assuming a high dependence of recovery by a two-personnel implementation task and a low dependence of recovery by plant parameter diagnostics after the task. This estimate was multiplied by 5 assuming very high stress level, step-by-step task, and skilled personnel. Finally, the failure probability of the AC damper manual operation was estimated 6.5×10^{-3} /demand as an average value using 10 of error factors.

3.5. Event Tree Quantification

The decay heat removal failure probability of each event sequence was obtained by introducing the failure probability in Section 3.4 into the event tree in Section 3.3. Figure 9 shows the heat removal failure probability by the snow hazard category. The higher the snowfall speed is, the higher the failure probability is. The failure probability increases when the snowfall duration is long (expressed as the snow depth in this figure).

The CDF by the snow hazard category can be calculated by multiplying each heat removal failure probability described above and each snow hazard occurrence frequency. The CDF brings total to less than 10^{-6}/year. Figure 10 shows the CDF by the snow hazard category. The snow hazard curve allowed the conditional CDFs to appear at relatively low snowfall velocities and short snowfall duration. Although the CDF is highly visible in the snowfall duration longer than 6 days (snow depth higher than 6 m in this figure) in 1 m/day, this value can be distinguished because this was assumed as core damage regardless of event sequences under this snow hazard category, mentioned in Section 3.2.3. This visible CDF could disappear if the snow hazard category is extended. As shown in Fig. 10, the dominant snow hazard category was a combination of 1−2 m/day of snowfall speed and 0.75−1.0 day of snowfall duration. Given that such a snowfall condition is not so rare in some areas in Japan, this PRA result is expected to be useful for future considerations against a lot of snow.

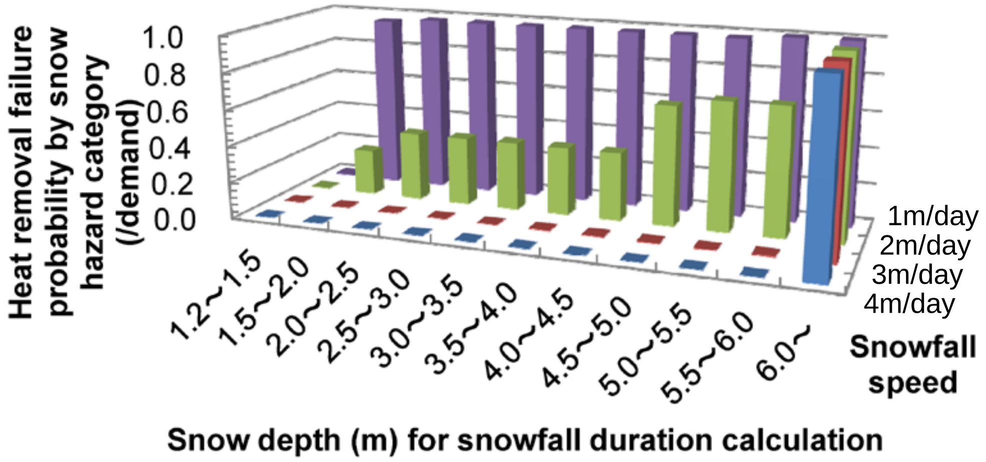


Figure 9: Core Damage Frequency by Snow Hazard Category

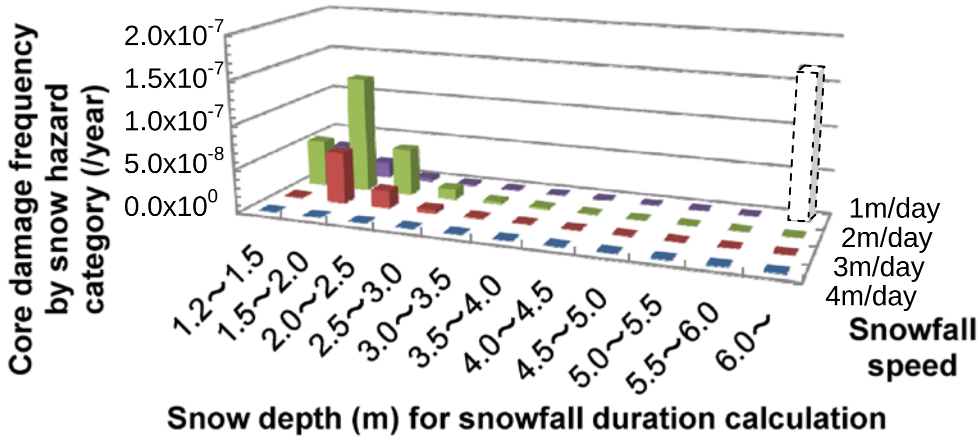


Figure 10: Core Damage Frequency by Snow Hazard Category

3.6. Sensitivity Analysis

A number of various assumptions could bring a large uncertainty in this PRA. Given that the failure probabilities would be changed at the headings in the event tree, their sensitivities should be analyzed for future usefulness and effectiveness of the snow PRA. In this paper, sensitivity analyses were carried out with parameters of the awareness times, the failure probability of awareness, the snow removal speed, and the failure probability of the AC damper manual operation.

The CDFs obtained in the sensitivity analyses are plotted in Fig. 11. When the awareness the snow removal necessity is once, the CDF does not significantly decrease as the snow removal speed. When the frequency of the awareness increased from once to twice, the CDF remarkably decreased by approximately three orders of magnitude. This suggests that the awareness more than once is very important. The CDF significantly decreased as the snow removal speed increased in the awareness both twice and three times. The twice awareness cases were shown similar to the three-time awareness cases even if the snow removal speed was changed. This was because the CDF lower than 10^{-6} cannot be reduced due to the simplification of the present PRA. The effectiveness of many awareness times and high snow removal speed would be investigated for future task. The CDF became three times higher in case of ten times manual operation failure probability and 0.6 times in case of 0.1 times probability. This indicated that the manual operation failure probability was less sensitive.

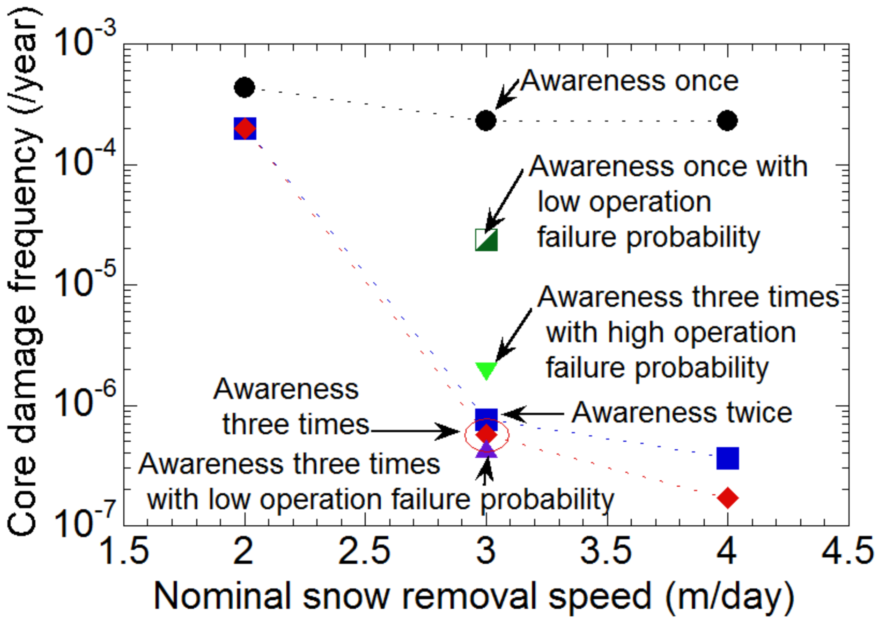


Figure 11: Sensitivity Analyses

4. CONCLUSION

This paper reported the first outcome of the four-year research project, which has started since 2012 to develop a margin assessment methodology of decay heat removal function against external hazards. The scope of external hazards in this study was shown above-ground hazards, which might influence the decay heat removal system of SFR. Through the screening process, this project selected extreme weathers (snow, tornado, wind and rainfall), volcanic eruption and forest fire as representative external hazards. This paper indicated the concept of the assessment methodology developed in this project, which consisted of both the margin assessment and PRA methodologies. On that account, we have initiated to develop the external hazard evaluation, the event sequence and the margin assessment methodologies for each external hazard.

This paper described the preliminary PRA results. The snow hazard evaluation methodology was developed through the assessment using 50-year data of the snow hazard indexes of the annual maximum snow depth and the annual maximum daily snowfall depth at the typical SFR site. Snow hazard categories were defined as the combination of the snowfall speed and snowfall duration. For each snow hazard category, the accident sequence was evaluated by producing event trees that consist of several headings representing the failure of the decay heat removal. In this paper, the snow PRA showed less than 10^{-6}/year of CDF. The dominant snow hazard category was the combination of 1−2 m/day of snowfall speed and 0.75−1.0 day of snowfall duration. Sensitivity analyses indicated important personnel actions, which were the snow removal speed improvement and frequent awareness of snow removal necessity.

In this snow PRA, the simplified evaluation brought conservative CDF by rough categorization of the snow hazard, thus finer hazard categorization than the present PRA is expected to improve the CDF estimation. Furthermore, plant walk-down should be carried out for the improvement of event tree development. The snow removal speed should be also investigated to reduce the uncertainty of sensitive parameter. In addition to the PRA, the margin assessment methodology will be developed against snow. In this project, the PRA methodology will be developed against other hazards: tornado, wind, rainfall, volcanic eruption and forest fire.

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