博士論文

Study on Severe Accident Consequence Index Aiming for Protection of People and the Environment

（人と環境を守るための過酷事故影響指標に関する研究）

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Chapter 1 Introduction

1.1 Background

1.1.1 IAEA fundamental safety objective [1.1]

The International Atomic Energy Agency (IAEA) clearly stated in its Fundamental Safety Principles [1.1] that *the fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation*. Here, "people" includes not only local populations but also populations remote from the source of radiation. This follows the definition of the IAEA. "The environment" is defined as the surroundings of the "people" which can directly affect their lives, thus are normally given importance to during the decision making process, e.g. functionalities of residential area, agricultural area, offices, schools, roads, forests and so on. We adopt a broad interpretation of the *harmful effects of ionizing radiation* from which people and the environment have to be protected - not only direct effects from *the radiation exposure* to people and from *the release of radioactive material* to the environment, but also all indirect effects to people and the environment have to be taken into account.

The IAEA further stated that *to ensure that facilities are operated and activities conducted so as to achieve the highest standards of safety that can reasonably be achieved, measures have to be taken:*

(a) To control the radiation exposure of people and the release of radioactive material to the environment;

(b) To restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation;

(c) To mitigate the consequences of such events if they were to occur.

As *safety is concerned with both radiation risks under normal circumstances and radiation risks as a consequence of incidents*, item (a) is there to ensure that concerned receptors (people and the environment) are not affected by ionizing radiation whether under normal operations or during accidents. Items (b) and (c) have their bases on the concept of risk - risk is normally defined as the combination of the likelihood of the anticipated incidents, and their consequences [1,2]. Item (b) corresponds to the likelihood and item (c) corresponds to the consequences of the incidents. Consequently, based on the above-mentioned interpretation of the IAEA fundamental safety objective, the responsible person or organization of the facilities must:

(1) Control the radiation exposure of people and the release of radioactive material to the environment during normal operations;
(2) Make an effort to minimize the likelihood of events that might lead to a loss of control over any sources of radiation to the reasonably achievable level;
(3) Make an effort to minimize all consequences of such events to people and the environment to the reasonably achievable level.

1.1.2 Accident at Fukushima Daiichi Nuclear Power Station

The accident at the Fukushima Daiichi Nuclear Power Station (hereinafter referred to as Fukushima accident) showed that a severe accident wreaks tremendous consequences to both people and the environment. Three huge tsunamis attacked the Fukushima Daiichi Nuclear Power Station after the Great East Japan Earthquake (magnitude 9.0) in March 11, 2011, which consequently led to station blackout (SBO). There were hydrogen explosions in units 1 and 3. Reactor core melting, and reactor vessel and containment vessel failures were strongly suspected in units 1 – 3 [1.3]. More than 140,000 people sheltered and evacuated [1.4] as there was a large amount of radioactive materials released from the scrapped reactors [1.5]. The sheltered and evacuated people lost their incomes throughout the period of sheltering and evacuation, and thousands square kilometers of area was contaminated. As the target area for decontamination is very large, the decontamination process would probably need several years, and thus evacuated people would not be able to return to the hometown for years. Also the decontamination of the area would result in a large amount of radioactive wastes which need to be managed properly. After the accident, public opinion toward the usage of nuclear power became very negative [1.6], and all electric companies could not easily restart their power plants after shutting them down [1.7]. All these consequences after the Fukushima accident support our broad interpretation of the *harmful effects of ionizing radiation* in Subsection 1.1.1, which suggest that we need to take into account not only direct effects from the radiation exposure to people and from the release of radioactive material to the environment, but also all other effects to the people and the environment.

1.1.3 Ideal severe accident consequence assessment scheme

In this study, we focus on item (c) in Subsection 1.1.1 which deals with mitigation of consequences of events that might lead to a loss of control over any sources of radiation. A "nuclear power plant" is selected as the source of radiation, and a "severe accident" is selected as the concerned event. Here, a "severe accident" is defined as an accident which is beyond the scope of design basis accidents. In order to be able to mitigate the consequences of a severe accident in a nuclear power plant if they were to occur, a comprehensive severe accident consequence assessment scheme is required. A comprehensive assessment scheme would help identify all anticipated consequences and their extent, and consequently contribute to the mitigation of the overall consequence. Based on the discussion above, this assessment scheme has to be able to include both direct and indirect consequences to both people and the environment. The conceptual diagram of the ideal severe accident consequence assessment scheme is shown in Figure 1.1. It can be assumed that consequences to people would be a subset of consequences to the environment, as the environment is the aggregate of the things surrounding the people.

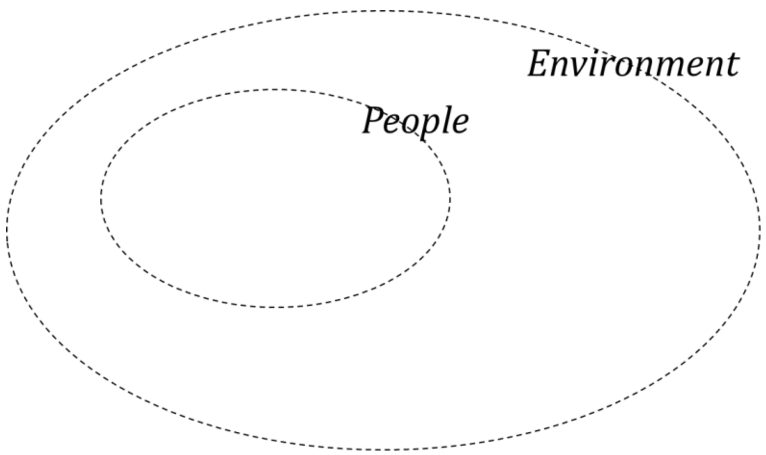

Figure 1.1. Conceptual diagram of ideal severe accident consequence assessment scheme.

1.2 Preceding and Other Ongoing Studies

The majority of earlier studies on severe accident consequence assessment [1.8-1.11] concentrated on the assessment of health effects due to radiation exposures. They estimated acute and chronic doses resulted from external exposure (by cloudshine, groundshine and resuspension) and internal exposure (by inhalation and food intake). There was basically no discussion on direct effect on the environment (contamination of the environment by the release) and any other indirect effects to people and the environment. This may be because the safety criteria in regard to the consequences of severe accidents commonly used in many countries are the individual radiation exposure doses [1.12]. Therefore, from a regulatory viewpoint, the researches being conducted by responsible organizations in respective countries had to focus on dose evaluation, in order to be able to assess the fulfillment of those criteria. In addition, as the emergency response is planned based on the results of these assessments, the sole objective of the preceding researches on emergency response [1.8, 1.13] was to minimize the individual radiation exposure by quick migration of people away from the affected power plant and restriction of food intake of those people. The safety criteria adopted and the corresponding researches show an excessive focus on protection of people from radiation exposure and point out the lack of awareness of possible consequences of an accident to the environment.

On the other hand, there have been a number of studies which attempt to integrate different consequences of a severe accident by monetizing them. ExternE [1.14], Pascucci et al. [1.15], Hirschberg [1.16] and IAEA Technical Reports Series No. 394 [1.17], evaluated various accident consequences in terms of monetary value, referring to the consequences of the accident at the Chernobyl Nuclear Power Plant (hereinafter referred to as Chernobyl accident). However, the objective of these studies was not to improve the comprehensiveness of the consequence assessment scheme, but to perform a comparative accident consequence assessment among the electricity generation systems. Therefore, consequences selected are those could be commonly taken into account by all electricity generation systems, thus there is a possibility for consequences particular to nuclear severe accidents to be overlooked. In Japan, Park [1.18] made an estimation of total costs which may be generated after a severe accident, but he considered only some extreme accident conditions, and some assumptions he adopted were not adequately realistic. In addition, he focused on the direct and indirect consequences to people, and did not take into account the consequences resulted from contamination of the area. After the Fukushima accident, other than the author, the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) [1.19] and the United States Nuclear Regulatory Commission (USNRC) [1.20] have also started a research on monetization of the consequences of a severe accident, which would help enlarge the scope and improve the quality of the severe accident consequence assessment scheme. The movement of these two important regulatory bodies confirms the important of reconsideration of the severe accident consequence assessment.

From the preceding and ongoing studies stated above, it can be concluded that there is a necessity to improve the severe accident consequence assessment in many aspects. Firstly, the assessment scheme have to be modified in order to take into account all anticipated consequences of a severe accident to people and the environment. Secondly, from a regulatory viewpoint, the confirmation of the safety of a nuclear power plant in regard to the consequences of a severe accident must include consideration of consequences to both people and the environment. This could be done by having discussion on appropriateness of current safety criteria from the viewpoint of coverage of consequences to people and the environment, which may consequently lead to a reconsideration of these criteria themselves, or the way to properly make use of them. Lastly, the emergency response after a severe accident, including accident management strategies and radiation protective measures, must be reconsidered in a manner that consequences to both people and environment are thoroughly taken into account.

1.3 Final Goal and Necessary Research Components

Based on discussion in previous sections, the final goal of this research is set to *establish a practice in a severe accident consequence assessment to comprehensively include direct and indirect consequences of a severe accident to people and the environment*. This could be done by:

(1) Developing a severe accident consequence assessment scheme which is as close as possible to the ideal scheme shown in Figure 1.1;
(2) Demonstrating the applicability of the scheme in order to promote the practice of comprehensive consequence assessment using this newly developed scheme.

Research components necessary to successfully complete both tasks are described below.

1.3.1 Development of severe accident consequence assessment scheme

A research must be conducted to form a comprehensive severe accident consequence assessment scheme which can take into account all anticipated direct and indirect consequences to people and the environment. This can be done by developing a quantitative index which can include all anticipated and quantifiable consequences in order to perform a quantitative consequence assessment, and have a separated qualitative discussion on non-quantifiable consequences parallel to the quantitative assessment. This quantitative index must be estimated using acceptable models and updated information under realistic assumptions. Additionally, the assessor and the decision maker who would make any decisions based on this consequence assessment must be aware of the existence of unanticipated consequences, which are excluded from the assessment scheme due to the limitation of the knowledge and the experience of the assessor.

1.3.2 Applications of severe accident consequence assessment scheme

In order to promote the practice of comprehensive consequence assessment using the aforementioned scheme, the scheme must be proved applicable for the assessment of the real situations which would normally be conducted for some specific objectives. We found that the consequence assessment of a severe accident is normally conducted:

(1) To confirm the safety of a nuclear power plant in regard to the consequences of a severe accident;
(2) To identify appropriate emergency response (including accident management strategies and radiation protective measures).

Applicability of the scheme for these two objectives must be at least demonstrated.

The former application may start with evaluation of the conformity of the current regulatory requirements regarding the consequences of a severe accident to the ideal consequence assessment scheme shown in Figure 1.1 using the abovementioned quantitative index. The research would include the proposal of reconsideration of the safety criteria, or suggestions for additional consideration by the licensee or the regulatory body apart from the confirmation of the fulfillment of the current safety criteria in order to comprehensively take into account all anticipated consequences. From the regulatory viewpoint, it is necessary for the research to consider the consequences of a severe accident from a bird-eye view to be able to grab the whole picture of the consequences of the accident. This is because the main task of the regulator (and also the licensee) is to ensure that the concerned nuclear power plant fulfills the safety criteria, rather than going into detail of the scenarios and the way to manage respective consequences. In addition, since this has a potential to be applied in all nuclear power plants, the assessment scheme must be adequately simple and comprehensible in order not to require excessive resources of the licensee or the regulatory body to perform the assessment.

The latter application is also very important since careful consideration of respective emergency response measures taking into account the resulted consequences to the people and the environment can contribute to minimization of the overall consequences of a severe accident, unlike forepassed practices which aimed only to minimize the consequences to people. In this regard, the influences of major parameters of the emergency response, e.g. the degree of reduction of source term, the potential of respective accident management strategies to delay the core melt, or the dose criteria which are used to trigger respective radiation protective measures, to the overall consequences, has to be carefully considered. A detailed consequence assessment scheme is needed for this purpose. The outcome of this research may be, for example, the scheme for accident management strategy selection or the optimized radiation protective scenario which can help minimize the consequences resulted from a severe accident.

If all issues mentioned above are thoroughly considered, a practice in a severe accident consequence assessment to comprehensively include direct and indirect consequences of a severe accident to people and the environment would be successfully established. This would consequently contribute to the protection of people and the environment, as stated in the safety objective of the IAEA.

1.4 Objectives of the Study

Following objectives are set as the objectives of this study in order to contribute to accomplishment of the final goal stated in Section 1.3 - to establish a practice in severe accident consequence assessment to comprehensively include direct and indirect consequences of a severe accident to people and the environment.

- ✓ To develop an index called “nuclear accident consequence index” that can include all anticipated and quantifiable consequences of a severe accident in a nuclear power plant on people and the environment.
- ✓ To modify the decontamination model being used in the estimation of the nuclear accident consequence index in order to ensure the level of quality of the model.
- ✓ To confirm that 100 TBq cesium 137 release into environment can be used as a safety criterion in regard to the consequences of a severe accident by using the simplified nuclear accident consequence index to assess the release.
- ✓ To investigate the correlations between nuclear accident consequence index and release parameters, namely release amount, release period and release starting time. These correlations would enable the anticipation of consequences resulted from respective types of releases to people and the environment, without spending resources to assess the nuclear accident consequence index.

Apart from this, sensitivity analyses and parameter surveys will be performed throughout the study. Their results would provide some clues to establishment of emergency response scheme which can potentially minimize the overall consequences resulted from a severe accident.

1.5 Expected Contributions of the Study to Severe Accident Consequence Assessment

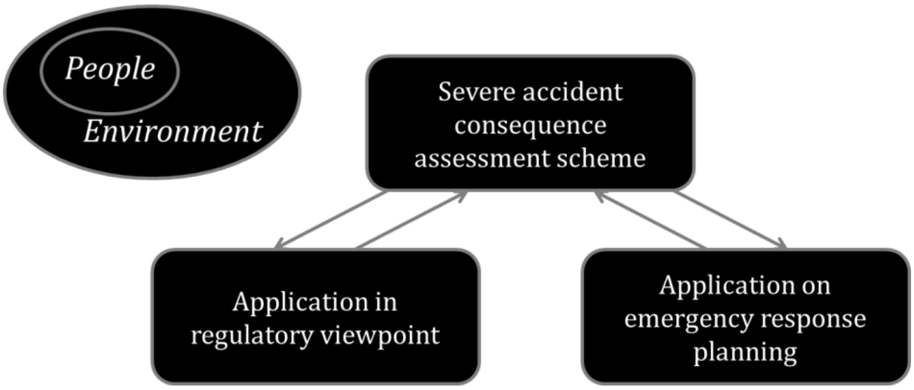

Figure 1.2. Status of severe accident consequence assessment when the final goal is accomplished.

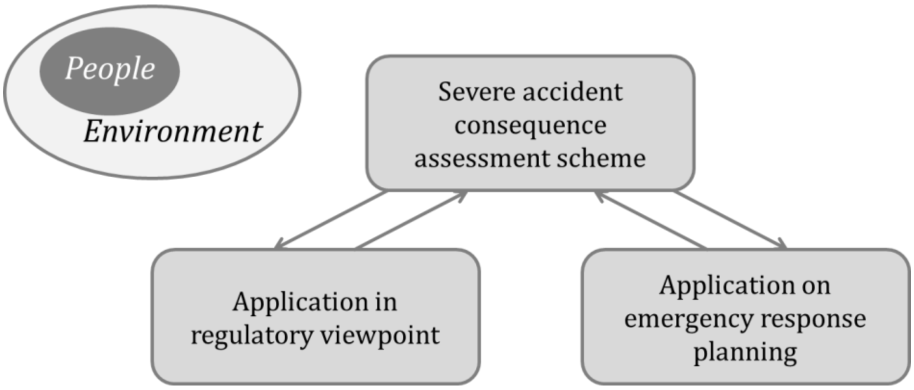

Figure 1.3. Current status of severe accident consequence assessment.

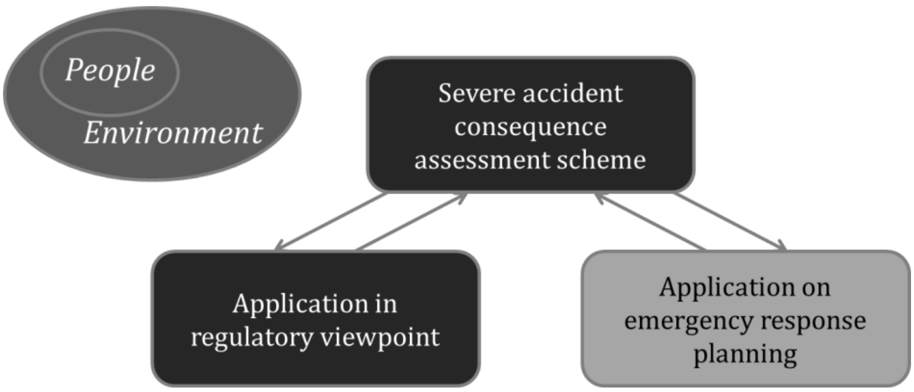

Figure 1.4. Status of severe accident consequence assessment after this study.

Figures 1.2 to 1.4 show the status of the severe accident consequence assessment of a nuclear power plant when the final goal is accomplished, the current status, and the status after this study, respectively. The degree of achievement of respective tasks are represented by the strength of the color in grayscale. The color white represent the stage when nothing is done, while the color black represent the accomplishment of the tasks.

Figure 1.2 is straightforward: all research components are painted black. When the final goal is achieved, the assessment would be able to include all anticipated and quantifiable consequences to people and the environment, whether direct or indirect. Concurrently, the quality of all models used in the assessment is ensured. Regarding the application in regulatory viewpoint, consequences to people and the environment can be comprehensively assessed by the licensee, the regulatory body or any other stakeholders with limited resources. Regarding the application on emergency response planning, emergency response activities are determined in the manner that minimize the overall consequences to people and the environment.

Figure 1.3 reflects the current status where the emphasis is placed on direct consequence on people. As described in Section 1.2, most assessments performed in recent years has included only the evaluation of radiation exposure dose of the population. Just few of them include some discussions on direct consequences to the environment, or any indirect consequences. This implies that the only available consequence assessment scheme is for the assessment of direct consequences to people. Nowadays, the regulatory process would include only confirmation of the direct consequences of anticipated severe accidents to people, and the emergency response activities are determined in the manner that minimize the radiation exposure of the people. Therefore, all research components are painted pale grey, which indicate plenty room for improvement. Since most assessments focus on direct consequences to people, the consequences to people is painted grey, while the color of consequences to the environment is almost white.

Figure 1.4 is what we are going to achieve after this study. The nuclear accident consequence index is designed to cover all anticipated and quantifiable consequences of a severe accident to people and the environment. The models used to estimate major components of the index are also carefully verified. This index will be included in the consequence assessment scheme in which the unquantifiable consequences are qualitatively discussed. Therefore, the color of the box of severe accident consequence assessment scheme is nearly black. As for the application in regulatory viewpoint, since the nuclear accident consequence index is used to discuss the appropriateness of the regulatory criteria regarding accident consequences, we can assume that there is sufficient discussion on consequences of a severe accident to people and the environment. In addition, as the correlations between the release parameters and the nuclear accident consequence index are identified, consequences to people and the environment can be assessed using those release parameters which would significantly reduce resources required for the assessment. Thus the box of this research component is almost black. Although there is no study dedicated to the application on emergency response planning, the results from sensitivity analyses performed thorough this study can provide some clues to the establishment of emergency response scheme which can potentially minimize the overall consequences to people and the environment. For that reason, the box is in a darker tone than that of Figure 1.3.

The large differences between the strength of color of respective components in Figure 1.4 and Figure 1.3 indicate the great contributions of this study to severe accident consequence assessment. However, the differences between the color of the boxes in Figure 1.4 and Figure 1.2 implies that there is still room for further research to achieve comprehensiveness in a severe accident consequence assessment. Therefore, severe accident consequence assessment would still be one of the interesting research topics worth for a researcher to work on.

1.6 Structure of the Thesis

This chapter, Chapter 1, is an introductory chapter which includes background of the study, review of preceding studies, discussion on final goal and researches necessary to accomplish the goal, and finally the objectives of the study.

Chapter 2 will describe the nuclear accident consequence index which is supposed to be used to assess all anticipated and quantifiable consequences resulted from a severe accident. It starts with the overview of the estimation, followed by the description of calculation conditions. Then a brief introduction of the Off-Site Consequence Analysis of Atmospheric Releases of radionuclides (OSCAAR) Code which is used to estimate the public exposure dose and the land contamination is provided. The largest part of this chapter is the explanation of the way to estimate the nuclear accident consequence index, following by the results and discussion. Lastly, the results of the ceteris paribus sensitivity analysis which is carried out to identify influential parameters are presented.

Chapter 3 deals with the modification of decontamination model, which is a very important model used in the estimation of the nuclear accident consequence index, and which was not fully mature in Chapter 2. It starts by stating why the decontamination model needs modification. Then the flow chart of the modification is introduced, and the detail of the new model is described. Elementary effects method is used to perform sensitivity analysis, and important parameters are identified. The model is simplified based on the sensitivity analysis results, and is verified by comparing with the full model. Finally, the nuclear accident consequence index estimated by the new model is compared with that estimated by the former model.

Chapter 4 discusses the applicability of the nuclear accident consequence index from regulatory viewpoint. It basically aims to identify the relation between the consequences of a severe accident, represented by the nuclear accident consequence index, and the accidental release, represented by release parameters. Firstly, the limitedness of consequences due to 100 TBq cesium 137 release into environment is investigated using the simplified nuclear accident consequence index, in order to prove its appropriateness as a safety criterion in regard to the severe accident consequences. Then the correlations between the nuclear accident consequence index and the release parameters, namely release amount, release starting time and release period, are thoroughly examined.

Chapter 5 concludes the thesis. It also indicates further studies which are needed to accomplish the final goal stated in Section 1.3.

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Chapter 2 Nuclear Accident Consequence Index[1]

2.1 Overview of Estimation of Nuclear Accident Consequence Index

Figure 2.1 shows the flow of the estimation of the nuclear accident consequence index. First of all, the reactor type and its location are determined. Then the severe accident sequences are defined in order to cover all anticipated severe accidents. Accident sequences that do not proceed until the accidental release are excluded from the scope of the study since they do not suit the objectives of the study. Subsequently, the source term data of respective accident sequences, including the release time, release duration and the amount of radioactive material released to the environment are calculated or taken from a level 2 probabilistic risk assessment (PRA) report. At the same time, the radiation protection scenario is set, and the containment failure frequencies (CFFs) of representative accident sequences are calculated or taken from a level 2 PRA report. The CFFs are used to weight the accident sequences in the estimation of average nuclear accident consequence index in order to prioritize the accident sequences according to their probabilities of occurrence. Next, the exposure dose of the people and the contamination of the land are evaluated using the Off-Site Consequence Analysis of Atmospheric Releases of radionuclides (OSCAAR) Code [2.2] which is a calculation code developed by Japan Atomic Energy Agency (JAEA) to perform level 3 PRA. Before the calculation of nuclear accident consequence index, the assessor should determine or confirm the scope of consequences to be taken into consideration. Then the results from the OSCAAR code are used as the input data to estimate the nuclear accident consequence index of each accident sequence. Finally, the average nuclear accident consequence index, which is the representative index for the assessment of nuclear accident consequences, is calculated. The detail of each step will be described in Sections 2.2 to 2.4.

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[1] The content of this chapter is based on the paper: Silva K, Ishiwatari Y, Takahara S. Cost per severe accident as an index for severe accident consequence assessment and its applications. Reliab Eng Syst Saf 2014;123:110-122 [2.1].

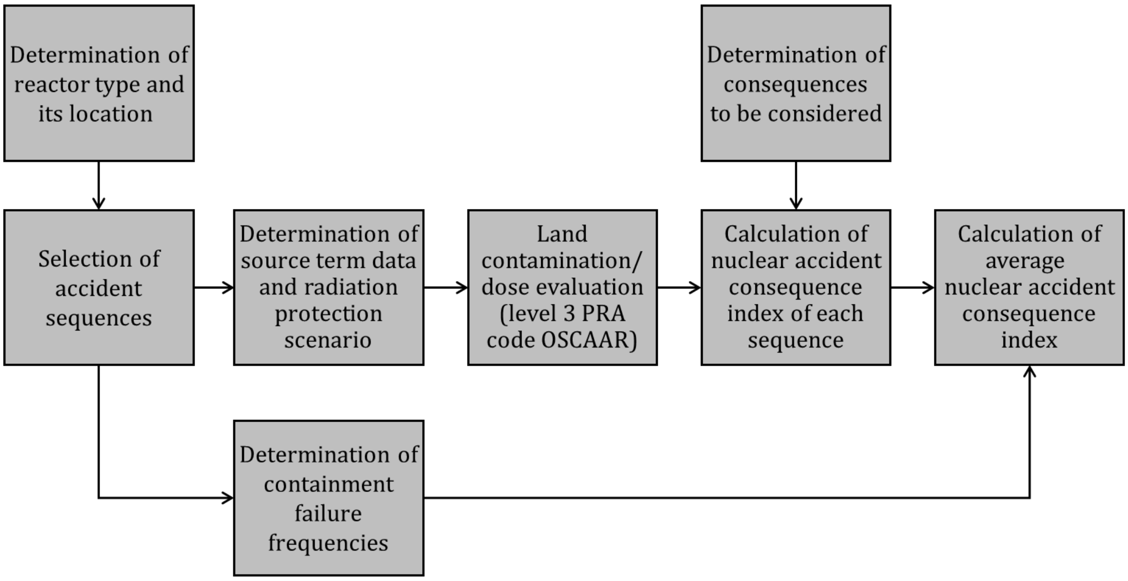

Figure 2.1. Flow of estimation of nuclear accident consequence index.

2.2 Calculation Conditions

2.2.1 Target plant and its location

A virtual 1,100 MWe (3,300 MWth) boiling water reactor (BWR-5) is selected as the target plant. It is assumed to be located at the center of Tokai Research and Development Center (TRDC) of Japan Atomic Energy Agency (JAEA).

2.2.2 Accident sequences, containment failure frequencies and source term data

The accident sequences used for the consequence assessment, their containment failure frequencies (CFFs), and their source term data, i.e., release times, release duration times, and release ratios, refer to the level 2 seismic probabilistic risk assessment (PRA) of the former Japan Nuclear Energy Safety Organization (JNES)[2] [2.3]. They are shown in Table 2.1. The reason that the seismic PRA was chosen is that it covers the accident sequences initiated by both internal events and earthquakes. The CFFs shown in Table 2 are the products of the conditional CFFs obtained from the report and the seismic probability of Ibaraki prefecture [2.4] at which TRDC is located. In order to calculate the amounts of source terms, the release ratios were multiplied to the core inventory which is obtained by multiplying the output ratio to the core inventory data shown in Table 2.2 [2.5].

[2] It was absorbed by the Japan Nuclear Regulatory Authority (NRA) in 2014.

Table 2.1. CFFs and source term data of each severe accident sequence.

Accident sequence[A]	Release sequence number	CFF [year^{-1}]	Release starting time [hr]	Release duration [hr]	Release ratio to core inventory [-]							
					Noble gas	Org. I	Inorg. I	Cs-Rb	Te-Sb	Sr-Ba	Ru	La
					1	2	3	4	5	6	7	8
TB	1	2.75E-05	12.7	4.0	2.9E-01	1.7E-04	3.1E-03	5.4E-03	1.1E-03	2.5E-04	4.5E-09	3.1E-07
	2		16.7	25.0	7.1E-01	6.3E-03	1.2E-01	4.2E-02	7.4E-02	2.7E-03	3.1E-08	3.3E-06
TW	1	2.61E-05	12.3	4.0	3.3E-02	1.7E-04	3.1E-03	1.6E-03	1.1E-03	2.5E-04	5.2E-09	3.6E-07
	2		16.3	12.7	6.3E-01	6.3E-03	1.2E-01	3.8E-02	4.9E-02	2.7E-03	3.0E-08	2.7E-06
	3		29.0	29.3	3.4E-01	0.0E+00	0.0E+00	3.6E-03	1.6E-02	0.0E+00	0.0E+00	4.0E-07
TBU	1	7.37E-06	1.0	7.3	5.4E-06	2.1E-08	3.9E-07	2.0E-07	2.1E-07	1.0E-08	9.6E-14	5.7E-12
	2		8.3	6.7	1.7E-01	2.8E-05	5.3E-04	1.5E-04	5.6E-04	1.2E-05	3.9E-11	7.8E-09
	3		15.0	26.7	3.4E-01	1.2E-03	2.3E-02	1.0E-02	1.3E-02	6.0E-06	5.0E-12	2.3E-08
TQUV	1	3.88E-06	0.8	9.2	1.2E-04	4.0E-09	7.5E-08	5.6E-08	1.2E-07	5.2E-09	2.2E-13	2.3E-10
	2		10.0	15.0	5.1E-01	5.5E-05	1.0E-03	4.4E-04	1.2E-04	1.1E-05	1.3E-12	5.0E-09
	3		25.0	16.7	2.5E-01	1.5E-05	2.9E-04	2.7E-04	4.4E-04	4.4E-05	2.0E-13	3.8E-09
PCVR(TB)	1	9.61E-07	12.7	2.8	5.8E-01	6.5E-05	1.2E-03	1.3E-03	1.9E-02	1.9E-04	1.4E-09	9.5E-08
	2		15.5	34.5	2.9E-01	1.2E-03	2.3E-02	1.5E-02	2.5E-02	5.6E-04	4.9E-09	1.2E-06
PCVR(TW)	1	9.14E-07	20.0	2.0	7.5E-02	1.7E-03	3.1E-02	2.9E-02	3.8E-02	4.9E-04	3.4E-10	3.1E-07
	2		22.0	6.7	6.9E-01	5.5E-04	1.0E-02	4.7E-03	3.7E-02	1.3E-02	4.6E-08	2.8E-06
	3		28.7	38.0	1.1E-01	1.1E-03	2.1E-02	6.7E-03	2.4E-02	9.0E-03	1.4E-08	3.1E-06

Table 2.1. CFFs and source term data of each severe accident sequence (continued).

Accident sequence[A]	Release sequence number	CFF [year^{-1}]	Release starting time [hr]	Release duration [hr]	Release ratio to core inventory [-]							
					Noble gas 1	Org. I 2	Inorg. I 3	Cs-Rb 4	Te-Sb 5	Sr-Ba 6	Ru 7	La 8
TC	1	5.36E-07	2.2	2.8	3.9E-01	2.2E-03	4.1E-02	2.0E-02	1.7E-02	3.6E-05	2.6E-09	1.8E-07
	2		5.0	5.0	2.7E-01	6.4E-03	1.2E-01	9.6E-02	6.9E-02	1.7E-03	2.6E-09	1.9E-06
	3		10.0	23.3	3.4E-01	1.0E-03	1.9E-02	2.0E-02	6.4E-02	5.0E-04	0.0E+00	6.0E-07
RBR(TB)	1	6.89E-09	12.5	4.2	1.7E-01	7.5E-04	1.4E-02	4.4E-03	3.8E-03	8.4E-04	1.2E-08	8.0E-07
	2		16.7	13.3	5.9E-01	1.4E-02	2.6E-01	7.6E-02	2.9E-02	5.7E-03	5.7E-08	6.3E-06
	3		30.0	28.3	1.1E-01	0.0E+00	0.0E+00	7.2E-03	2.4E-02	0.0E+00	1.0E-08	2.2E-06
RBR(TW)	1	6.53E-09	50.0	3.3	7.5E-02	3.7E-04	7.0E-03	6.6E-03	7.4E-03	4.8E-05	3.4E-10	2.3E-08
	2		53.3	46.7	8.0E-01	1.7E-02	3.2E-01	8.7E-02	7.6E-03	1.3E-03	7.9E-08	2.7E-06
RVR	1	1.34E-08	0.0	1.7	1.3E-07	1.6E-08	3.0E-07	2.3E-07	2.5E-07	1.1E-08	5.3E-14	5.4E-12
	2		1.7	2.5	2.9E-03	3.7E-06	7.0E-05	5.8E-05	6.5E-05	5.6E-06	5.4E-11	5.5E-09
	3		4.2	37.5	8.7E-01	3.8E-03	7.2E-02	4.2E-02	4.2E-03	7.9E-05	1.1E-10	5.0E-08
TQUX	1	6.70E-09	1.0	6.5	1.7E-04	1.1E-08	2.1E-07	7.2E-08	4.2E-08	1.2E-08	3.1E-13	2.1E-11
	2		7.5	8.3	2.9E-01	3.2E-05	6.2E-04	3.6E-04	1.1E-03	4.9E-05	4.8E-10	3.7E-08
	3		15.8	25.8	4.7E-01	2.2E-03	4.1E-02	6.3E-02	3.2E-03	8.0E-06	7.0E-11	2.6E-08
AE	1	6.70E-09	0.0	4.2	1.4E-04	2.1E-08	4.0E-07	4.2E-07	4.9E-07	3.2E-08	7.1E-11	5.4E-11
	2		4.2	19.2	5.8E-01	8.5E-05	1.6E-03	1.0E-02	8.6E-04	2.9E-05	6.9E-11	2.8E-08
	3		23.3	15.0	2.9E-01	2.5E-03	4.7E-02	1.8E-02	2.0E-03	1.6E-04	0.0E+00	9.0E-09

Table 2.1. CFFs and source term data of each severe accident sequence (continued).

Accident sequence[A]	Release sequence number	CFF [year^{-1}]	Release starting time [hr]	Release duration [hr]	Release ratio to core inventory [-]							
					Noble gas 1	Org. I 2	Inorg. I 3	Cs-Rb 4	Te-Sb 5	Sr-Ba 6	Ru 7	La 8
V	1	6.70E-09	0.0	4.0	4.4E-01	8.5E-03	1.6E-01	1.5E-01	1.3E-01	8.6E-03	3.7E-06	1.6E-04
	2		4.0	29.3	4.3E-01	2.5E-03	4.8E-02	2.3E-02	4.0E-02	6.4E-03	6.0E-07	3.0E-05

Note

A TB: Long-term loss of all AC power
TW: Loss of all decay heat removal function
TBU: Short-term loss of all AC power
TQUV: Transient with loss of ECCS function
PCVR: Primary containment vessel rupture
TC: ATWS events
RBR: Reactor building rupture
RVR: Reactor vessel rupture
TQUX: Transient with loss of Depressurization
AE: LOCA with loss of ECCS injection
V: LOCA with loss of water injection

Table 2.2. Core inventory of a 3,300 MWth boiling water reactor.

No.	Isotope	Group	Activity [Bq]	No.	Isotope	Group	Activity [Bq]
1	Kr-85	1	3.06E+16	28	Co-60	6	2.24E+16
2	Kr-85M	1	1.11E+18	29	Mo-99	6	5.94E+18
3	Kr-87	1	2.02E+18	30	Rh-105	6	2.24E+18
4	Kr-88	1	2.73E+18	31	Ru-103	6	4.50E+18
5	Xe-133	1	6.62E+18	32	Ru-105	6	3.00E+18
6	Xe-135	1	1.57E+18	33	Ru-106	6	1.23E+18
7	I-131	2	3.15E+18	34	Tc-99M	6	5.12E+18
8	I-132	2	4.64E+18	35	Ba-140	6	6.01E+18
9	I-133	2	6.62E+18	36	Am-241	7	2.68E+14
10	I-134	2	7.23E+18	37	Cm-242	7	7.06E+16
11	I-135	2	6.21E+18	38	Cm-244	7	3.82E+15
12	Cs-134	3	5.15E+17	39	La-140	7	6.14E+18
13	Cs-136	3	1.39E+17	40	Nb-95	7	5.15E+18
14	Cs-137	3	3.09E+17	41	Nd-147	7	2.33E+18
15	Rb-86	3	1.71E+15	42	Pr-143	7	5.22E+18
16	Sb-127	4	2.84E+17	43	Y-90	7	2.57E+17
17	Sb-129	4	9.86E+17	44	Y-91	7	4.13E+18
18	Te-127	4	2.75E+17	45	Zr-95	7	5.43E+18
19	Te-127M	4	3.69E+16	46	Zr-97	7	5.60E+18
20	Te-129	4	9.25E+17	47	Ce-141	8	5.46E+18
21	Te-129M	4	2.43E+17	48	Ce-143	8	5.32E+18
22	Te-131M	4	4.68E+17	49	Ce-144	8	3.55E+18
23	Te-132	4	4.57E+18	50	Np-239	8	6.93E+19
24	Sr-89	5	3.39E+18	51	Pu-238	8	4.81E+15
25	Sr-90	5	2.40E+17	52	Pu-239	8	1.31E+15
26	Sr-91	5	4.40E+18	53	Pu-240	8	1.53E+15
27	Co-58	6	1.87E+16	54	Pu-241	8	2.63E+17

2.2.3 Radiation protection scenarios

The selected radiation protection scenarios are shown in Table 2.3. The periods and the dose levels of recommending sheltering and evacuation follow the IAEA recommendations [2.6]. The areas of sheltering and evacuation refer to the plume protection planning zone (PPZ) and the urgent protective action planning zone (UPZ) announced by the Nuclear Safety Commission of Japan (NSC) [2.7]. The dose levels for recommending relocation and returning home were taken from the lower threshold of the reference level of emergency exposure and the upper threshold of the reference level of existing exposure recommended by the International Commission on Radiological Protection (ICRP) [2.8]. The times of starting the countermeasures refer to Homma T et al. [2.2].

Food intake restriction in order to mitigate the internal exposure is also taken into account. The concentrations of the radioactive materials in agricultural and livestock products [Bq/kg] which are used as the intervention level for the restriction are shown in Table 2.4 [2.9].

Table 2.3. Radiation protection scenarios.

Measure	**Area and dose level**	**Time of starting the measure**	**Period**
Sheltering	Within 50 km and over 10 mSv/week	1 hour after the release starts	24 hours
Evacuation	Within 30 km and over 50 mSv/week	After the release starts	7 days
Relocation	Starting: over 20 mSv/year Returning: under 20 mSv/year	After finishing the evacuation	Returning home after the dose level reaches 20 mSv/year

Table 2.4. Intervention levels for different radioisotopes and different agricultural and livestock products.

Radioisotope	**Intervention level [Bq/kg]**	
	Milk/dairy products	**Other agricultural and livestock products**
Sr-89	200.0	500.0
Sr-90	200.0	500.0
I-131	300.0	2000.0
I-133	300.0	2000.0
Cs-134	200.0	500.0
Cs-136	200.0	500.0
Cs-137	200.0	500.0
Pu-238	1.0	10.0
Pu-239	1.0	10.0
Pu-240	1.0	10.0
Pu-241	1.0	10.0
Am-241	1.0	10.0
Cm-242	1.0	10.0
Cm-244	1.0	10.0

2.3 Off-Site Consequence Analysis of Atmospheric Releases of radionuclides (OSCAAR) Code

The Off-Site Consequence Analysis of Atmospheric Releases of radionuclides (OSCAAR) code is used to estimate the public exposure dose and the extent of land contamination. Specifically, it estimates the periods, the numbers of people, and the size of the land involved in the radiation protection measures, i.e., sheltering, evacuation and relocation. It also calculates the individual early (or acute) and chronic doses, and the collective dose. In addition, it calculates the amount of agricultural and livestock products being restricted, and the wastes resulted from the agricultural and livestock products restrictions.

The calculation flow of OSCAAR is shown in Figure 2.2. ADD module uses the source term information and meteorological data to simulate the advection and diffusion of the release resulting from the accident and their deposition amounts. MS preprocessor code uses the bin sampling method [2.10] to pick up 248 representative sequences from 8760 meteorological sequences to consider the effects of the meteorological conditions (8760 meteorological sequences were obtained by recording the meteorological data of the selected location every hour for one year). These meteorological sequences are selected in a manner that can include all kinds of weather conditions in a year from a very moderate one to very extreme one, and from the driest one to the wettest one.

EARLY and CHRONIC modules use the outputs from ADD module as its inputs to calculate the individual early and chronic doses. Dose conversion factors for internal and external exposures used by these two modules are prepared by DOSDAC preprocessor code.

PM module calculates the dose reduction and the reduction of the land-deposited radioactive materials due to the radiation protection measures and the decontamination activities. Population data, agricultural and livestock products data, information on assets of the people are provided to PM module by CURRENT preprocessor code. Information regarding the time needed for sheltering and evacuation are prepared by HINAN preprocessor code. Receiving information from these preprocessor codes, PM module calculates (1) the sheltered, evacuated and relocated populations and periods, and the total area affected by respective measures; (2) the amount of agricultural and livestock products being restricted due to the contamination of the land.

HE module, which receives the information on individual early and chronic doses from PM module, calculates the collective dose and health effects regarding the radiation exposure. Only the function that calculates the collective dose is used in this study. Therefore, the HEINPUT preprocessor code, which is used to prepare data for estimation of health effects, is not also used.

ECONO module, which estimates the economic impacts due to sheltering, evacuation, relocation and food intake restriction, is not used as well. All consequences results from a severe accident is estimated at the same time by the nuclear accident consequence index (NACI), and its calculation method is to be described in the next section.

As various meteorological conditions are taken into account, the results of the consequence analysis are given in statistical values: expected values and the 5th, 50th, 90th, 95th, 99th, 99.9th percentile values. The expected values of respective outputs are chosen as the representative values because they can better represent the whole picture of the calculation. These values will be used for the following calculation of the nuclear accident consequence index.

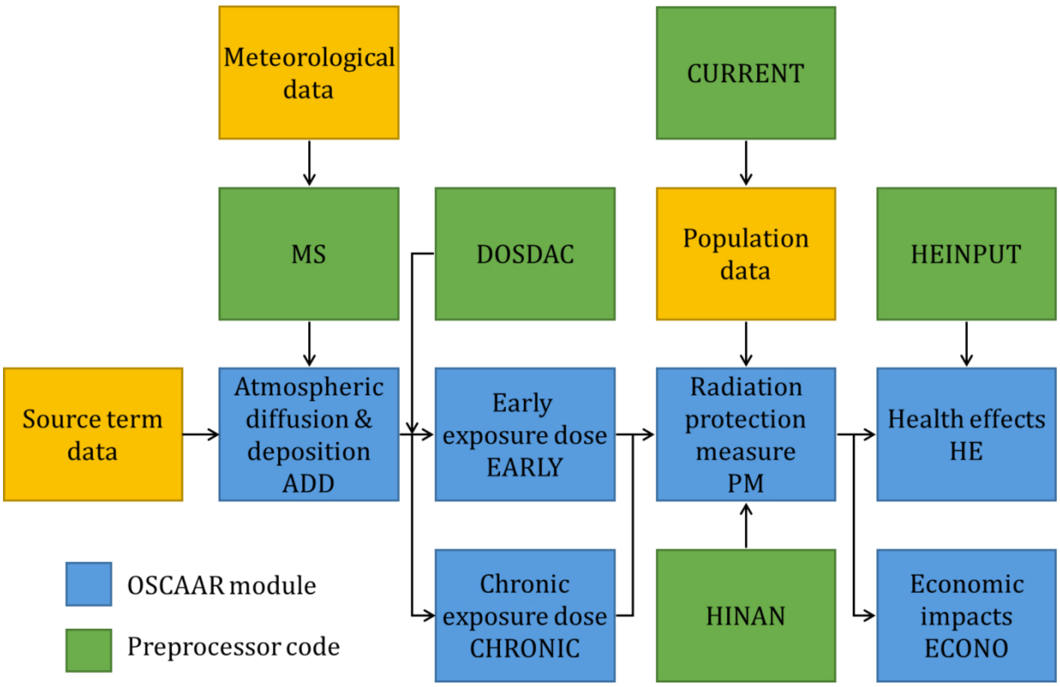

Figure 2.2. Calculation flow of the OSCAAR code.

2.4 Estimation of Nuclear Accident Consequence Index

2.4.1 Determination of consequences to be considered

In Chapter 1, it was concluded that the nuclear accident consequence assessment must be able to include all anticipated consequences to people and the environment. This section will discuss what are the consequences needed to be considered within the scope of the assessment.

Being aware that the consequence assessment to be performed in this study is a quantitative one, the consequences taken into account should be quantifiable. However, no matter how mature and justified the methods are, we decided to include all consequences whose methods for quantification exists. This is because disregarding those existing consequences would merely result in underestimating the consequences of the accident [2.11]. In this regard, it would still be better to be able to include those consequences, even if the methods are premature and the results are associated with large uncertainties.

Finally, ten categories of consequences from a nuclear accident to people and the environment are taken into account in this study. The effects from radiation exposure and the psychological effect associated with the accident are considered the direct consequences to people. The reason to the former is that, the radiation exposure of the people caused by the accidental release has a potential to affect their health. In regard to the latter, various psychological effects can be observed after the historical severe accidents, and they directly deal with the individuals.

Two types of consequences can be included into the group of consequences to the environment, namely decommissioning and decontamination. The term "the environment" used in this study is specifically defined as the area surrounding the location of the accident (typically a nuclear power station) and its belongings. Therefore, in accidents which are followed by the release of radioactive materials, decommissioning which is the effort to decontaminate the scrapped reactor itself and the site, and decontamination which deals with the cleanup of the contaminated area around the nuclear power station would definitely be included in the consequences to the environment.

The remaining consequences belong to consequences to both people and the environment. The first three are the consequences from the radiation protection measures, namely sheltering, and evacuation and relocation. They affect both people and the environment because they force "people" to change "the environment" they normally belong to. Sheltering forces people to remain inside concrete buildings, or in some cases their own houses, while they would be in their offices, schools, fields, or any other places in their normal daily lives. Evacuation and relocation deal with a larger change of living environment. Evacuated and relocated people have to totally change their living environment, the former for a week or so and the latter for a longer period up to several decades. According to these facts, we can say that these radiation protection measures can affect both the people and their old and new living environments. The restriction of the food intake after the accident is also a measure to protect people from internal exposure after an accident. Besides, the wastes generated by the measure would affect the environment. Additional expenses from the replacement of the lost power for the nuclear power plant by the alternative electricity sources would directly affect the people living near the power plant and the people in the electric company, and also the environment, in case fossil-fired power plant is selected as the alternative source. Lastly, the harmful rumor is also considered consequences to both people and the environment, as it affects the mentality of the people, the economics and the overall environment of the contaminated area and the vicinity.

Figure 2.3 shows how the ten categories of accident consequences fit in the nuclear accident consequence assessment framework. The sizes of the circles of respective consequences actually reflect the extent of those consequences estimated by the nuclear accident consequence index (NACI). This will be discussed in detail in Section 2.5.

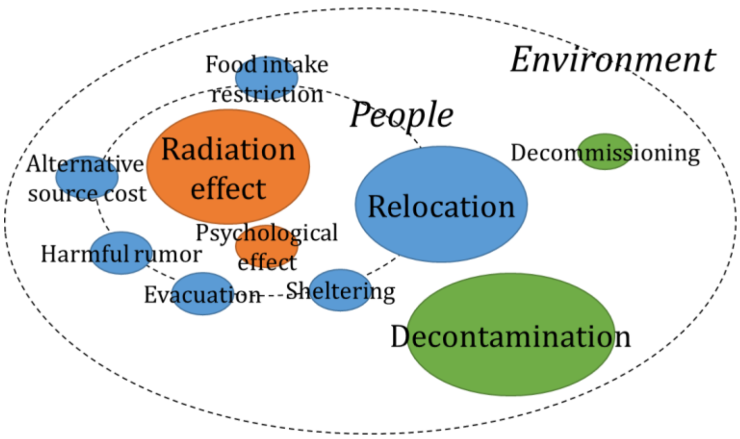

Figure 2.3. Consequences of a nuclear accident on people and environment which are taken into account in the estimation of nuclear accident consequence index.

2.4.2 Accident Cost Unit

In preceding studies [2.12, 2.13], consequences stated above were quantified using monetary unit. Though the results could be easily understood, it can be easily mistaken for estimation of economic losses resulted from specific accidents, such as Three Mile Island Accident, Chernobyl Accident, or Fukushima Accident, which does not represent the impacts of a severe accident to people and the environment.

In order to avoid confusion between the nuclear accident consequence index (NACI) and other economic losses evaluations, and to be confident that the NACI can certainly serve the objectives of this study, the author decided to use the "accident cost unit (ACU)" instead of a currency unit. The sum of the major components of the cost per severe accident, namely radiation effect cost, relocation cost, and decontamination cost, resulted from a 100 TBq cesium 137 release into environment is set to one accident cost unit (1 ACU) [2.14]. The ACU will be used as a unit for all monetary values in the estimations of the indices composing the NACI being discussed below.

2.4.3 Estimation of Components of Nuclear Accident Consequence Index

2.4.3.1 Radiation effect index[3]

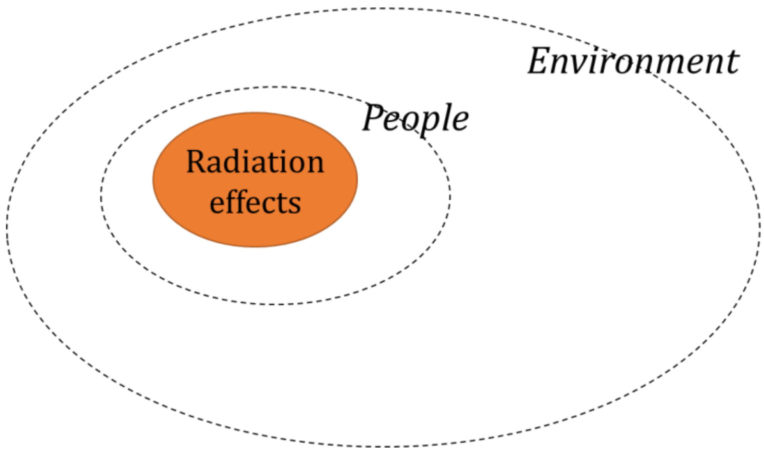

Figure 2.4. Radiation effects within consequence assessment framework.

ICRP divides the health effects into deterministic and stochastic effects. The deterministic effect is the "*injury in populations of cells, characterised by a threshold dose and an increase in the severity of the reaction as the dose is increased further*", where the stochastic

[3] Estimation scheme of radiation effect index is reconsidered in Section 3.3 due to the revision of the decontamination model.

effects are the "*malignant disease and heritable effects for which the probability of an effect occurring, but not its severity, is regarded as a function of dose without threshold*" [2.8]. However, the deterministic effects are not included into the scope of assessment. This is because it is internationally recognized that the national government must do their best to prevent the deterministic effects regardless of the cost of the radiation protection measures [2.15]. Even though there are some measure that can significantly reduce some major consequences due to the accident, if that measure has a possibility to increase the deterministic effects, it must not be taken. Therefore, there is no point to consider the deterministic effects at the same time as other consequences. However, the author has to note that this does not mean that the deterministic effects are not important. A separate assessment for deterministic effects to complement the insights regarding the consequences of severe accident from the nuclear accident consequence index is indeed needed.

Stochastic effects due to radiation exposure resulted from an accident are supposed to be in linear relationship with the exposure dose according to the linear non-threshold (LNT) hypothesis of the ICRP [2.16]. Therefore, a simple multiplication of the collective dose and the unit radiation effect index can be used to estimate these effects. There are two things typically used to monetize the radiation effects: (1) medical expenses spent for sickness or diseases caused by radiation exposure and (2) willingness to pay (WTP) of the people to avoid the radiation exposure. The author adopts the latter since it is more widely used. The radiation effect index *REI* [ACU] is thus estimated by

$$REI = CD \times WTP \tag{2.1}$$

where *CD* and *WTP* represent the collective dose resulted from the accident [Sv] and willingness to pay per unit radiation exposure [ACU/Sv], respectively. The collective dose for respective accident sequences are calculated by the OSCAAR code, and the WTP per unit exposure is referred to NUREG-1530 [2.17]. It is to be emphasized that only stochastic effects are taken into account in the WTP estimation in NUREG-1530 which is consistent to the international recognition mentioned above.

2.4.3.2 Psychological index

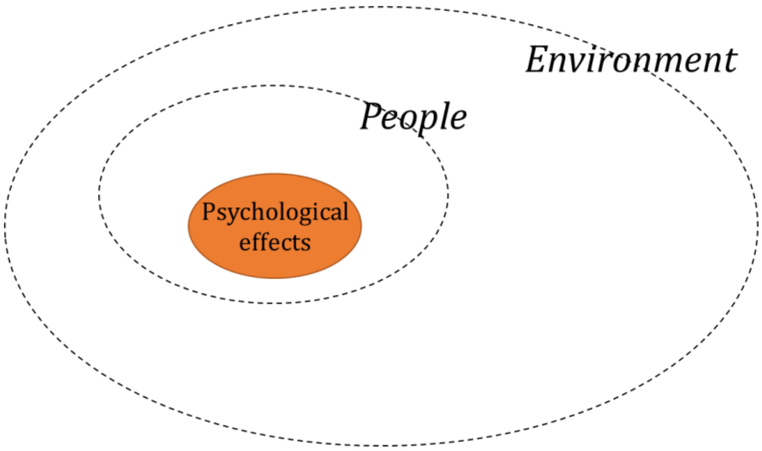

Figure 2.5. Psychological effect within consequence assessment framework.

Though the psychological burdens people may suffer from an accident involving radionuclide release are expected to be considerably large, there are not many means to quantify the extent of these burdens. In this study, the author referred to the compensation paid by the Japanese Government to the sheltered, evacuated and relocated people to compensate their psychological burdens due to the radiation protection measures: sheltering, evacuation and relocation, they have been forced to take after the Fukushima Accident [2.18]. Therefore, the psychological effect index *PEI* [ACU] can be expressed by

$$PEI = \sum_x (POP_x \times T_x \times UPEI) \qquad (2.2)$$

where the suffix *x* represents the radiation protection measures taken, namely sheltering *s*, evacuation *e* and relocation *r*. *POP*, *T* and *UPEI* stand for the population associated with respective radiation protection measures [person], the period those measures are taken [year], and the compensation to people forced to take those measures [ACU/year], respectively.

In this study, the periods of sheltering and evacuation are set to one day and seven days, respectively. On the other hand, the relocated period is determined by the dose for starting relocation and the dose for returning home, hence it is not constant. Both the population associated with respective radiation protection measures and the relocated period are calculated within the OSCAAR code. However, in the cases that the relocated period exceeds one year, it is reduced to one year to comply with the reference stated above

[2.18]. The value of the unit compensation is also taken from the same report [2.18]

2.4.3.3 Decommissioning index

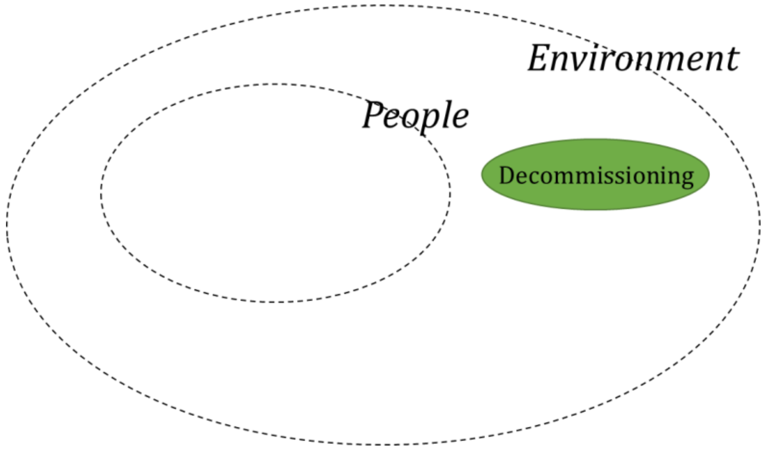

Figure 2.6. Decommissioning within consequence assessment framework.

Comparing to the typical decommissioning procedure, the additional decommissioning work for a scrapped power plant would be dominated by the cleanup of the site of the power plant which is contaminated by the radioactive materials released, thus it could be included into consequences to the environment.

The decommissioning index *DMI* [ACU], which represents the additional decommissioning work after the accidental release from a nuclear power plant, is calculated by

$$DMI = EP/EP_f \times DMI_f \tag{2.3}$$

where the suffix *f* represents the values obtained from the Fukushima Accident, and *EP* [MWe] stands for the electric power of the power plant, while EP_f [MWe] is equal to the total electric power of units 1 – 3 of the Fukushima Daiichi Nuclear Power Station. DMI_f [ACU] refers to the Report of the Commission of Management and Financial Survey of TEPCO [2.19]. It can be seen from Equation (2.3) that the degree of additional decommissioning work is assumed to be proportional to the electric power. Though the author is aware that there are some other parameters that can affect the extent of the additional decommissioning work, e.g. the severity of the accident or the effectiveness of the personnel associated with the decommissioning work, this simple assumption is adopted mainly due to lack of information regarding those parameters, and the difficulties of determination of the relations between those parameters and the degree of additional decommissioning work.

2.4.3.4 Decontamination index[4]

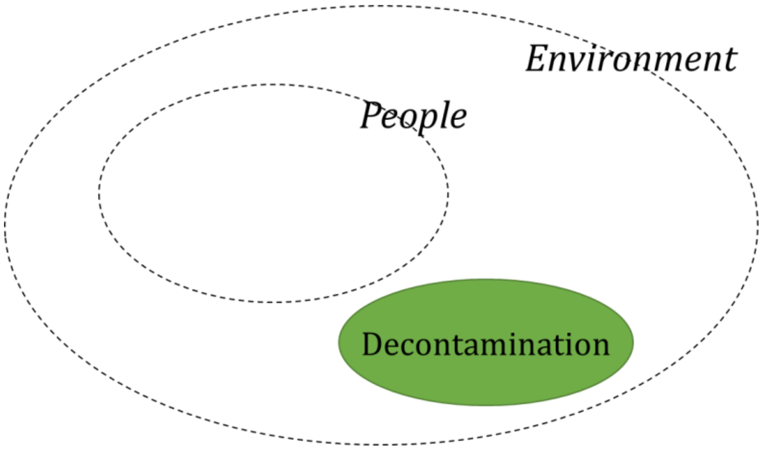

Figure 2.7. Decontamination within consequence assessment framework.

The term decontamination used in this study covers the decontamination procedure itself and the management of the wastes generated by the decontamination. Therefore, the decontamination index combines decontamination procedure indices DP_l [ACU] which are the contributions from the decontamination procedure, and waste management indices WM_l [ACU] which are the contributions from the management of the wastes generated by decontamination. The former group of indices are calculated by

$$DP_l = A_l \times UDP_l, \tag{2.4}$$

while the latter group are calculated by

$$WM_l = (M_l \times D_l \times UTR) + \{M_l/(VR_l \times MVC_l) \times UWD\}. \tag{2.5}$$

Here, the decontamination target area is divided into five land use types, namely houses and buildings *hb*, gardens and playgrounds *gp*, agricultural and farming lands *af*, forests *fr*, and roads *rd*, referring to the studies after the Chernobyl Accident and the Fukushima Accident

[4] Estimation scheme of decontamination index is reconsidered in Section 3.3 due to the revision of the decontamination model.

[2.20, 2.21], and the suffix l in Equations (2.4) and (2.5) represents these land use types. A_l is the decontamination target area [m^2], and UDP_l is the unit decontamination procedure index [ACU/m^2] which is the sum of the accident unit costs of materials, equipment and labors spent in the decontamination procedures of respective land use types. M, D and UTR represent the mass of the wastes generated by decontamination [ton], the distance for the transportation of the wastes [km], and the unit transportation index [ACU/ton-km]. VR is the volume reduction factor which indicates the volume reduction regarding the incineration of the wastes and the evaporation of moisture in the wastes, MVC is the mass-volume conversion factor [ton/m^3] and UWD is the unit waste disposal index [ACU/m^3].

Decontamination techniques are selected to suit the abovementioned land use types based on the data from the decontamination demonstration project of JAEA [2.20] which evaluates the appropriateness of those decontamination techniques by considering their efficiencies and costs (Table 2.5). The unit decontamination procedure indices were calculated based on EURANOS report [2.21]. The decontamination target area of each land use type are obtained by multiplying the area belonged to the relocated people calculated by the OSCAAR code, to the fraction of each land use type of Ibaraki prefecture [2.22], which is the prefecture in which the virtual reactor used in this study is located.

In regard to the waste management index, the mass of the wastes are calculated within the OSCAAR code. The assumption of the distance for waste transportation follows the previous study [2.2]. The unit transportation index is calculated using the information of the unit costs and utilization rates of respective vehicles in The Survey on Transport Energy [2.23]. The volume reduction rate and the mass-volume conversion factor are taken from articles of the Japan Patent Office and the Japan Industrial Waste Information Center, respectively [2.24, 2.25]. The unit waste disposal index refers to the reference unit cost to dispose the waste generated during decommissioning of a BWR [2.26].

The decontamination index DCI [ACU] is finally estimated by

$$DCI = \sum_l (DP_l + WM_l). \tag{2.6}$$

Table 2.5. Suitable decontamination techniques for different land use types.

Land use types	**Decontamination techniques**
Houses and buildings	roofs: high pressure water, sandblast
	walls: wiping with clothes
Gardens and playgrounds	removing soil, replacing soil with subsoil, cutting leaves and shrubs
Agricultural and farming lands	removing soil, replacing soil with subsoil
Forests	removing soil, cutting leaves and shrubs
Roads	high pressure water

2.4.3.5 Sheltering index

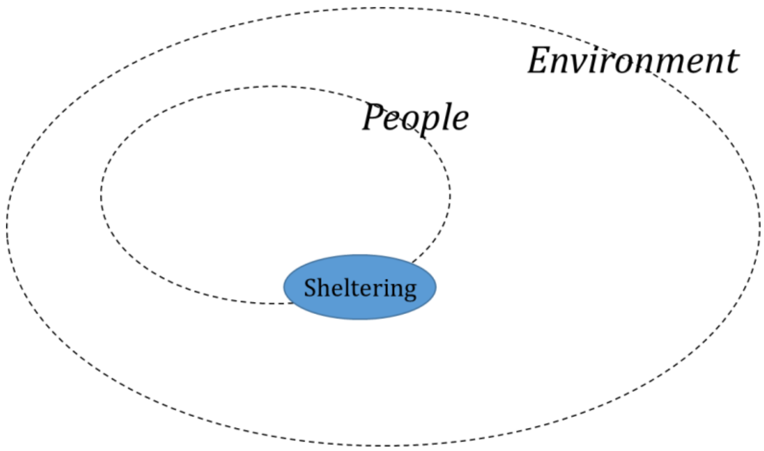

Figure 2.8. Sheltering within consequence assessment framework.

The sheltering index SI [ACU] can be estimated by the income losses due to sheltering. It is calculated by

$$IL_x = POP_x \times T_x \times GDP \qquad (2.7)$$

where the suffix x represents the radiation protection measures taken: sheltering s, evacuation e and relocation r. Therefore, Equation (2.7) can also be used to estimate the income losses resulted from evacuation and relocation. POP, T and GDP stand for the population associated with respective measures [person], the period those measures are taken [year], and the yearly gross domestic product (GDP) per capita [ACU/year], respectively. The first two parameters on the right-hand side can be obtained from the OSCAAR code, and the last parameter in obtained by subtracting the gross agricultural and livestock production and the total house rental fee of Ibaraki prefecture [2.9, 2.27] from the prefecture's gross production [2.28], and divide by the population of the prefecture [2.29].

The sheltering index SI [ACU] is finally estimated by

$$SI = IL_s. \tag{2.8}$$

2.4.3.6 Evacuation index

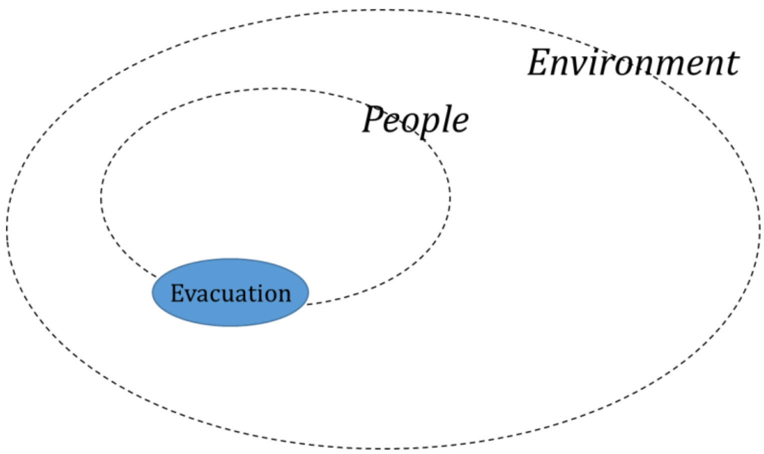

Figure 2.9. Evacuation within consequence assessment framework.

Evacuation index consists of three elements, namely income losses index IL_e [ACU], transportation index TR_e [ACU] and accommodation index AC_e [ACU]. Income loss index can be estimated by Equation (2.7). Transportation index TR_e [ACU] and accommodation index AC_e [ACU] can be estimated using

$$TR_x = POP_x \times D_x \times UTR \tag{2.9}$$

and

$$AC_x = POP_x \times T_x \times UAC \quad , \tag{2.10}$$

respectively. As with previous subsections, POP, D, T and UTR stands for the number of population involved [person], the transportation distance [km], the period of the measure [year] and the unit transportation index [ACU/ton-km], respectively. The suffix x represents the radiation protection measures taken: evacuation e and relocation r, thus these two equations can also be used to estimate the transportation and accommodation indices of the relocation index. *UAC* represents the unit accommodation index [ACU/person-year], which is taken from the average house rental fee in respective prefectures [2.27].

The evacuation index *EI* [ACU] is finally estimated by

$$EI = IL_e + TR_e + AC_e. \quad (2.11)$$

2.4.3.7 Relocation index[5]

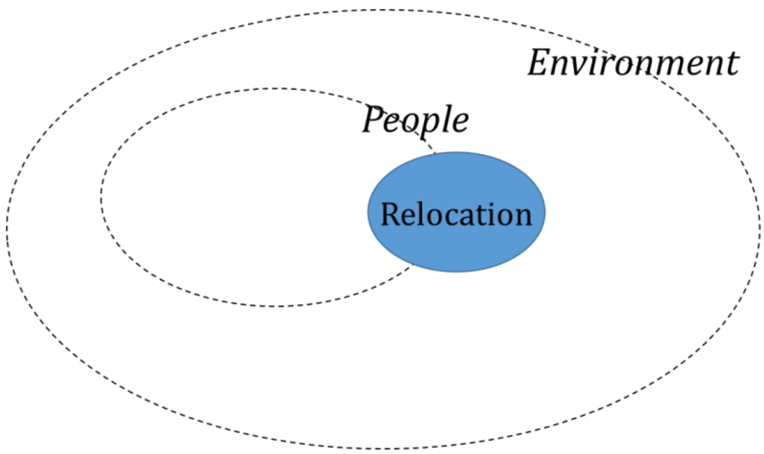

Figure 2.10. Relocation within consequence assessment framework.

The relocation index is the sum of five indices, three of which can be estimated by Equations (2.7), (2.9) and (2.10). The remaining indices, namely the land capital losses index *LLC* [ACU] and the index for capital losses other than land capital losses *LOC* [ACU], can be estimated by

$$LLC = A_r \times T_r \times LC \times IR. \quad (2.12)$$

and

$$LOC = POP_r \times T_r \times OC \times (1 - DP) \times (DP + I), \quad (2.13)$$

[5] Estimation scheme of relocation index is reconsidered in Section 3.3 due to the revision of the decontamination model.

respectively. Same as in previous subsections, the suffix r is for relocation, and POP and T stand for the population involved [person] and the period of the measure [year]. A_r, LC and OC are the relocated area [km^2], the unit land capital [ACU/km^2], and the unit value of capitals other than land capital [ACU/person], respectively. Finally, IR, DP and I are for the investment recovery rate, the depreciation rate and the interest rate. The relocated period T_r can be estimated within the OSCAAR code. However, T_r used for the calculation of income losses index due to relocation IL_r is set to one year based on the relocated period that the Japanese Government used to calculate the compensation to the relocated people after the Fukushima accident [2.18]. This is attributed to the fact that the relocated people could find a new source of income at the place they relocated. T_r used in the calculation other indices refer to the value calculated by the OSCAAR code. The relocated area can also be estimated by the OSCAAR code. In this study, we assumed the value of respective prefectures for the unit land capital, and the Japan average value for the capitals other than land capital [2.30, 2.31]. The difference in the two assumptions is attributed to data unavailability. The investment recovery rate, the depreciation rate and the interest rate refer to the common rates used by the Bank of Japan.

The relocation index RI [ACU] is finally estimated by

$$RI = IL_r + TR_r + AC_r + LLC + LOC. \tag{2.14}$$

2.4.3.8 Food intake restriction index

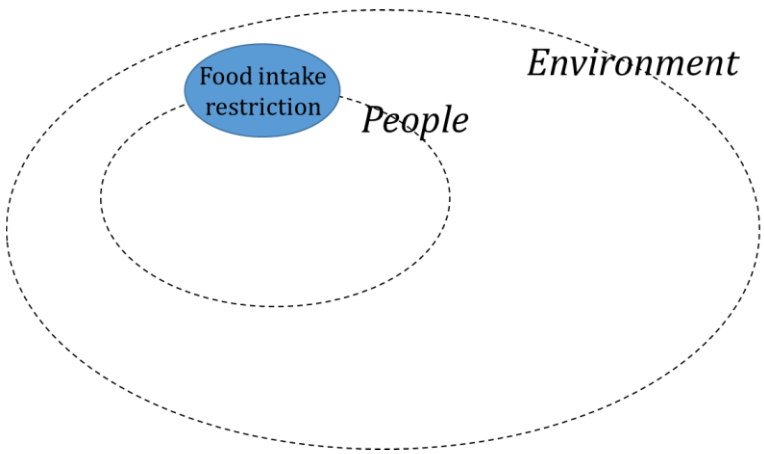

Figure 2.11. Food intake restriction within consequence assessment framework.

Food intake restriction index *FRI* includes two groups of indices. One is the indices for losses of the agricultural and livestock products LF_y [ACU] and the other is the waste management indices WM_y [ACU]. The former can be estimated by

$$LF_y = G_y \times M_y \times T_y, \qquad (2.15)$$

and the latter by

$$WM_y = \left(M_y \times D_y \times UTR\right) + \left\{M_y/\left(VR_y \times MVC_y\right) \times UWD\right\}. \qquad (2.16)$$

y represents the six types of the agricultural and livestock products: milk *ml*, dairy products *dp*, meat *mt*, cereals *cr*, root vegetables *rv* and leafy vegetables *lv*. *G* is the gross value of the products [ACU/ton], *M* is the mass of the products [ton/year] and *T* is the periods of restriction [year]. As can be seen in decontamination index, *D*, *UTR*, *VR*, *MVC* and *UWD* represent the distance for the transportation of the wastes [km], and the unit transportation index [ACU/ton-km], the volume reduction factor, the mass-volume conversion factor [ton/m^3] and the unit waste disposal index [ACU/m^3], respectively.

The mass of the products and the periods of restriction are estimated by OSCAAR based on the contamination of the land by the radioactive materials and the intervention levels listed in Table 2.4. The gross values of the products are taken from the Japan Statistics 2002 [2.9]. References for other parameters are described in Subsection 2.4.3.4.

The food intake restriction index *FRI* [ACU] is finally estimated by

$$FRI = \textstyle\sum_y \left(LF_y + WM_y\right). \qquad (2.17)$$

2.4.3.9 Alternative source index

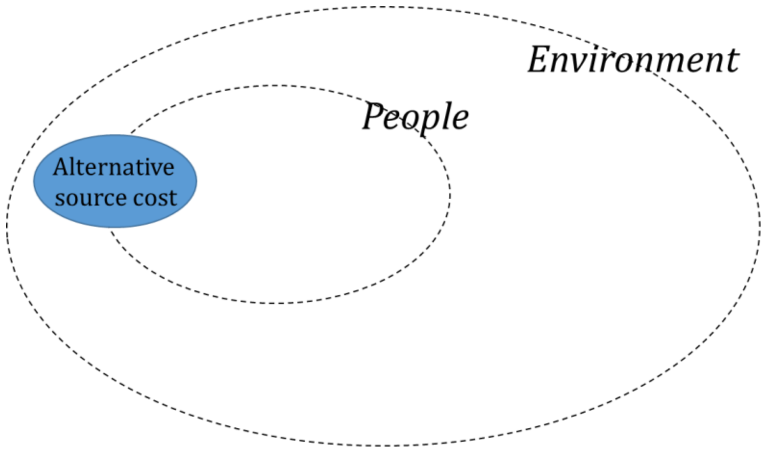

Figure 2.12. Alternative source within consequence assessment framework.

Fossil fired power plant is considered the potential power source to replace the scrapped nuclear power plant since it can serve as the base load power source. Therefore the alternative source index can be estimated by

$$ASI = T_a \times AF \times EP \times UC_{fs} \times UC_{nc}. \qquad (2.18)$$

Here, T_a, *AF*, *EP* and *UC* represent the period that we need to rely on the alternative power source [year], the available factor, the electric power of the target power plants [MW] and the annual expense for the power source [ACU/MW-year], respectively. The subscripts *fs* and *nc* stands for the fossil fires power plants and nuclear power plants, respectively.

As two out of the three historical severe accidents (Three Mile Island accident, Chernobyl accident and Fukushima accident) happened soon after the commission of the plant, the accident is assumed to happen at the first year of the operation of the power plant, and consequently the period that the alternative power source is needed (= the remaining lifetime of the nuclear power plant before the accident) is set to 30 years. This period refers to the rule for aging management of Japan Ministry of Economics, Trade and Industry (METI) which requires the establishment of the long-term maintenance planning after the plant is operated for 30 years in order to extend the lifetime of the power plant [2.32]. The available factor is set to 70% based on the available factor of Japanese nuclear power plant before the Fukushima accident. The annual expenses for the power sources is taken from the report of the Institute of Energy Economics, Japan [2.33].

2.4.3.10 Harmful rumor index

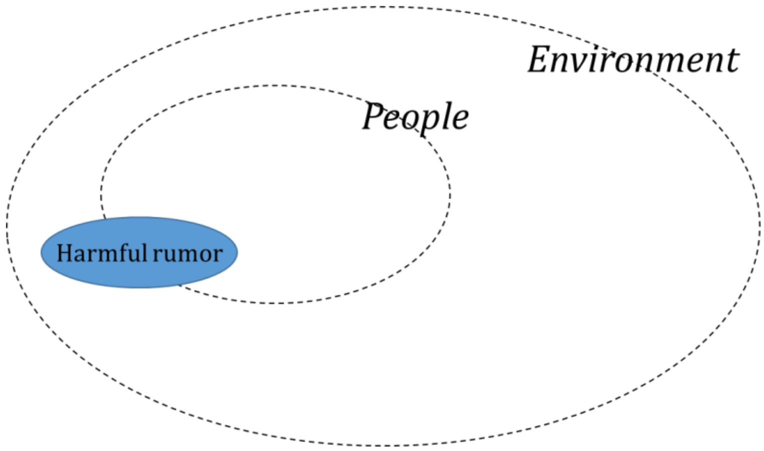

Figure 2.13. Harmful rumor within consequence assessment framework.

The estimation of the consequences from the harmful rumors after the accident requires the statistical data of the impacts of those rumors which can be obtained only after the accident. The damages from harmful rumors after the Fukushima accident can then be used as the representative value of the harmful rumor index *HRI*, though we must be aware that the actual value when the actual accidents happen may be very different according to the location of the accident, the size and the period of the release, the response of the government, the public and the foreign countries, or any other factors. Finally,

$$HRI = HR_f \tag{2.19}$$

is used to estimate the harmful rumor index *HRI* [ACU] where HR_f represents the total damages resulted from harmful rumors after the Fukushima accident [ACU] [2.19] which includes rejection of agricultural and livestock from Fukushima prefecture or neighboring area, and impacts of the accident to the tourist and service industries.

2.4.4 Nuclear Accident Consequence Index

2.4.4.1 Nuclear Accident Consequence Index for Respective Accident Sequences

All ten indices estimated in Subsection 2.4.3 are finally summed up to obtain the nuclear accident consequence index of respective accident sequences. The nuclear accident consequence index $NACI_s$ [ACU] of the *s*th accident sequence can be calculated by

$$NACI_s = REI + PEI + DMI + DCI + SI + EI + RI + FRI + ASI + HRI. \quad (2.20)$$

2.4.4.2 Average Nuclear Accident Consequence Index

The nuclear accident consequence indices of respective accident sequences $NACI_s$ [ACU] calculated above are then averaged using their containment failure frequencies CFF_s [reactor year^{-1}]:

$$\overline{NACI} = (\textstyle\sum_s NACI_s \times CFF_s)/\textstyle\sum_s CFF_s. \quad (2.21)$$

Here, $\overline{\mathrm{NACI}}$ represents the average nuclear accident consequence index [ACU].

2.5 Results and Discussion

2.5.1 Estimated nuclear accident consequence index

Nuclear accident consequence indices of respective accident sequences are shown together with their containment failure frequencies in Figure 2.14. This figure shows both the occurrence probabilities (containment failure frequencies: CFFs) and the consequences (nuclear accident consequence indices: NACIs) which are significant indicators to assess the risk of severe accidents in nuclear power plants. Accidents with large CFFs (larger than 10^{-6} reactor year^{-1}) tend to have relatively small NACIs. On the other hand, accidents with small CFFs (smaller than 10^{-6} reactor year^{-1}) have scattered NACIs, from a relatively small one to a very large one. This risk information can play an important role in the decision making procedure. For example, if only the CFF is used to indicate the risk or if the risk is shown as the product of the CFF and the NACI, the accident sequence "V" which has a very small probability but an extremely large consequence may be overlooked. Showing both the probability and the consequence can avoid this kind of problems.

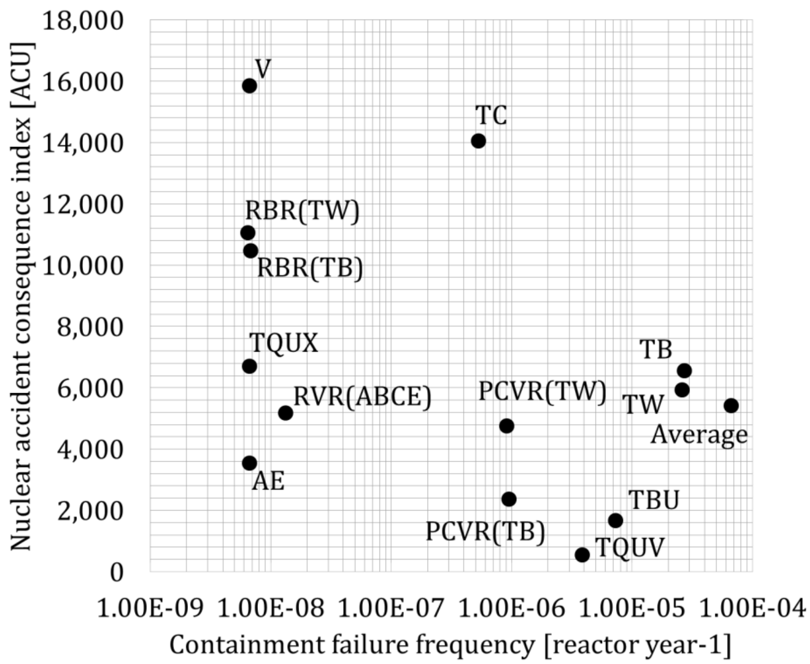

Figure 2.14. Nuclear accident consequence indices and containment failure frequencies of respective accident sequences.

2.5.2 Breakdown of nuclear accident consequence index

Breakdowns of nuclear accident consequence indices (NACIs) of respective accident sequences are shown in Figure 2.15. Accident sequences were sorted by their total NACIs in ascending order. When the release is very small (TQUV and TBU) all components that are constant values, i.e., decommissioning index, alternative source index and harmful rumor index, dominate the NACIs When the release is relatively small (PCVR(TB), AE, PCVR(TW) and RVR(ABCE)), the radiation effect index dominates the NACI since the annual dose rates in almost entire area are not high enough to relocate the people or decontaminate the area. When the release is relatively large (TW, TB, TQUX, RBR(TB) and RBR(TW)), the radiation effect index, the relocation index and the decontamination index are almost the same, and the sum of these three indices account for 80 – 90% of the NACI. This is because the relocated area and the relocated period increase with the amount of source term released, which consequently enlarge the decontamination target area since the decontamination is assumed to be done in entire relocated area. When the release is very large (TC, V), the relocation index and the decontamination index dominate the NACI. This is because the relocated area and the decontamination target area are significantly enlarged when the amount of source term increases, while the increase of collective dose which determines the radiation effect index is rather moderate.

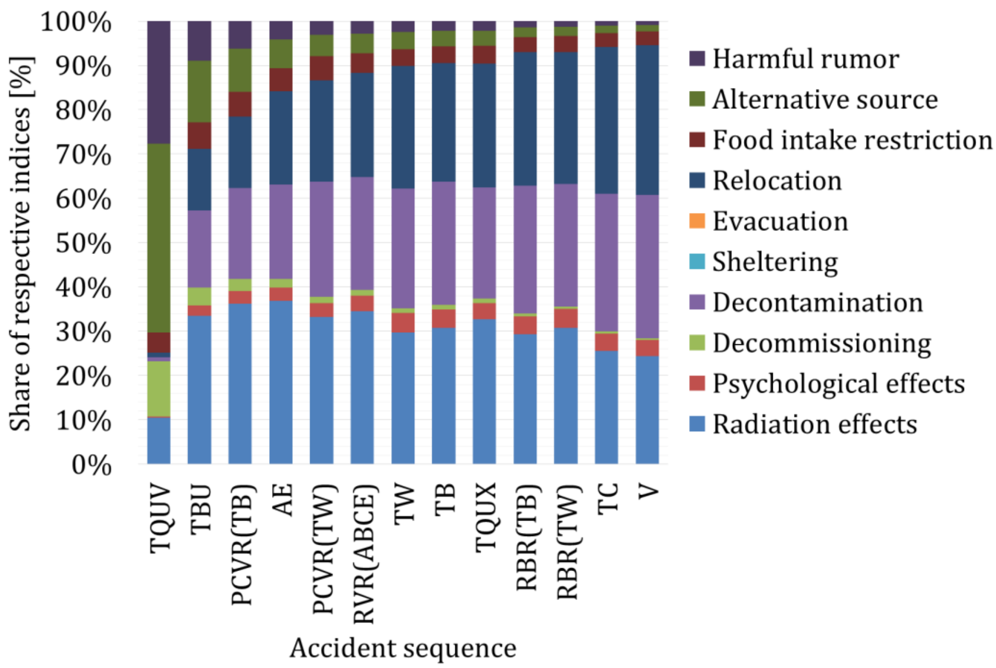

Figure 2.15. Breakdowns of nuclear accident consequence indices of respective accident sequences.

Breakdown of the average NACI is shown in Figure 2.16. The radiation effect index accounts for the greatest proportion of the average NACI, followed by the decontamination index and the relocation index. The large radiation effect index is partially attributed to the usage of the willingness to pay (WTP) which normally leads to a more conservative result comparing to the case that the human capital method is used [2.34]. The reasons for the large relocation index and decontamination index are that the relocated population, relocated area and decontamination target area are very large, and the relocated period is relatively long, since relatively conservative radiation protection scenarios are adopted (Table 2.3). Other indices are relatively small comparing to the three indices mentioned above. From Figures 2.15 and 2.16, it can be concluded that the radiation effect index, the relocation index and the decontamination index are the three dominant components of the NACI. Therefore, measures related to radiation protection, relocation and decontamination have to be carefully considered in the decision makings related to severe accident management.

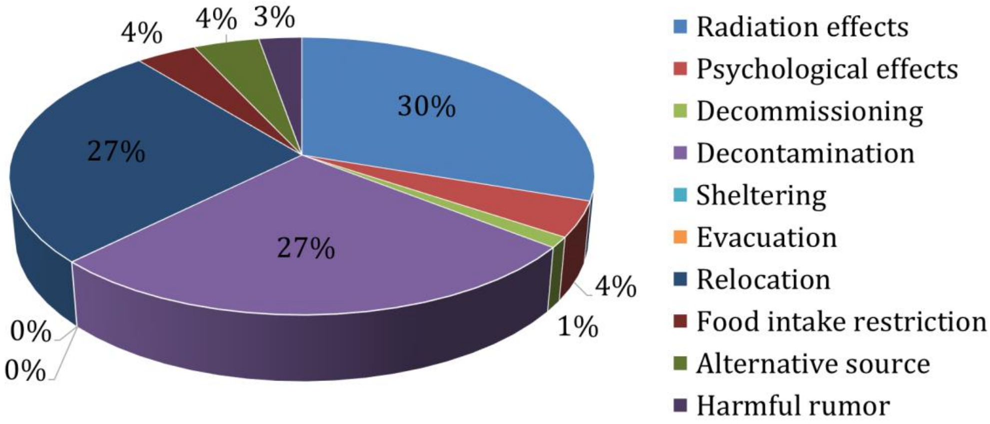

Figure 2.16. Breakdown of average nuclear accident consequence index.

2.5.3 Simplified nuclear accident consequence index

As can be seen in previous subsection, the three dominant components of the NACI, namely radiation effect index, relocation index and decontamination index, totally cover almost 90% of the average NACI. Therefore, in cases that time and resources available for the consequence assessment are limited, the assessor(s) can consider simplifying the NACI by evaluating only the three dominant components. Figures 2.17 and 2.18 show the breakdowns of the simplified NACI of respective accident sequences and the breakdown of average simplified NACI, respectively. Except for the accident sequences with very small release (TQUV and TBU), the two graphs look much alike the Figures 2.15 and 2.16. It can be seen from Figure 2.17 that when the release is larger, the radiation effect index reduce its share while the other two gradually increase. This is the same trend observed in breakdowns of normal NACI in Figure 2.15. Figure 2.18 shows that the three components share roughly one third of the simplified NACI. This is similar to the breakdowns of simplified NACI of accidents with relatively large release (TW, TB, TQUX, RBR(TB) and RBR(TW)) which dominate the probability of occurrence of the accidents.

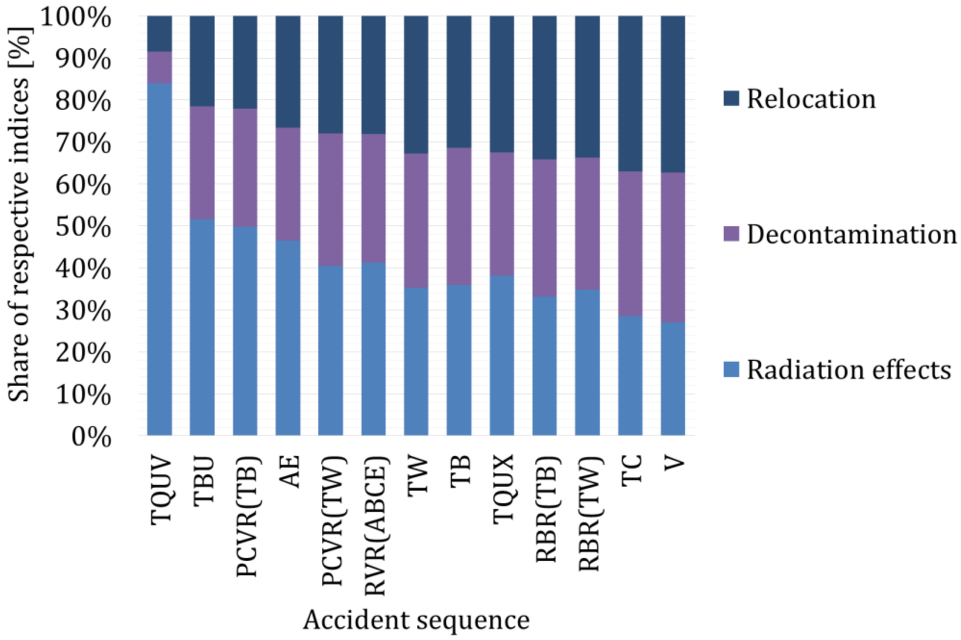

Figure 2.17. Breakdowns of simplified nuclear accident consequence indices of respective accident sequences.

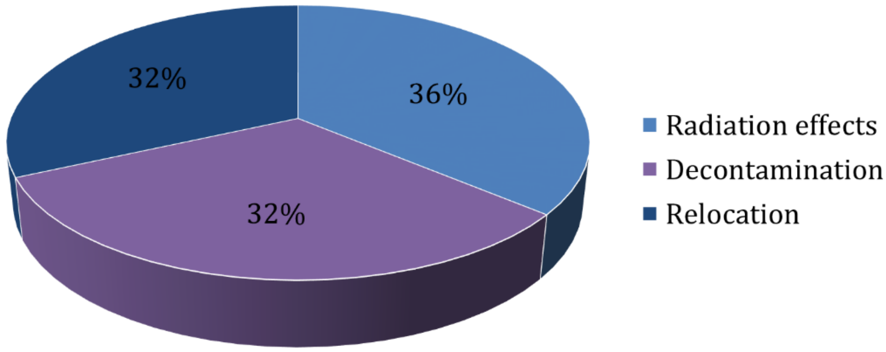

Figure 2.18. Breakdown of average simplified nuclear accident consequence index.

2.6 Sensitivity analysis

Ceteris paribus sensitivity analysis is performed in order to primarily check the influences of major parameters to the nuclear accident consequence index. Sensitivities of parameters in Table 2.6 are investigated. Table 2.7 shows the changes of the NACI and its components when respective parameters are changed. The results obtained in Table 2.7 is then ranked using the extent of influence of the parameters on the NACI, i.e. the change of NACI when the parameters are changed. The ranking is shown in Table 2.8 along with the index that dominates the changes of the NACI when respective parameters are changed. It can be seen from Table 2.8 that there are only three indices that dominate the changes of NACI for the top eleven parameters, namely radiation effect index, relocation index and decontamination index. This confirm the validity of the simplification of NACI mentioned in the previous section. The detailed description of the top three parameters, namely the dose level for returning home after relocation (and the dose level for recommending relocation), the number of reactor units under consideration and the waste volume reduction, are provided below.

Table 2.6. Parameters of which sensitivity analysis was performed.

No.	Parameters	Baseline case	Sensitivity analysis cases
1	Radiation effect estimation method	Value of statistical life	Human capital method
2	Exposure dose reduction factor	0.9	0.8 (large reduction) and 1.0 (no reduction)
3	Unit value of the psychological effect compensation	Compensation after Fukushima accident	Compensation for traffic accidents
4	Period of compensation for psychological effects due to relocation	1 year	2 years
5	Waste volume reduction	By incineration/ evaporation	No consideration
6	Decontamination target area	Entire relocated area	Reduced by factor of 0.2, 0.5 and 0.8
7	Decontamination methods	Based on the information from Fukushima accident	Decontamination methods are determined in the manner that gives minimum and maximum decontamination procedure indices
8	Unit decontamination procedure indices	Based on the information from Fukushima accident	Halved and doubled
9	Dose level for recommending sheltering	10 mSv	1 mSv and 20 mSv
10	Dose level for recommending evacuation	50 mSv	20 mSv and 100 mSv
11	Dose level for recommending relocation	20 mSv/year	100 mSv/year
12	Dose level for returning home (after relocation)	20 mSv/year	1 mSv/year and 5 mSv/year
13	Period of loss of income for relocated people	1 year	Entire relocated period

Table 2.6. Parameters of which sensitivity analysis was performed (continued).

No.	Parameters	Baseline case	Sensitivity analysis cases
14	Intervention levels for food intake restriction	Intervention levels recommended by IAEA	Intervention levels recommended by CODEX
15	Period of using alternative power source	30 years	16 years, 40 years
16	Type of alternative power source	Fossil fired power plant	Nuclear power plant
17	Value of harmful rumor index	Same as the case of the Fukushima accident	Twice the case of the Fukushima accident
18	Number of reactor units under consideration	Single unit	Average number of units in a nuclear power station in Japan (54/17 = 3.18 units)
19	Population density of the target site	Based on the population data in the proximity of TRDC, JAEA	Based on the average population in the proximity of the nuclear power stations in Japan
20	Availability factor	0.7	0.6 and 0.8

Table 2.7. Results of sensitivity analysis.

No.	Parameters	Index	Difference [%]
1	Radiation effect estimation method		
1.1	Human capital method	Radiation effect	-68%
		NACI	**-21%**
2	Exposure dose reduction factor		
2.1	0.8 (large reduction)	Radiation effect	-4%
		Relocation	-4%
		Food intake restriction	-5%
		NACI	**-2%**
2.2	1.0 (no reduction)	Radiation effect	+3%
		Relocation	+4%
		Food intake restriction	+38%
		NACI	**+3%**
3	Unit value of the psychological effect compensation		
3.1	Compensation for traffic accidents	Psychological effect	+67%
		NACI	**+3%**
4	Period of compensation for psychological effects due to relocation		
4.1	2 years	Psychological effect	+70%
		NACI	**+3%**
5	Waste volume reduction		
5.1	No consideration	Decontamination	+376%
		Food intake restriction	+220%
		NACI	**+110%**
6	Decontamination target area		
6.1	Reduced by factor of 0.2	Decontamination	-20%
		NACI	**-5%**
6.2	Reduced by factor of 0.5	Decontamination	-50%
		NACI	**-13%**
6.3	Reduced by factor of 0.8	Decontamination	-80%
		NACI	**-22%**
7	Decontamination methods		
7.1	Minimum decontamination procedure indices	Decontamination	-66%
		NACI	**-18%**
7.2	Maximum decontamination procedure indices	Decontamination	+65%
		NACI	**+18%**

Table 2.7. Results of sensitivity analysis (continued).

No.	Parameters	Index	Difference [%]
8	Unit decontamination procedure indices		
8.1	Halved	Decontamination	-10%
		NACI	**-3%**
8.2	Doubled	Decontamination	+19%
		NACI	**+5%**
9	Dose level for recommending sheltering		
9.1	1 mSv	Radiation effect	-0.4%
		Psychological effect	+0.07%
		Sheltering	+221%
		NACI	**-0.1%**
9.2	20 mSv	Radiation effect	+0.3%
		Psychological effect	-0.02%
		Sheltering	-52%
		NACI	**+0.08%**
10	Dose level for recommending evacuation		
10.1	20 mSv	Radiation effect	-0.8%
		Psychological effect	+0.07%
		Sheltering	-42%
		Evacuation	+113%
		NACI	**-0.2%**
10.2	100 mSv	Radiation effect	+0.8%
		Psychological effect	-0.04%
		Sheltering	+20%
		Evacuation	-54%
		NACI	**+0.2%**
11	Dose level for recommending relocation		
11.1	100 mSv/year	Radiation effect	+23%
		Psychological effect	-88%
		Decontamination	-86%
		Relocation	-71%
		Food intake restriction	-7%
		NACI	**-40%**

Table 2.7. Results of sensitivity analysis (continued).

No.	Parameters	Index	Difference [%]
12	Dose level for returning home (after relocation)		
12.1	1 mSv/year	Radiation effect	-34%
		Relocation	+622%
		Food intake restriction	+494%
		NACI	**+180%**
12.2	5 mSv/year	Radiation effect	-17%
		Relocation	+111%
		Food intake restriction	+108%
		NACI	**+30%**
13	Period of loss of income for relocated people		
13.1	Entire relocated period	Relocation	+30%
		NACI	**+8%**
14	Intervention levels for food intake restriction		
14.1	Intervention levels recommended	Radiation effect	-1%
	by CODEX	Food intake restriction	+34%
		NACI	**+1%**
15	Period of using alternative power source		
15.1	16 years	Alternative source	-47%
		NACI	**-2%**
15.2	40 years	Alternative source	+33%
		NACI	**+1%**
16	Type of alternative power source		
16.1	Nuclear power plant	Alternative source	-39%
		NACI	**-2%**
17	Value of harmful rumor index		
17.1	Twice the case of the Fukushima	Harmful rumor	+100%
	accident	**NACI**	**+3%**

Table 2.7. Results of sensitivity analysis (continued).

No.	Parameters	Index	Difference [%]
18	Number of reactor units under consideration		
18.1	Average number of units in a nuclear power station in Japan (54/17 = 3.18 units)	Radiation effect	+134%
		Psychological effect	+149%
		Decommissioning	+218%
		Decontamination	+193%
		Sheltering	+51%
		Evacuation	+149%
		Relocation	+206%
		Food intake restriction	+116%
		Alternative source	+218%
		NACI	**+170%**
19	Population density of the target site		
19.1	Based on the average population in the proximity of the nuclear power stations in Japan	Radiation effect	-49%
		Psychological effect	-49%
		Sheltering	-49%
		Evacuation	-49%
		Relocation	-37%
		NACI	**-27%**
20	Availability factor		
20.1	0.6	Alternative source	-14%
		NACI	**-1%**
20.2	0.8	Alternative source	+14%
		NACI	**+1%**

Table 2.8. Ranking of influence of sensitivity analysis parameters to NACI.

Rank	**No.**	**Parameters**	**Index which dominates the change of NACI**
1	12	Dose level of returning home (after relocation)	Relocation
2	18	Number of reactor units under consideration	Decontamination, relocation, radiation effect
3	5	Waste volume reduction	Decontamination
4	11	Dose level of recommending relocation	Relocation, decontamination
5	19	Population density of the target site	Radiation effect, relocation
6	6	Decontamination target area	Decontamination
7	1	Radiation effect estimation method	Radiation effect
8	7	Decontamination methods	Decontamination
9	13	Period of loss of income for relocated people	Relocation
10	8	Unit decontamination procedure indices	Decontamination
11	2	Exposure dose reduction factor	Radiation effect, relocation
12	3	Unit value of the psychological effect compensation	Psychological effect
13	4	Period of compensation for psychological effects due to relocation	Relocation
14	17	Value of harmful rumor index	Harmful rumor
15	15	Period of using alternative power source	Alternative source
16	16	Type of alternative power source	Alternative source
17	14	Intervention levels for food intake restriction	Food intake restriction
18	20	Availability factor	Alternative source
19	9	Dose level of recommending sheltering	Radiation effect
20	10	Dose level of recommending evacuation	Radiation effect

Dose level for returning home after relocation comes as a set with dose level for recommending relocation, as the latter is used to suggest people to relocate, and the former is used to lead them back to their hometown. In this sensitivity analysis, the dose level for recommending relocation is raised from 20 mSv/year in the baseline case to 100 mSv/year since it is the upper threshold of the reference level for emergency exposure recommended by the ICRP [2.8]. The dose level of returning home is reduced from 20 mSv/year in the baseline case to 1 mSv/year or 5 mSv/year, since 1 mSv/year is the lower threshold of the reference level for existing exposure recommended by the ICRP [2.8] and 5 mSv/year is the lower threshold of the dose band for voluntary relocation in the Chernobyl accident [2.35]. The NACI is significantly sensitive to both dose levels as can be seen in numbers 11 and 12 in Table 2.7. This is because the dose level for recommending relocation determines the number of relocating population and the size of area which would lose its function due to the relocation of people. On the other hand, the dose level for returning home determine the period of relocation. Also these two dose levels decide the total exposure dose of the population. If the dose level of recommending relocation is set higher, the area of which the integrated exposure dose reaches the dose level will be smaller. However, since fewer people relocated, the collective dose of the population will be higher. Yet it can be observed from the result in number 11 in Table 2.7 that the increase in collective dose, i.e. the increase in radiation effect index is much smaller than the decrease of relocated population and area, i.e. the decreases of relocation and decontamination indices. On the contrary, if the dose level for returning home is set lower, it takes time until the integrated exposure dose of the relocated area decreases to the determined dose level. Consequently, the relocated population has to relocate for a longer period. The longer relocated period reduces the collective dose of the population and subsequently the radiation effect index. Yet the degree of reduction of the radiation effect index is much less that the increase of the relocation index. These sensitivity analysis results indicate that the higher dose levels give the smaller NACI, i.e. the smaller consequences of a severe accident. It was not the change in radiation effect index but the changes in relocation and decontamination indices that dominate the change in the NACI.

Next influential parameter is the number of reactor units under consideration. As observed in the Fukushima accident, there is a possibility for the severe accident to occur in more than one unit at the same time. As there are 54 units in 17 sites of nuclear power stations in Japan (as of November 2013), a nuclear power station is assumed to possess 54/17 = 3.18 reactor units. We assume the same accident happening in all reactors located in the same power station by multiplying the source term by 3.18 times. Most indices composing NACI increase, and the NACI itself increases by 1.70 times (see Table 2.7). The fact that this parameter is influential to the extent of consequences of a severe accident underscores the lesson learned from the Fukushima accident that it is very important to consider the chance of accident in multiple units in the same site and find measures to prevent the occurrence and mitigate the consequences, should this worst case scenario happen.

The waste volume reduction is also one of the parameters with high influence on NACI. When the wastes are discarded without burning or evaporation to reduce their volume, the decontamination index increased significantly, which led to a 110% increase in the NACI. This is because the waste management index dominates the decontamination index, and the decontamination index is an important component of the NACI[6]. This implies that the waste management conditions must be carefully selected in the actual situation.

It is important to keep in mind that this sensitivity analysis is performed under specific conditions based on the actual situations observed after the Fukushima accident and information obtained from related literatures. If the conditions are significantly changed, the results in Table 2.7 may notably change, and the ranking in Table 2.8 may be totally different.

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[6] However, note that it is quite impractical to discard the waste without burning or evaporation.

2.7 Summary of Findings

The nuclear accident consequence index (NACI) which is an index that can include all anticipated consequences of a severe accident to people and the environment was developed.

- ✓ Showing both components of severe accident risk: probability which is represented by the containment failure frequency (CFF) and the consequences which is represented by the NACI, can avoid overlooking accidents with very small probabilities but significantly large consequences.
- ✓ The radiation effect index, the relocation index and the decontamination index are the three important components which dominate the NACI of most accident sequences and the average NACI.
- ✓ The three abovementioned components can represent the consequences of a severe accident to people and the environment in the form of simplified NACI.
- ✓ After a sensitivity analysis, three parameters were identified highly influential on the NACI: the dose level for returning home after relocation, the number of reactor units in a nuclear power station, and the waste volume reduction. The first parameter indicates the importance of careful consideration of dose levels associated to relocation. The second parameter indicate the necessity to perform a study the can evaluate the simultaneous accidents in multiple units in the same site. The third parameter emphasize that the attention must be paid to the determination of the conditions of the management of wastes generated after a severe accident.

The author is aware of other consequences which are not included in the NACI. Some of them are not included because they are negligibly minimal comparing to other consequences, e.g. the expenses for health inspection and the expenses for the temporary returns of the evacuees. Others are not included because they cannot be easily quantified, especially those related to social impacts, e.g. difficulties in restarting the existing nuclear power plant and the trend of energy policies in many countries toward denuclearization. In the actual severe accident consequence assessment, these consequences must be discussed and qualitatively evaluated, apart from the quantitative assessment using the NACI.

2.8 References

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Chapter 3 Modification of Decontamination Model[7]

3.1 Room for Improvements in Decontamination Model

Though the nuclear accident consequence index (NACI) and its simplified version introduced in Chapter 2 can be a practical mean to comprehensively assess the consequences of a severe accident, there is still room for improvements. As described in Chapter 2, there are three important components that dominates the NACI, namely radiation effect index, relocation index and decontamination index. These three indices are used to develop the simplified NACI which can be used instead of the NACI in order to save the resources spent for the assessment. The calculation models of the radiation effect index and the relocation index are based on well-established models of the OSCAAR code developed by Homma T et al [3.2]. However, the decontamination index was calculated by a newly formed estimation scheme using assumptions that are simple and are believed conservative. As the concept of decontamination has not been introduced in the OSCAAR code, matters related to decontamination which can affect radiation effect index or radiation effect index were also haphazardly taken into consideration. For example, the dose reduction due to the decontamination, which could contribute to the reduction of the radiation effect index, was modeled independently and has no connections to the dose reduction capacity of respective decontamination techniques. In addition, since the development of the estimation scheme was the primary objective of the study, the values of the parameters used in the estimation of the decontamination index were determined without adequate data collection. This may crucially affect the conclusions of the study, as the results may not be valid if the values of important parameters are not correctly chosen.

Therefore, this chapter will be dedicated to the development of a robust decontamination model, of which the assumptions are sufficiently realistic, and in which the distributions of the parameters are determined based on adequate and updated data obtained from reliable sources. We set it as an additional requirement that the newly developed model must not require a lot of resources for the calculation, in order to keep the assessment simple and practical. This new model would contribute to a more realistic and reliable, yet simple and practical severe accident consequence assessment.

[7] The content of this chapter is based on the paper: Silva K, Okamoto K, Ishiwatari Y, Takahara S, Promping J. Consideration of decontamination model for severe accident consequence assessment. J Nucl Sci Technol. DOI: 10.1080/00223131.2015.1005033 [3.1].

3.2 Development of Modified Decontamination Model

Figure 3.1 shows the overview of tasks related to the development of the new decontamination model. First, all factors related to the decontamination of the environment contaminated after an anticipated severe accident that have potential to cause some consequences to people or the environment are listed. They are then qualitatively screened by selecting only factors that can directly affect the three indices composing the simplified nuclear accident consequence index (simplified NACI), i.e. decontamination index, relocation index and radiation effect index. After that, the OSCAAR code [3.2] which is used to estimate the public exposure dose and the extent of land contamination is examined in order to identify decontamination-related parameters in the manner that can cover all factors mentioned above. The detail of these three steps and the selected factors and parameters can be found in Subsection 3.3.1. Next, the estimation schemes of all three indices of the simplified NACI are modified taking into account all decontamination-related factors (see Subsection 3.3.2). After the modification of the estimation schemes, the sensitivity analysis is performed to identify important parameters, to be able to fix parameters with negligible influence to the simplified NACI to constants and simplify the model. The elementary effect method which is adopted as the sensitivity analysis method is explained in Subsection 3.4.1. In preparation for the sensitivity analysis, the distributions of respective decontamination-related parameters are determined (see Subsection 3.4.2). Taking into account the results of the sensitivity analysis, the simplified decontamination model is developed by fixing parameters with low importance to constants (see Subsection 3.5.1). The simplified model is compared with the full model (where all parameters are distributed) under various conditions in order to verify the simplified model (see Subsection 3.5.2). Finally, the simplified NACI is calculated using this simplified decontamination model and the results are compared with that of Section 2.5.

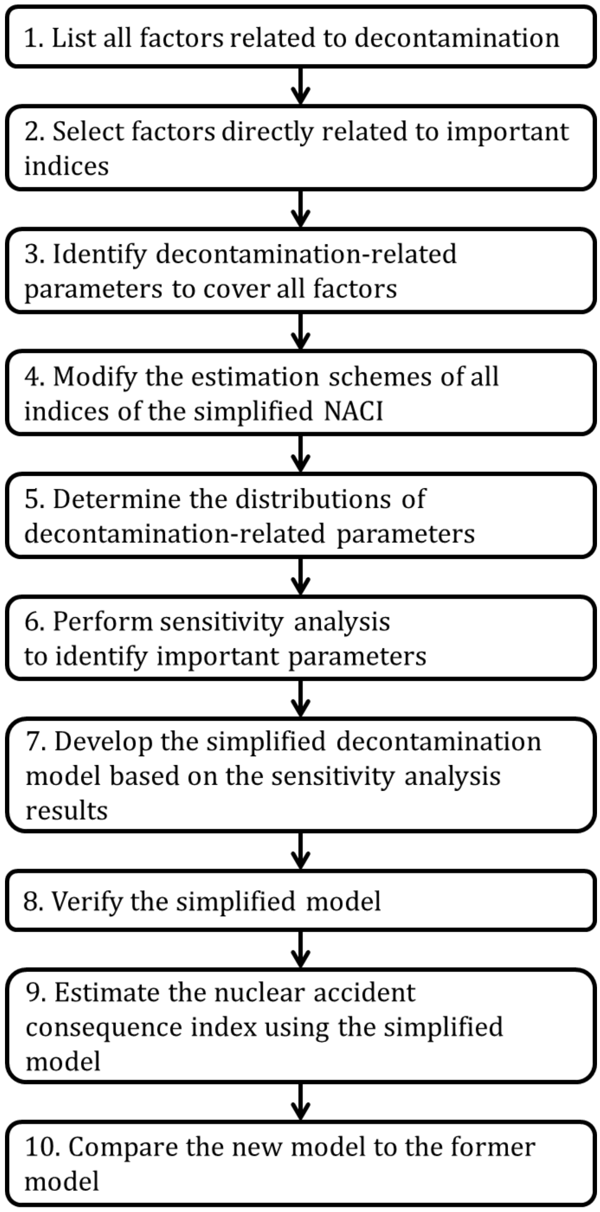


Figure 3.1. Flow of development of decontamination model.

3.3 Decontamination Model Description

3.3.1 Parameters selection

Factors related to decontamination which may affect the three indices of the simplified NACI, namely decontamination index, relocation index and radiation effect index, are listed in the first column of Table 3.1. The reasons these factors are taken into account are described below. Determination of decontamination target area evidently affects the decontamination index: decontamination of a large area requires large effort and consequently brings about large consequences. Decontamination techniques used in respective land use types and the associated unit decontamination procedure indices are also influential to the decontamination index since they determine the decontamination procedure index per unit decontaminated area. Waste generated by respective decontamination techniques will determine the total amount of waste generated from the decontamination procedures. Amount of this waste and the way it is managed can crucially affect the waste management index. As the waste management index is a component of the decontamination index, the aforementioned waste-related factors would finally affect the decontamination index. Decontamination speed can have an impact on relocation index. If the decontamination of the contaminated area is completed within a short period, the relocated people can soon return to their homes. When the relocated periods of these people are shortened, the capital losses which is one of the major components of the relocation index is reduced. The dose reduction factors for respective decontamination techniques or for respective land use types can be introduced in the calculation of radiation effect index in order to take into account the contribution of decontamination to the reduction of the exposure dose of people living in that area. The period of staying in specific areas per day is also needed in this calculation, thus it is included in the table. The occupational dose for workers involved with decontamination has influence on radiation effect index because it can increase the collective dose which is one of the parameters used to determine the radiation effect index.

After examining the OSCAAR code, we identified 99 decontamination-related parameters shown in the second column of Table 3.1 in order to incorporate all aforementioned factors into the decontamination model which is a new built-in module of the code. The parameter numbers in the third column of the table are used to represent decontamination-related parameters in all sections below (see Section 3.4).

Table 3.1. Decontamination related factors and parameters that affect the simplified nuclear accident consequence index.

Factor	Parameter	Parameter No.
Factors/parameters that affect decontamination index		
Determination of decontamination target area	Dose for decontamination target area setting [mSv/year]	1
Decontamination techniques[1] used in respective land use types	Fraction for application of respective decontamination techniques on roofs and walls of houses and buildings[2] [%] (2: B, 3: HPW)	2-3
	Fraction for application of respective decontamination techniques on gardens and playgrounds[2] [%] (4: RL, 5: RSS, 6: WLM, 7: RS, 8: CL)	4-8
	Fraction for application of respective decontamination techniques on agricultural and farming lands[2] [%] (9: P, 10: RSS, 11: RS)	9-11
	Fraction for application of respective decontamination techniques on forests[2] [%] (12: RSF, 13: RS, 14: CL)	12-14
	Fraction for application of respective decontamination techniques on roads[2] [%] (15: SB, 16: CS, 17: W)	15-17
Unit decontamination procedure indices	Unit decontamination procedure indices of 12 decontamination techniques[1] [ACU/m^2] (18: Determination of random number(s) used to determine unit decontamination procedure indices [3], 19: Random number to determine the unit decontamination procedure indices for the case of same random number, 20: HPW, 21: B, 22: RS, 23: RL, 24: CL, 25: RSS, 26: WLM, 27: P, 28: RSF, 29: W, 30: SB, 31: CS)	18-31
Waste generated by respective decontamination techniques	Liquid and solid waste generated by respective decontamination techniques[1,4] [m^3/m^2] (32: HPW (s), 33: HPW (l), 34: B (s), 35: B (l), 36: RS (s), 37: RL (s), 38: CL (s), 39: WLM (s), 40: RSF (s), 41: W (s), 42: W (l), 43: SB (s), 44: CS (s))	32-44

Table 3.1. Decontamination related factors and parameters that affect the simplified nuclear accident consequence index (continued).

Factor	**Parameter**	**Parameter No.**
Factors/parameters that affect decontamination index (continued)		
Waste management	Determination whether or not to take into consideration: 45: Temporary waste storage, 47: Waste transportation, 49: Waste treatment, 53: Interim storage, 55: Waste disposal	45, 47, 49, 53, 55
	Unit waste management indices [ACU/m^3] of: 46: Temporary waste storage, 48: Waste transportation, 50: Liquid waste treatment, 51: Solid waste treatment (incineration), 52: Solid waste treatment (classification and chemical process), 54: Interim storage, 56: High level radioactive waste disposal, 57: Disposal of controlled type waste	46, 48, 50-52, 54, 56-57
	Volume reduction rates [dimensionless] for: 58: Non-burnable solid waste, 59: Burnable solid waste	58-59
Factors/parameters that affect relocation index		
Decontamination speed	Number of workers that can involve in the decontamination work [man/year]	60
	Work speed of respective decontamination techniques(1)[m^2/man-day] (61: HPW, 62: B, 63: RS, 64: RL, 65: CL, 66: RSS, 67: WLM, 68: P, 69: RSF, 70: W, 71: SB, 72: CS)	61-72
Factors/parameters that affect radiation effect index		
Dose reduction factors	Selection of data set of dose reduction factors	73
	Dose reduction factors for respective decontamination techniques(1) [dimensionless] (74: HPW, 75: B, 76: RS, 77: RL, 78: CL, 79: RSS, 80: WLM, 81: P, 82: RSF, 83: W, 84: SB, 85: CS)	74-85

Table 3.1. Decontamination related factors and parameters that affect the simplified nuclear accident consequence index (continued).

Factor	Parameter	Parameter No.
Factors/parameters that affect radiation effect index (continued)		
Dose reduction factors (continued)	Dose reduction factors for respective land use types [dimensionless] (86: houses, 87: buildings, 88: agricultural and farming lands(5), 89: forests, 90: roads)	86-90
Period of staying in specific areas per day(6)	Period of staying in respective land use type per day [hr] (91: houses,92: buildings, 93: gardens and playgrounds, 94: agricultural and farming lands, 95: forests, 96: roads)	91-96
Occupational dose for workers involved in decontamination	Selection of range for calculation of occupational dose	97
	Average (98) and maximum (99) occupational dose calculation factors [dimensionless]	98-99

Notes

(1) Following abbreviations represent 12 decontamination techniques, where:
HPW = High pressure water, B = Brushing, RS = Removing soil or covering with soil, RL = Removing, covering with or harvesting lawn, CL = Cutting leaves and shrubs, RSS = Replacing soil with subsoil, WLM = Weeding or lawn mowing, P = Ploughing, RSF = Removing sediments and fallen leaves, W = Water, high pressure water SB = Sandblast or shotblast, CS = Cutting surface or resurfacing.

(2) The sums of the fractions of the decontamination techniques for respective land use types are normalized to 100%, except for CL which can be applied in the area where other decontamination techniques has already been applied.

(3) Using same random number for all decontamination techniques or different random numbers for each decontamination techniques.

(4) (s) stands for solid waste and (l) for liquid waste.

(5) The same dose reduction factor is also used for gardens and playgrounds due to absence of data.

(6) The sum of periods of staying is normalized to 24 hours.

3.3.2 Modification of simplified nuclear accident consequence index

99 decontamination-related parameters are included in the estimation schemes of the decontamination index, the relocation index and the radiation effect index, in order to reflect the influence of decontamination to respective indices composing simplified NACI. For each scheme, the differences between the former scheme introduced in Subsection 2.4.3 and the new scheme are explained first, followed by the descriptions of the equations used in the new estimation schemes.

3.3.2.1 Decontamination index

A number of improvements are needed to incorporate parameters in Table 3.1, and to ensure that the new decontamination index estimation scheme can take into account the actual conditions of the decontamination after the Fukushima accident and the Chernobyl accident of which information can be obtained from several reports and papers [3.3-3.8]. The modifications made to the model are described as follows:

(1) It can be seen after the two accidents that the decontamination target area is not necessarily identical to the relocated area. It can be smaller or larger depending on the concerns of the people and the decision of the government. For this reason, we introduced a parameter called dose for decontamination targer area setting [mSv/year] which is used to determine the target area for decontamination and is independent from the dose for starting relocation. This parameter is in the form of distribution, and its values for each run is randomly selected (correspond to parameter number 1 in Table 3.1).

(2) Decontamination techniques of respective land use types are changed to match with the decontamination techniques actually applied in the area contaminated after the Fukushima accident and the Chernobyl accident [3.3-3.7].

(3) Fractions for application of different decontamination techniques on respective land use types are introduced in the forms of distributions. Their values for each run are randomly selected from respective distributions (correspond to parameters number 2-17 in Table 3.1).

(4) Distributions of the unit decontamination procedure indices of different decontamination techniques are determined based on the information obtained from studies after the Fukushima accident and the Chernobyl accident [3.3-3.8]. Their values for each run are randomly selected from respective distributions (correspond to parameters number 18-31 in Table 3.1).

(5) Distributions of the amount of waste generated by respective decontamination techniques are determined based on the information obtained from studies after the Fukushima accident and the Chernobyl accident [3.3-3.8]. Their values for each run are randomly selected from respective distributions (correspond to parameters number 32-44 in Table 3.1).

(6) Not only the waste disposal index, but the unit waste management indices for the entire process of waste management, including temporary waste storage, waste transportation, waste treatment, interim storage and waste disposal, are introduced. Inclusions of unit waste management indices of each waste management step are randomly determined. All unit waste management indices are determined based on the information obtained from studies after historical severe accident [3.3-3.8]. They are in the forms of distributions, and their values for each run are randomly selected (correspond to parameters number 45-57 in Table 3.1).

(7) Volume reduction rates of burnable and non-burnable wastes are set to different values to reflect the actual volume reduction efficiency. They are in the forms of distributions, and their values for each run are randomly selected (correspond to parameters number 58-59 in Table 3.1).

Alike the former decontamination index estimation scheme, the decontamination index of the new scheme is also obtained by adding the total decontamination procedure indices of all decontamination techniques for all land use types to the summation of the waste management indices. The decontamination procedure index of the *t*th decontamination technique for the *l*th land use type $DP_{l,t}$ [ACU] is calculated by

$$DP_{l,t} = F_{l,t} \times A_l \times UDP_t, \text{ where } \sum_t F_{l,t} = 1. \quad (3.1)$$

$F_{l,t}$, which corresponds to parameters number 2-17 in Table 3.1, represents the fraction for application of the *t*th decontamination technique for the *l*th land use type [dimensionless]. $F_{l,t}$s that do not appear in Table 3.1 as parameters number 2-17 are set to zero. A_l and UDP_t represent the fraction for application of the *t*th decontamination technique for the *l*th land use type [dimensionless], the total area of the *l*th land use type [m^2] and the unit decontamination procedure index of the *t*th decontamination technique [ACU/m^2], respectively. The waste management index of the *t*th decontamination technique for the *l*th land use type $WM_{l,t}$ [ACU] is estimated by

$$WM_{l,t} = F_{l,t} \times A_l \times [\{(WS_t + WL_t) \times X_{TS} \times U_{TS}\} + \\ \{(WS_t + WL_t) \times X_{TR} \times U_{TR}\} + \\ \{X_{WT} \times (WS_t \times U_{WT,WS_t} + WL_t \times U_{WT,WL_t})\} + \\ \{X_{IS} \times WS_t \times VR_t \times U_{IS}\} + \\ \{X_{WD} \times (WS_t \times VR_t \times U_{WD} + WS_t \times (1 - VR) \times U_{CWD})\}. \quad (3.2)$$

Subscripts *TS*, *TR*, *WT*, *IS*, *WD* and *CWD* stand for temporary waste storage, waste transportation, waste treatment[8], waste interim storage, high level radioactive waste disposal and disposal of controlled type waste, respectively. WS_t and WL_t are solid and liquid wastes generated by the *t*th decontamination technique per unit area [m^3/m^2] and VR_t [dimensionless] is volume reduction rate for the *t*th decontamination technique which can be either the volume reduction rate for burnable waste or non-burnable waste. *X* [dimensionless] is used to determine whether or not to include the respective step into the waste management index (If yes, $X = 1$, if no, $X = 0$.). U represents the unit waste management indices of respective waste management steps [ACU/m^3]. The decontamination index *DC* [JPY] can finally be calculated by

$$DC = \sum_l \sum_t (DI_{l,t} + WM_{l,t}). \quad (3.3)$$

3.3.2.2 Relocation index

Comparing the parameters affecting relocation index (parameters number 60-72 in Table 3.1) with Equations (2.7), (2.9), (2.10), (2.12) and (2.13) which are used to estimate the indices constituting relocation index, there is no parameter in common. This implies that these equations needs no modification. The only parameter needs modification is the relocated period T_r. The decontamination speed which can be calculated using parameters 60-72 in Table 3.1 can affect the relocated period because the relocated people can move back to their homes faster if the decontamination is completed within a shorter period. The estimation scheme of the decontamination capacity *DCP* [m^2/year] which is used to represent the decontamination speed and its relation with the relocated period are described below.

Decontamination capacity *DCP* [m^2/year] is estimated by

$$DCP = \sum_l \sum_t F_{l,t} \times F_l \times NWK \times WSP_t \times 365 \quad (3.4)$$

[8] Incineration is used to treat the burnable waste and chemical treatment is used to treat non-burnable wastes. These waste treatments contribute to waste volume reduction.

where

$$\sum_l \sum_t F_{l,t} \times F_l = 1. \tag{3.5}$$

$F_{l,t}$ and F_l represent the fraction for application of the tth decontamination technique for the lth land use type [dimensionless], and the share of the area of the lth land use type from the entire decontamination target area [dimensionless], respectively. NWK and WSP_t stand for the number of workers that can involve in the decontamination procedure [man/year] and the work speed of the tth decontamination technique, which correspond to parameters number 60-72 in Table 3.1. The values of $F_{l,t}$s, NWK, and WSP_ts are randomly selected from respective distributions for each run. For each year in the calculation, if the summation of the area where the dose for decontamination target area setting is larger than the decontamination capacity, it is reduced to the decontamination capacity. In other words, the decontamination capacity will limit the size of the area than can be decontaminated each year. The remaining contaminated land will be decontaminated in the next year or later. Unfortunately, we cannot explain the relation between the decontamination capacity and the relocated period using simple equations. The dose for decontamination target area setting has its own distribution which is independent from the dose for starting relocation and dose for returning home. Therefore, there is a possibility that the decontamination is performed in a non-relocated area. In addition, decontamination cannot eliminate all the contaminants from the contaminated area (the decontamination efficiency is represented by the dose reduction factors). There is hence a possibility for the dose of some area to still be higher than the dose of returning home even after the decontamination. Consequently, some relocated people may need to wait for several years for the dose to be low enough for them to permanently return home. These possibilities made it difficult to mathematically explain the relation between the decontamination capacity and the relocated period.

In addition to the impact on the relocation index, the decontamination capacity can also affect the decontamination index since it determines the speed of the decontamination process. If the decontamination capacity is low, i.e. the decontamination process is slow, the natural decay of the radioactive contaminants may reduce the dose in some areas while it is waiting for the decontamination to be done until it falls below the dose decontamination target area setting. This will eliminate the need of decontamination of those areas, and consequently decrease the decontamination index.

3.3.2.3 Radiation effect index

Similar to the case of relocation index, there is no need to modify the equation (2.1) which is used to estimate the radiation effect index. However, parameters 73-99 in Table 3.1 can affect the value of the collective dose CD [Sv] which is the major parameter of the radiation effect index. In the new model, the dose reduction factors (dimensionless) are set based on the literature [3.4-3.7, 3.9] for respective decontamination techniques (DR_ts; correspond to parameters number 74-85 in Table 3.1) or for respective land use types (DR_ls; correspond to parameters number 86-90 in Table 3.1). It is randomly determined whether to use the set of DR_ts or the set of DR_ls based on parameter number 73 in Table 3.1. The collective dose CD [Sv] can be calculated by

$$CD = DR \times (CD_{POP} + CD_{OCP}), \tag{3.6}$$

$$DR = \sum_l \sum_t F_{l,t} \times F_l \times DR_t, \text{ where } \sum_l \sum_t F_{l,t} \times F_l = 1 \tag{3.7}$$

when the set of DR_ts is selected, and

$$DR = \sum_l T_l \times DR_l, \text{ where } \sum_l F_l = 1 \tag{3.8}$$

when the set of DR_ls is selected. CD_{POP} and CD_{OCP} are the collective doses [Sv] of the population and of the decontamination workers before taking into account the dose reduction, and DR is the average dose reduction factor [dimensionless]. $F_{l,t}$ and F_l represent the fraction for application of the tth decontamination technique for the lth land use type [dimensionless], and the share of the area of the lth land use type from the entire decontamination target area [dimensionless], respectively. T_ls represent the period of staying in respective land use types per day which correspond to the parameters number 91-96 in Table 3.1. $F_{l,t}$s, T_ls, DR_ts, and DR_ls are randomly selected from respective distributions for each run. Since the OSCAAR code can estimate only the the collective dose of the population CD_{POP}, the collective dose of the decontamination workers CD_{OCP} is calculated using the occupational dose calculation factor OD [dimensionless] which can be determined by parameters 97-99 in Table 3.1. The collective dose of the decontamination workers CD_{OCP} can be derived from

$$CD_O = \sum_d \sum_r \sum_y X_{DC,d,r,y} \times OD \times AD_{d,r,y} \times N_{WK,d,r,y}. \tag{3.9}$$

$X_{DC,d,r,y}$ is used to indicate whether or not decontamination is done in the area represented by mesh (d,r) in the yth year (If yes, X = 1, if no, X = 0.) in the OSCAAR code. d and r represent the 25 distances and 32 directions of the meshes used by the OSCAAR code. $AD_{d,r,y}$ and $N_{WK,d,r,y}$ are the annual dose and the number of decontamination workers in the area represented by mesh (*d*,*r*) in the *y*th year, respectively.

3.4 Sensitivity Analysis

A sensitivity analysis is performed in order to:

(1) Check the influence of respective decontamination-related parameters to the simplified NACI and its components, namely decontamination index, relocation index and radiation effect index.
(2) Simplify the model by fixing parameters of which the influence is negligible to constant and keep only important parameters distributed.

This section consists of three subsections. The first subsection briefly describes the elementary effects method which is the method selected for the sensitivity analysis. The second subsection introduces the way the distributions of the decontamination-related parameters are determined, and presents some examples of important parameters. The last subsection discusses the results.

3.4.1 Elementary effects method (Morris method)

The elementary effects method (the version proposed by Morris [3.10], and revised by Campolongo et al. [3.11] is selected as the sensitivity analysis method in this study because it can simultaneously take into account a number of parameters while keeping the operations and the results simple and straightforward. The two main results which can be obtained from this method are:

(1) μ^* which is the average of the absolute values of the elementary effects (to be hereinafter described). Since μ^*s of respective parameters represent the extent that the output is affected by that specific parameter, they help identify parameters with large influence to the output.
(2) σ which is the standard deviation of the elementary effects. σs of respective parameters represent the changes of other parameters when that specific parameter is varied, thus they help identify parameters that have large extent of interactions with other parameters.

Parameter which has significantly small μ^* and σ can be fixed to a constant, e.g. the average or the median of its distribution, in order to simplify the model.

In the elementary effects method, we assume that the model inputs can be expressed by the k-dimensional vector $\mathbf{X}$ (k is equal to the number of the model inputs). $\mathbf{X}$ has components X_i each of which can assume p integer values between 0 and 1. These integer values are normally fixed to multiples of $1/(p-1)$ in order to obtain a set of integer values with equal interval: {0, $1/(p-1)$, $2/(p-1)$, … , $(p-2)/(p-1)$, 1}. This forms a k-dimensional p-level experimental region $\mathbf{\Omega}$ ($k \times p$ matrix). For a given value x of X, the elementary effect of the ith input parameter is defined as

$$d_i(\mathbf{x}) = \{y(x_1, \dots, x_{i-1}, x_i + \Delta, x_{i+1}, \dots, x_k) - y(\mathbf{x})\}/\Delta \tag{3.10}$$

where Δ is a predetermined multiple of 1/(p – 1), and $\mathbf{x} = (x_1, x_2, \dots, x_k)$ is a set of selected values in $\mathbf{\Omega}$ such that the transformed point $(\mathbf{x} + \mathbf{e_i}\Delta)$, where $\mathbf{e}_i$ is a vector of zeroes but with one as its ith component, is still in $\mathbf{\Omega}$ for each index i (i = 1, 2, … , k). Δ typically adopt a value that is slightly larger than 0.5 in order to ensure that the original point $\mathbf{x}$ and the transformed point $(\mathbf{x} + \mathbf{e_i}\Delta)$ will not be in the same side of the distribution.

The model is run for r times for respective components, each time the elementary effects $d_i(\mathbf{x})$ of the output y is calculated. After the rth run of the kth component X_k, the average of the absolute values of the elementary effects μ^*, and the standard deviation of the elementary effects σ, of each component X_i are calculated by

$$\mu^* = \sum_{i=1}^{r}(|d_i|/r), \tag{3.11}$$

and

$$\sigma = \sqrt{\sum_{i=1}^{r}\{(d_i - \mu)^2/r\}}, \text{where } \mu = \sum_{i=1}^{r}(d_i/r) \tag{3.12}$$

Actually, both μ and μ^* can be used as an indicator to identify parameters with large influence to the output. However, μ^* is preferable to μ because $d_i(\mathbf{x})$s can give negative values and some effects may cancel each other out when computing the average if μ is used [3.11].

In this sensitivity analysis, we have the simplified NACI as the main output, and its components, namely the decontamination index, the relocation index and the radiation effect index, as the secondary outputs. The elementary effects of all outputs can be calculated by Equation (3.10). The model input is a 99-dimensional vector (k = 99), since there are 99 decontamination-related parameters to be examined. The number of levels p and the difference of the elements Δ are set to 10 and 5/9. The number of runs r for each component X_i is set to 20.

In each run, $\mathbf{x}$ is randomly selected from $\mathbf{X}$, and $y(\mathbf{x})$ is estimated. Then the ith component is transformed by $\mathbf{e_i}\Delta$, and $y(\mathbf{x} + \mathbf{e_i}\Delta)$ is calculated. Finally, the elementary effect $d_i(\mathbf{x})$ is calculated. To calculate the outputs y (simplified NACI, decontamination index, relocation index and radiation effect index) both before transformed $y(\mathbf{x})$, and after transformed $y(\mathbf{x} + \mathbf{e_i}\Delta)$, x_is are used as the percentile to pick up a value from the distribution of the ith parameter (the sequence of the parameters is defined as the parameter numbers in Table 3.1). For example, if x_{44} = 4/9, the 44.44th percentile value of the distribution of parameter number 44, i.e. the waste generated by cutting the surface of or resurfacing the roads, will be selected as the representative value of parameter number 44 in that run. After the 20th run of the 99th component, the average of the absolute values of the elementary effects μ^* and the standard deviation of the elementary effects σ are estimated for respective components.

3.4.2 Determination of parameter distributions

Distributions of 99 parameters in Table 3.1 are determined based on the information obtained from reports after the Chernobyl accident and updates from the Fukushima accident [3.3-3.9]. All other parameters adopt the values used in Chapter 2 [3.12]. Distributions of parameters with non-negligible influence on simplified NACI, i.e. parameters which are not fixed to constant in order to simplify the model in Subsection 3.5.1, are presented in Table 3.2. All parameters adopt either discrete or uniform distribution since the numbers of data used to determine the distributions are relatively small and the data points are relatively scattered. Further data collection when more information is available from the decontamination of the lands around Fukushima Daiichi Nuclear Power Station would help determine the appropriate type of distribution of respective parameters

Table 3.2. Distributions of parameters with non-negligible influence on simplified nuclear accident consequence index.

No.	Parameter	Type of Distribution	Min.	Max.	Remarks
1	Dose for decontamination target area setting [mSv/year]	Discrete	1	20	4 annual dose rates (1, 5, 10 and 20) with same probability density (P(x) = 0.25).
4	Fraction for removing, covering with or harvesting lawn of gardens or playgrounds	Uniform	0	100	The sum of values of parameters number 4-8 is normalized to 100%
5	Fraction for replacing soil of gardens or playgrounds with subsoil	Uniform	0	100	
6	Fraction for weeding or lawn mowing of gardens or playgrounds	Uniform	0	100	
7	Fraction for removing soil or covering with soil of gardens or playgrounds	Uniform	0	100	
8	Fraction for cutting leaves and shrubs of gardens or playgrounds	Uniform	0	100	

Table 3.2. Distributions of parameters with non-negligible influence on simplified nuclear accident consequence index (continued).

No.	Parameter	Type of Distribution	Min.	Max.	Remarks
9	Fraction for ploughing agricultural or farming lands [%]	Uniform	0	100	The sum of values of parameters number 9-11 is normalized to 100%
10	Fraction for Replacing soil of agricultural or farming lands with subsoil [%]	Uniform	0	100	
11	Fraction for removing soil or covering with soil of agricultural or farming lands [%]	Uniform	0	100	
15	Fraction for applying sandblast or shotblast on roads [%]	Uniform	0	100	The sum of values of parameters number 15-17 is normalized to 100%
16	Fraction for cutting road surface or road resurfacing [%]	Uniform	0	100	
17	Fraction for applying water or high pressure water on roads [%]	Uniform	0	100	
18	Determination of random number(s) used to determine unit decontamination procedure indices	Discrete	Same	Different	[0, 0.5) = same/ [0.5, 1) = different.
19	Random number to determine the unit decontamination procedure indices for the case of same random number	Uniform	0	1	

Table 3.2. Distributions of parameters with non-negligible influence on simplified nuclear accident consequence index (continued).

No.	Parameter	Type of Distribution	Min.	Max.	Remarks
36	Waste generated by removing soil or covering with soil [m^3/m^2]	Uniform	0.000	0.079	
38	Waste generated by cutting leaves and shrubs [m^3/m^2]	Uniform	0.002	0.122	
44	Waste generated by cutting surface or resurfacing [m^3/m^2]	Uniform	0.008	0.296	
45	Determination whether or not to consider temporary waste storage	Discrete	0	1	[0, 0.5) = no/ [0.5, 1) = yes.
47	Determination whether or not to consider waste transportation	Discrete	0	1	[0, 0.5) = no/ [0.5, 1) = yes.
49	Determination whether or not to consider waste treatment	Discrete	0	1	[0, 0.5) = no/ [0.5, 1) = yes.
53	Determination whether or not to consider interim storage	Discrete	0	1	[0, 0.5) = no/ [0.5, 1) = yes.
54	Unit waste management index of interim storage [JPY/m^3]	Uniform	100,000	572,000	
55	Determination whether or not to consider waste disposal	Discrete	0	1	[0, 0.5) = no/ [0.5, 1) = yes.

Table 3.2. Distributions of parameters with non-negligible influence on simplified nuclear accident consequence index (continued).

No.	Parameter	Type of Distribution	Min.	Max.	Remarks
56	Unit waste management index of waste disposal [JPY/m^3]	Uniform	650,000	3,018,000	
58	Volume reduction rate for non-burnable solid waste [dimensionless]	Uniform	0.70	0.93	
60	Number of workers that can involve in the decontamination work [man /year]	Uniform	5,000	50,000	Determined by the evaluator

3.4.3 Results and discussion

The main results of the sensitivity analysis, i.e. the μ^*s and σs of all parameters for simplified NACI are shown in Figures 3.2(a) and 3.2(b). The accident sequence TB (long-term station blackout) which possess the largest containment failure frequency and an average meteorological condition are adopted for the calculation. Figure 3.2(a) shows the whole picture of the μ^*s and σs of all parameters where the graph is zoomed in in Figure 3.2(b) to visualize parameters with small μ^*s and σs. The numbers in the two graphs correspond to the parameter numbers in Table 3.1. It can be observed from Figure 3.2(a) that μ^* strongly correlates with σ (coefficient of determination $R^2 = 0.95$). This correlation suggests that parameters which are influential on the simplified NACI tend to also have large extent of interactions with other parameters. Discussion below is thus based solely on μ^* as it could also roughly represent the discussion on σ.

It is obvious from Figure 3.2(a) that the dose for decontamination target area setting (1[9]) which has the largest μ^* is one of the most influential parameters for the simplified NACI. This is because this parameter is used to determine the size of the decontamination target area, and consequently determine the decontamination index which is one of the major components of the simplified NACI. The figure also shows the high

[9] All numbers in the bracket in this Subsection represent the parameter numbers in Table 3.1.

importance of four parameters related to waste management (53, 55, 56 and 58) of which the μ^*s and σs are over 0.20. This implies that waste management is a very important step after a severe accident, and the waste resulted from decontamination of the contaminated area could cover a large part of the overall consequences of a severe accident. Especially, the high μ^*s and σs of the determination whether or not to consider waste disposal (55) and the unit waste management index of waste disposal (56) emphasize the importance of consideration of the consequences due to waste disposal which was omitted in earlier studies [3.5, 3.9]. Another important parameter is the number of workers that can involve in the decontamination work (60) since it determines the decontamination speed which can consequently affect the relocated period and the size of the area being decontamination each year as discussed in Subsection 3.3.2.2. As these parameters have significant influences on simplified NACI which represent the consequences of a severe accident, following recommendations can be provided to the decision makers:

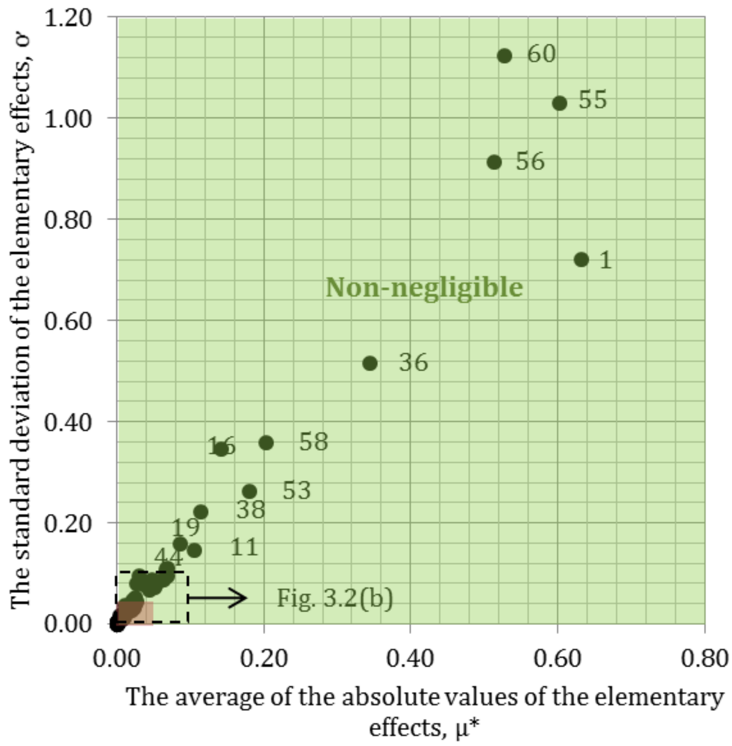
(1) The dose for decontamination target area setting must be selected after thorough deliberation of the circumstances after the accident, e.g. the extent of the land contamination, the resources needed to be spent for the decontamination process, the anxiety of the people; since it can significantly affect the consequences of a severe accident resulted by the decontamination of the contaminated area.
(2) The way the waste generated by the decontamination after a severe accident must be deliberately discussed among the stakeholders taking into account the circumstances after the accident. This is because the waste management is composed of many step, each of which require a great deal of resources, thus it could cover a large part of the overall consequences of a severe accident.
(3) The number of workers involving in the decontamination work can determine the decontamination speed. The number of workers that is suitable for the decontamination process must be selected after careful consideration.

In addition to highly influential parameters mentioned above, the waste generated per unit area of the decontamination techniques which generate a large volume of waste, i.e. removing soil or covering with soil (36), cutting leaves and shrubs (38) and cutting surface or resurfacing (44) also seems to be influential on the simplified NACI (see Figure 3.2(a)) as they affect the total waste amount. It is also observable from the figure that fractions for application of decontamination techniques with large unit decontamination procedure indices, i.e. the fraction for removing soil or covering with soil of agricultural or farming lands (11) and the fraction for cutting road surface or road resurfacing (16) can be quite influential to the main output. The large μ^* of the random number to determine the unit decontamination procedure indices for the case of same random number (19) indicates that if a single number is used to select a value from respective distributions of the unit decontamination procedure indices, it may have large effect on the simplified NACI.

Figure 3.2(b) shows that there are 13 more parameters of which the μ^*s and σs are equal to or larger than 0.05. They are considered non-negligible and will not be fixed to constants to simplify the decontamination model. The 13 parameters are:

(1) Fractions for application of several decontamination techniques, including replacing soil of gardens or playgrounds with subsoil (5), removing soil or covering with soil of gardens or playgrounds (7), cutting leaves and shrubs of gardens or playgrounds (8) and ploughing agricultural or farming lands (9).
(2) Determination of random number(s) used to determine unit decontamination procedure indices (18).
(3) Unit decontamination procedure index of replacing soil with subsoil (25).
(4) Parameters related to waste management other than those mentioned above: determinations whether or not to consider temporary waste storage (45), waste transportation (47) and waste treatment (49), and unit waste management index of interim storage (54).
(5) Work speeds of some decontamination techniques, including removing soil or covering with soil (63), replacing soil with subsoil (65) and sandblast or shotblast (71).

All other parameters of which both μ^*s and σs are under 0.05 are theoretically negligible. They can be fixed to constants in order to simplify the model.



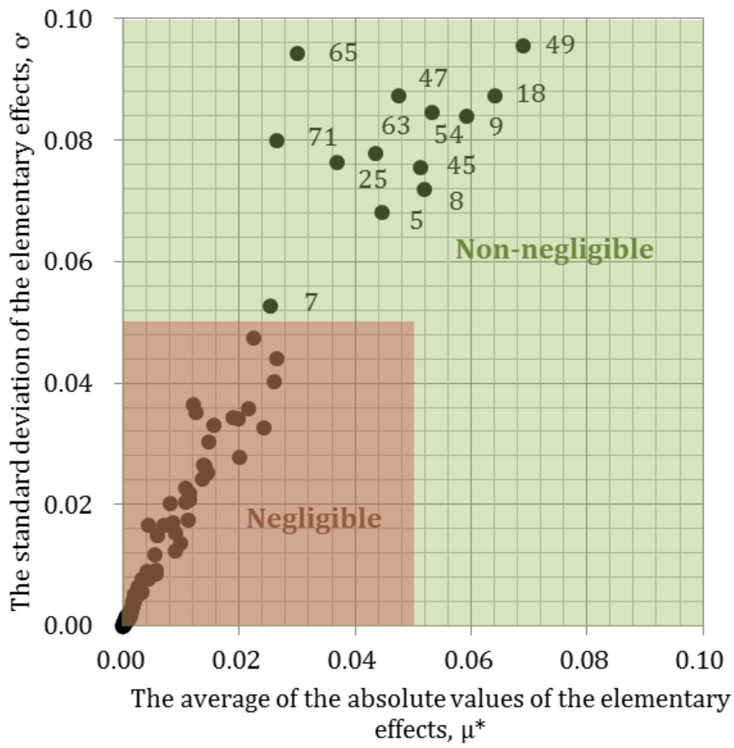


Figure 3.2. (a) μ^*s and σs of all parameters for simplified NACI (top).
(b) Zoomed in version of Figure 3.2(a) ($0 \leq \mu^* \leq 0.10$ and $0 \leq \sigma \leq 0.10$)(bottom).

Figures 3.3 to 3.5 show the μ^*s and σs of all parameters for decontamination index, relocation index and radiation effect index, respectively. Figure 3.3 is almost identical with Figure 3.2(a). The first ten parameters that have largest μ^*s and σs are the same, though the values of μ^*s and σs are different. It stands to reason that the behaviors of the parameters related to the decontamination index dominate the influences of the parameters toward the simplified NACI since this study aims to develop a decontamination model. On the other hand, it is rather surprising that parameters number 60 – 73 which is supposed to represent the influence of decontamination on relocation in terms of relocation period are hardly influential on the relocation index (see Figure 3.4). Instead of them, parameters which are believed to have influence on the radiation effect index, especially those related to the determination of the dose reduction factor (73, 74, 75, 86, 88 and 94), are parameters which have large μ^*s and σs. This is because these parameters decide the extent of the dose reduction attributed to the decontamination, thus they indirectly determine whether the dose of the decontaminated area is low enough for the relocated people to return. It also seems that the fractions for application of some decontamination techniques on roofs and walls of houses and buildings (2 and 3) and on agricultural and farming lands (11) have significant influence on the relocation index. This is linked to the dose reduction due to decontamination as well. As people spend more time in their daily life in houses and buildings, or in agricultural and farming lands, the fractions for application of decontamination techniques on these areas which can determine the extent of dose reduction by decontamination have significant influence. Lastly, it can be seen from Figure 3.5 that most parameters that determine the dose reduction factor (73, 74, 76, 79, 81, 84, 86, 88, 90, 94 and 95) and the occupational dose for workers involved in decontamination (97 and 99) have some influence on the radiation effect index. However, these parameters do not appear in both Figures 3.2(a) and 3.2(b), which means they are not influential on the simplified NACI. This may be because:

(1) Most people will be relocated before they are exposed to high radiation dose. Therefore, the dose reduction due to the decontamination may not necessarily reduce the dose to the people.
(2) The reduction of the collective dose to the people who did not relocate or those who moved back after the annual dose had fallen below the dose for returning home after relocation may be cancelled out by the increase of the collective dose to the people who moved back earlier than have been planned due to the dose reduction by decontamination. This is because the total dose received by the relocated people during the relocated period is set to zero in the calculation, thus they receive more dose when they moves back earlier.

However, this does not necessarily mean that the radiation effect index is not important. As the study aims to develop the decontamination model, parameters that are hardly related to decontamination but may have significant influence on the radiation effect index, e.g. willingness to pay (WTP) per unit exposure dose, are not taken into account in this study. The only conclusion which can be derived from this observation is that the interaction between decontamination and the radiation effect index is significantly small. This is however a crucial conclusion since it implies that the decontamination which intend not only to clean up the contaminated area but also to reduce the dose to the population, i.e. the consequences to the people, consequently would not affect the extent of the dose to the people. Therefore, it is important to carefully deliberate the objectives of decontamination before starting to decontaminate the contaminated area.

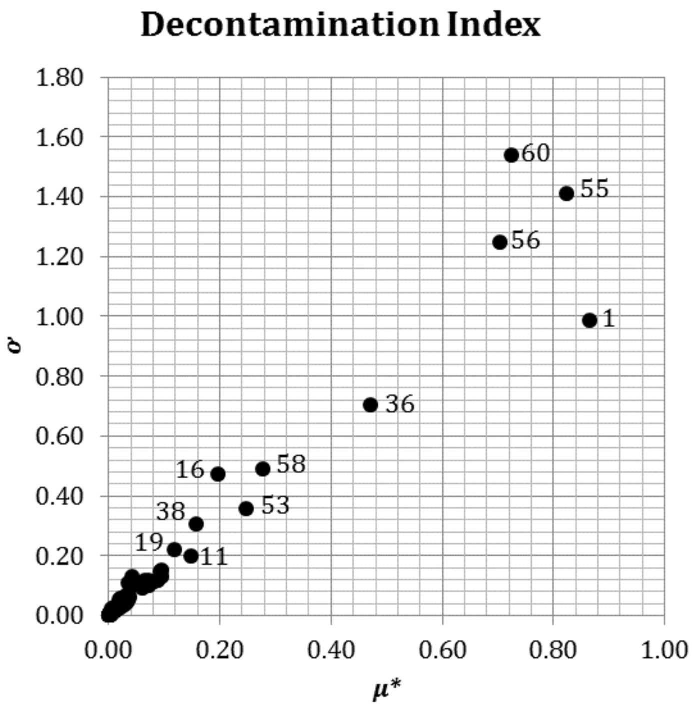


Figure 3.3. μ^*s and σs of all parameters for decontamination index.

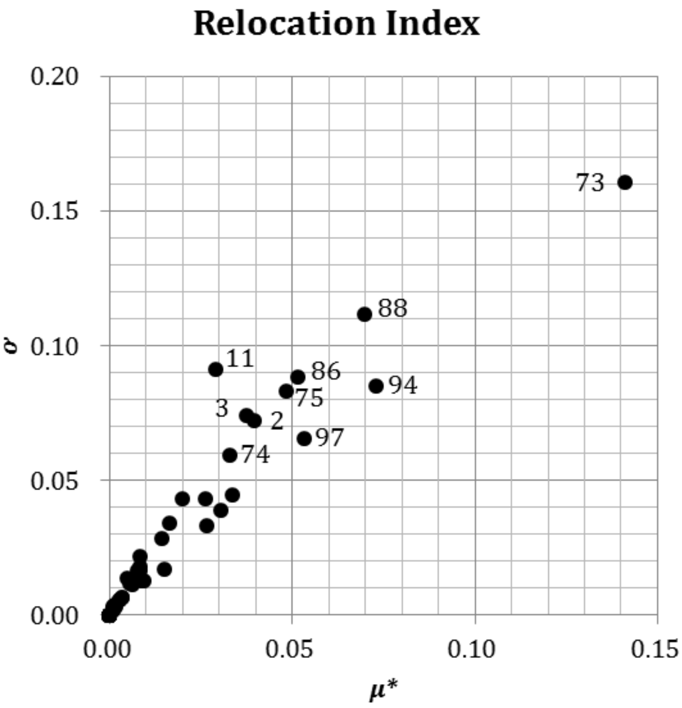


Figure 3.4. μ^*s and σs of all parameters for relocation index.

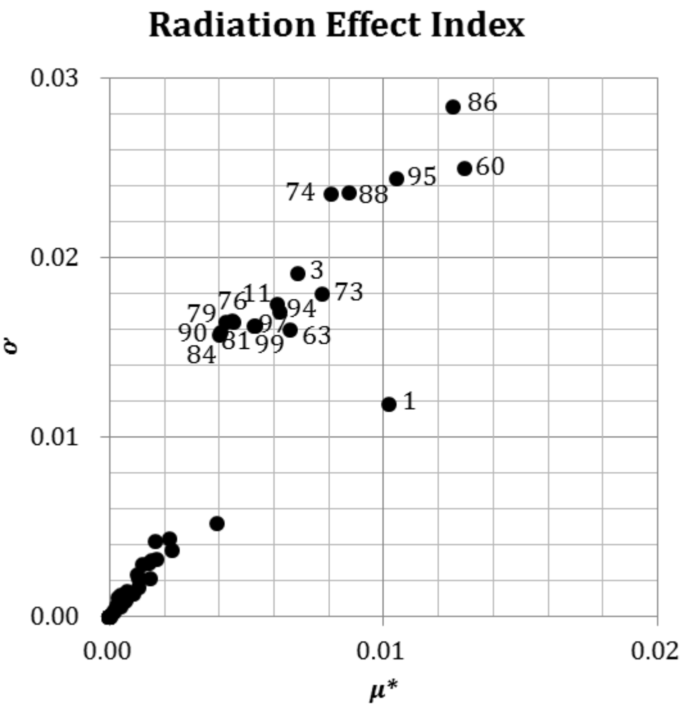


Figure 3.5. μ^*s and σs of all parameters for radiation effect index.

3.5 Simplified Decontamination Model

3.5.1 Simplification of decontamination model

The decontamination model described in Subsection 3.3.2 is simplified based on the results obtained in Subsection 3.4.3 in order to reduce the resources spent for the calculation. The model can be easily simplified by keeping 25 non-negligible parameters (1, 5, 7, 8, 9, 11, 16, 18, 19, 25, 36, 38, 44, 45, 47, 49, 53, 54, 55, 56, 58, 60, 63, 65 and 71) in the form of distribution and fix all other 74 negligible parameters to constants. In the process of fixing parameters to constants, the median value of respective parameters, which is actually also equal to the mean value since either discrete or uniform distribution is selected, is selected as the representative constant. However, parameters that belong in the same group had better be treated in the same way. For this reason, parameters which remain in the form of distribution are reconsidered. If the major part of the parameters are non-negligible ones, all parameters in the same group are kept in the form of distribution. If more than half of the parameters in the same group are negligible ones, all are fixed to constants. Fraction for applications of all decontamination techniques for gardens and playgrounds, agricultural and farming lands, and roads (4-8, 9-11 and 15-17) are all kept in the form of distribution. The unit decontamination procedure index of replacement of soil by subsoil is fixed to its median value in order to get along with other unit decontamination procedure indices. Following the work speeds of other decontamination techniques, the work speeds of removing soil or covering with soil (63), cutting leaves and shrubs (65) and sandblast or shotblast (71) are fixed to their median value. Eventually, there are 26 parameters (1, 4, 5, 6, 7, 8, 9, 10, 11, 15, 16, 17, 18, 19, 36, 38, 44, 45, 47, 49, 53, 54, 55, 56, 58 and 60) which are treated as distribution.

3.5.2 Verification of simplified decontamination model

In this subsection, the simplified decontamination model obtained in Subsection 3.5.1 is verified by checking its differences from the model before simplification (hereinafter referred to as full model). The comparisons of the simplified NACI and its three components calculated by the full model and the simplified model are shown in Figures 3.6(a) – 3.6(d). Calculation are repeated 1,000 times using the accident sequence TB (long-term station blackout) and an average meteorological condition. Simplified NACI, decontamination index, relocation index and radiation effect index at each percentile are displayed as the results. It can be seen from Figures 3.6(a) and 3.6(b) that the values of the simplified NACI and the decontamination index calculated by the simplified model are nearly identical to those of the full model. On the other hand, Figures 3.6(c) and 3.6(d) show that the values of the relocation index and the radiation effect index of the two models are rather different, even though the averages are almost the same. This is because the parameters that are influential to the relocation index and the radiation effect index, i.e. parameters related to the dose reduction factor (see Figures 3.4 and 3.5), are parameters fixed to its median value to simplify the model in Subsection 3.5.1. For this reason, the values of the relocation index and the radiation effect index of the simplified model only vary slightly near their average, rather than broadly distributed as in the case of the full model.

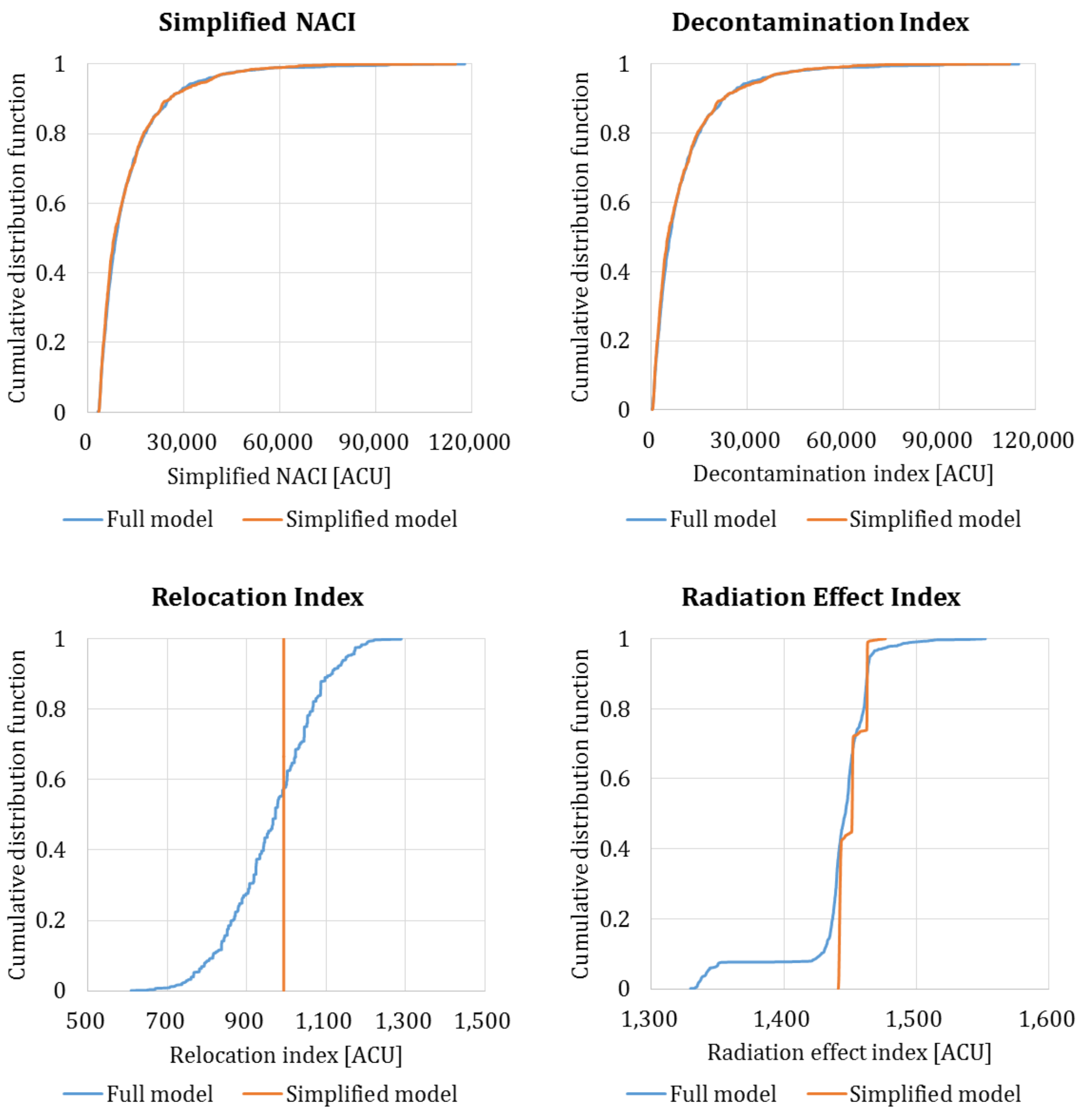


Figure 3.6. Comparison of simplified NACI and its components calculated by the full model and the simplified model.
(a) Simplified NACI (top-left). (b) Decontamination index (top-right).
(c) Relocation index (bottom-left). (d) Radiation effect index (bottom-right).

3.5.3 Consideration of variation in meteorological conditions

Variation in the meteorological conditions in one of the most important aleatoric uncertainties in the severe accident consequence assessment, which are taken into account in many earlier studies [3.2, 3.13, 3.14]. The preceding study using the OSCAAR code determined 248 meteorological sequences to cover all types of weather [3.2]. The results of ten trial calculations of the simplified NACI of the accident sequence TB calculated with 248 meteorological sequences are shown in Figure 3.7. Significant variation of the simplified NACI can be observed around the 70th to the 90th percentile. The variation in the values of simplified NACI of respective trial calculations can be even larger than the difference between the simplified model and the full model. This makes it difficult to verify the simplified model by comparing it to the full model. Iterative calculation is then needed to reduce the variation in different trial calculations. It is found that comparison would become possible when the calculations are repeated for more than ten times.

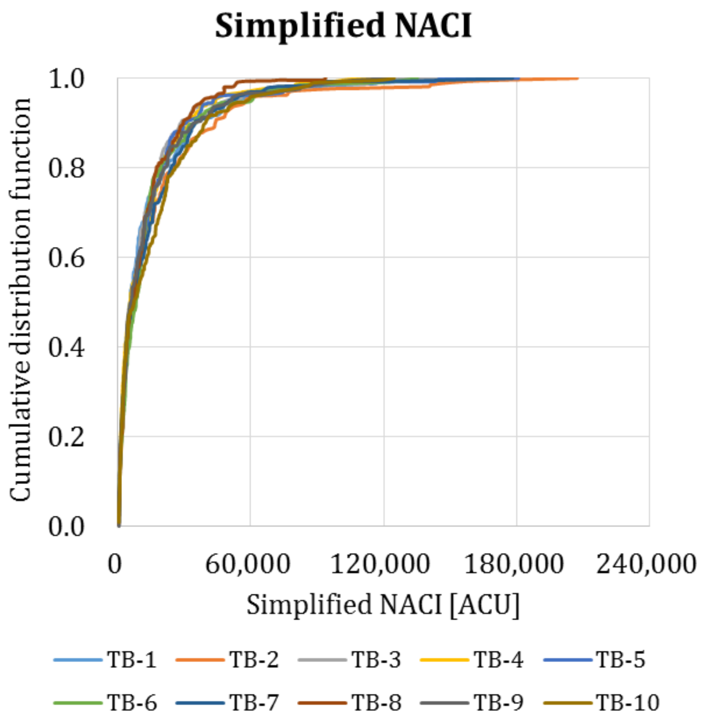


Figure 3.7. Results of ten trial calculations of the simplified NACI of the accident sequence TB calculated with 248 meteorological sequences.

Accordingly, the simplified NACI and its components of the accident sequence TB are repeatedly calculated for ten times with 248 meteorological sequences using the simplified model and the full model. The comparison of the results from the two model is shown in Figures 3.8(a) – 3.8(d). It can be seen from Figures 3.8(c) and 3.8(d) that the values of the relocation index and the radiation effect index of the two models are nearly identical. On the other hand, as for the simplified NACI and the decontamination index, the values under 80th percentile of the two models are almost the same, while the simplified model give slightly larger simplified NACI and decontamination index over the 80th percentile. Though there are slight differences between the values calculated by the simplified model and the full model, they are considered acceptable because the total uncertainties associated with the calculation is so large that the abovementioned differences would be negligible.

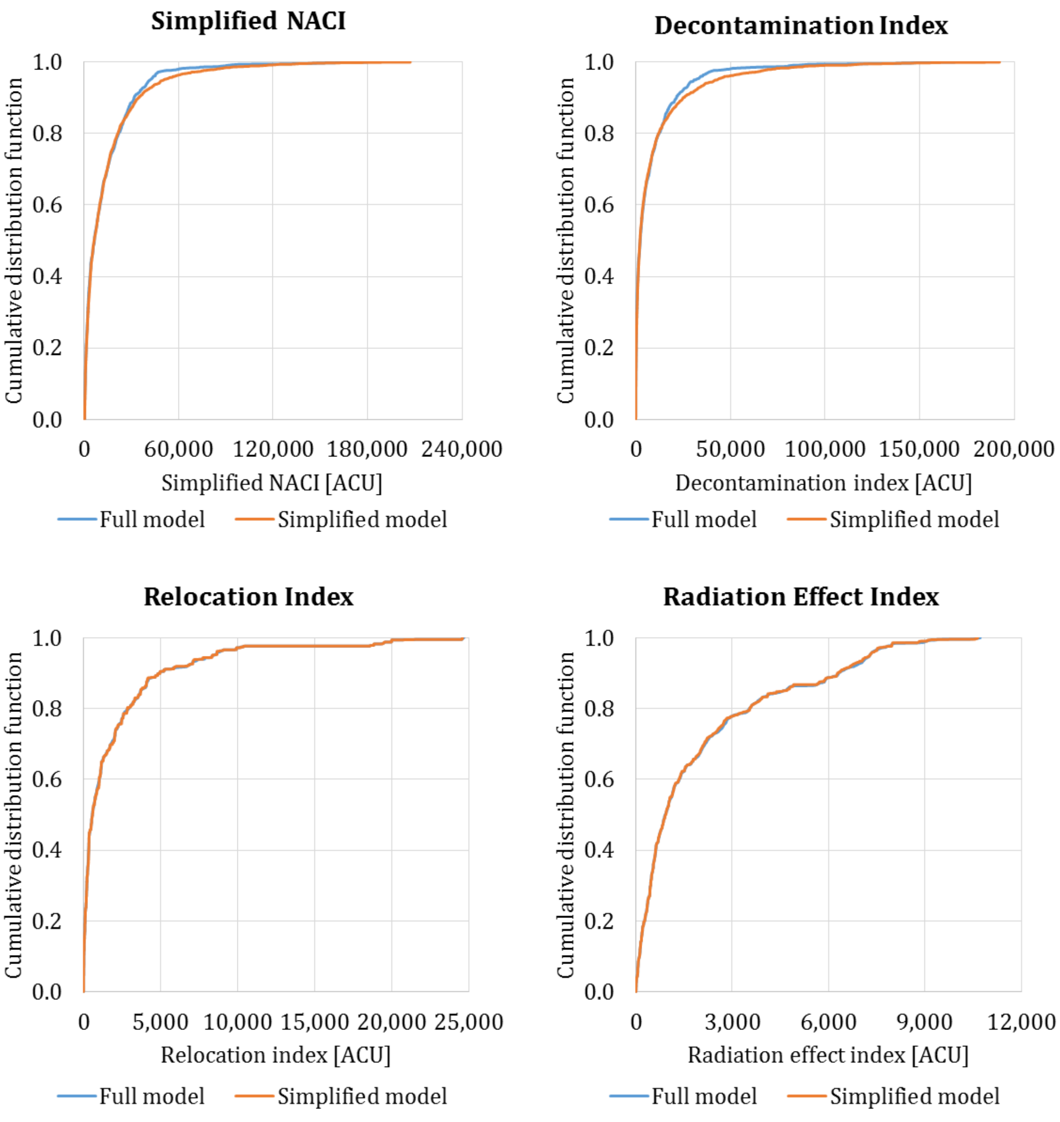


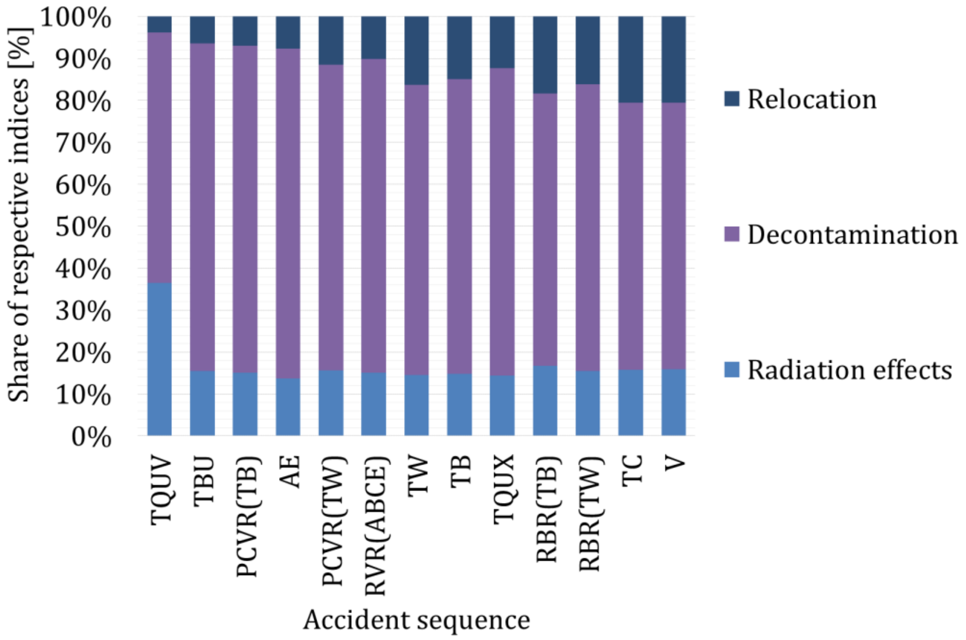
Figure 3.8. Comparison of simplified NACI and its components of the full model and the simplified model calculated with 248 meteorological sequences.
(a) Simplified NACI (top-left). (b) Decontamination index (top-right).
(c) Relocation index (bottom-left). (d) Radiation effect index (bottom-right).

3.6 Comparison of the former model to the modified model

Simplified NACI of the 13 accident sequences taken from the level 2 seismic PRA of the former JNES [3.15] are recalculated by the modified decontamination model (the simplified model obtained in Section 3.5). Figures 3.9 and 3.10 respectively show the breakdowns of the simplified NACI of respective accident sequences and the breakdowns of the average simplified NACI calculated by the modified decontamination model along with the breakdowns obtained from the previous model described in Chapter 2. All breakdowns are normalized using the occurrence probabilities of the 248 meteorological sequences. It is obvious from the two figures that the decontamination index of the modified model significantly increases its share within the simplified NACI comparing to that of the previous model. The simplified NACI increased by approximately 2.4 times, which implies that the decontamination index significantly increased while the other two indices only changed slightly. This is supposed to be attributed to:

(1) The consideration of the entire waste management process. This greatly increased the influence of the waste management index toward both the decontamination index and the simplified NACI.
(2) The consideration of the variation of the dose for decontamination target area setting. It was set to 20 mSv/year is the previous model while it is randomly selected from 1, 5, 10 and 20 mSv/year is the modified model. As a result, the expected value of the dose for decontamination target area setting of the modified model is notably lower than that of the previous model. Reduction of the dose level would significantly broaden the decontamination target area, and finally increase the decontamination index.

These results reconfirm the findings in the Subsection 3.4.3 that the dose for decontamination target area setting (parameter number 1 in Table 3.1), and the waste management (being represented by parameters number 53, 55, 56 and 58 in Table 3.1) play a very important role in determining the simplified NACI, i.e. the consequences of a severe accident.



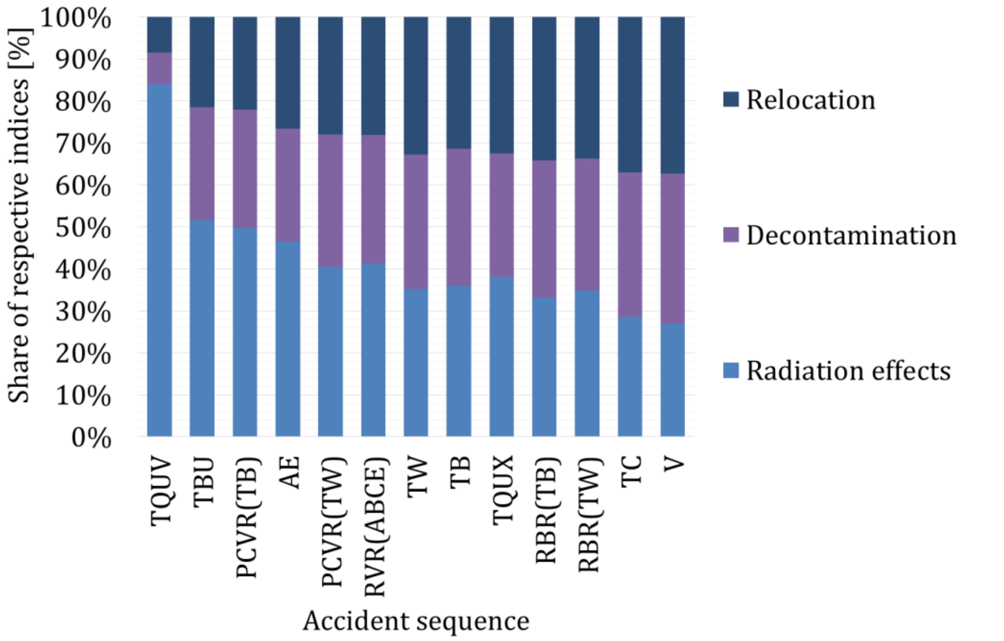


Figure 3.9. Breakdowns of simplified NACI of respective accident sequences.

(a) Calculated by the modified decontamination model (top).

(b) Calculated by the previous model described in Chapter 2 (bottom).

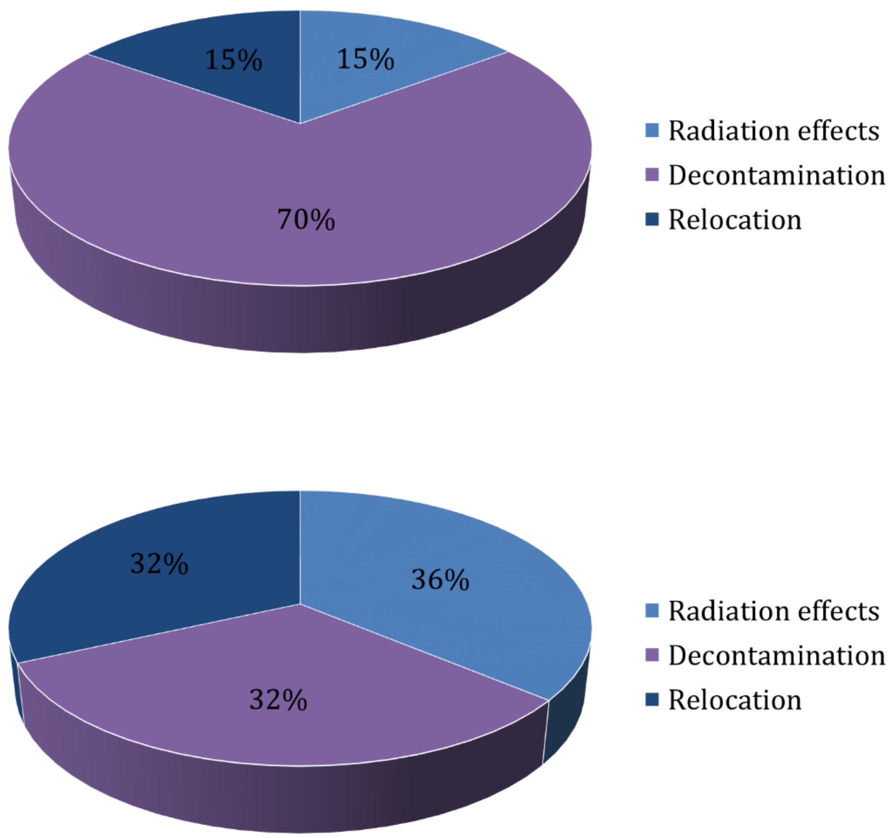


Figure 3.10. Breakdowns of average simplified NACI.
(a) Calculated by the modified decontamination model (top).
(b) Calculated by the previous model described in Chapter 2 (bottom).

However, the results in Figures 3.9 and 3.10 do not necessarily imply that the only important component of the simplified NACI is the decontamination index. We have to keep in mind that the results presented above are only the expected values which are obtained by averaging the results of a number of calculations. There are some calculations in the batch where the relocation index or the radiation effect index dominates the simplified NACI. Figure 3.11 shows the fractions of decontamination index out of the simplified NACI calculated with 248 meteorological sequences of three representative accident sequences: TQUV representing accidents with small release, TB representing accidents with average release, and V representing accidents with large release. This figure thus represents the distributions of fractions of decontamination index out of the simplified NACI of all release categories. It is observable from the figure that the fraction of decontamination index distributes from 0% to 100% in all accident sequences. This figure implies that the relocation index and the radiation effect index are definitely important components of the simplified NACI, though their expected values may be relatively small comparing with that of the decontamination index.

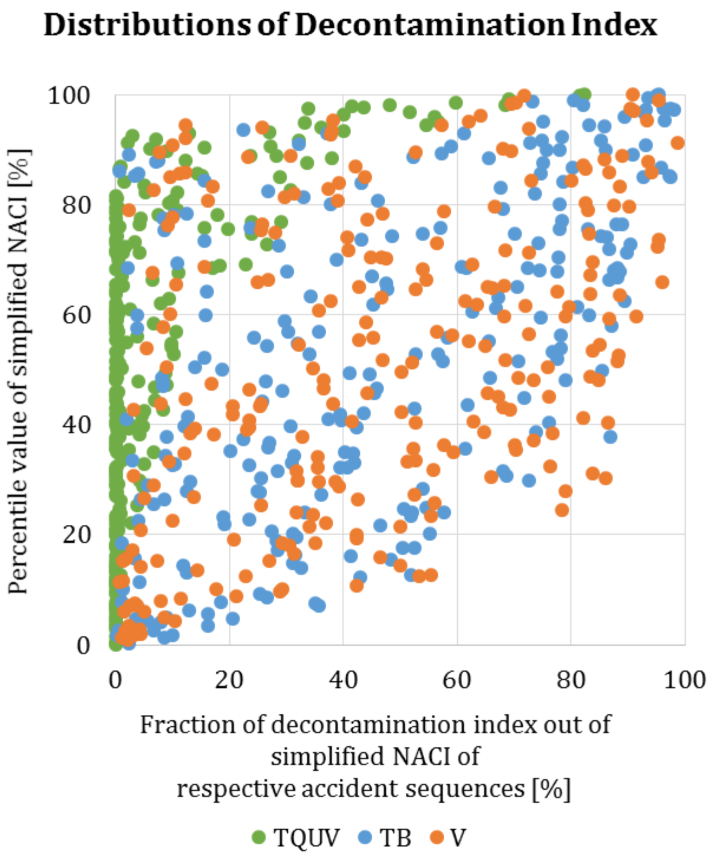


Figure 3.11. Distributions of fractions of decontamination index out of the simplified NACI of accident sequences TQUV, TB and V.

3.7 Summary of Findings

A robust decontamination model for the severe accident consequence assessment using simplified NACI, of which the assumptions are sufficiently realistic, and in which the distributions of the parameters are determined based on the adequate and updated data obtained from reliable sources, was developed.

- ✓ A sensitivity analysis using elementary effects method was performed in order to identify important parameters that have large influence on the simplified NACI and large extent of interactions with other parameters.
- ✓ Four parameters were identified as parameters highly influential on the simplified NACI, namely the dose for decontamination target area setting, the determination whether or not to consider waste disposal, the unit waste management index of waste disposal and the number of workers involving in the decontamination work. This implies that the decision makers need to thoroughly consider all circumstances following a severe accident, and carefully determine the dose for decontamination target area setting, the waste management process and the working plan for the decontamination of the contaminated area, since they can significantly affect the consequences of the accident.
- ✓ The interaction between decontamination and the radiation effect index was significantly small. It implies that the decontamination which intend not only to clean up the contaminated area but also to reduce the dose to the population, would not consequently affect the extent of the dose to the people. It is thus important to carefully deliberate the objectives of decontamination before starting the decontamination.
- ✓ The simplified decontamination model was developed by fixing most negligible parameters to their median value, and validated by comparing with the full model.
- ✓ The simplified decontamination model was used to calculate the simplified NACI and compared with that of the previous model described in Chapter 2. The decontamination index increased its importance notably. It emphasizes the findings above that we have to pay great attention to the determinations of dose level for decontamination target setting and the waste management process, since they have significant influence on the simplified NACI.

3.8 References

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Chapter 4 Relations between Release Parameters and Consequences of a Severe Accident

4.1 Motivation of the Study

The study on nuclear accident consequence index (NACI) in Chapter 2 succeeded in including consequences to both people and the environment into the severe accident consequence assessment. Especially, the simplified nuclear accident consequence index (simplified NACI) which is composed of three components: (1) the radiation effect index which represent the consequences to people, (2) the decontamination index which represent the consequences to the environment, and (3) the relocation index which cover both consequences to people and the environment can estimate the consequences of a severe accident in a relatively comprehensive manner with limited resources. However, at the reactor design approval stage or any stages when the reactor construction has not yet been concluded, it is better for the vendor or the operator to economize the investment on this kind of assessments. In addition, at these stages, much of the data related to the site and the reactor itself may not be available or its disclosure may not be allowed. Therefore, this chapter will make an effort to enable a comprehensive assessment of consequences to people and the environment which does not require enormous quantity of data, time and human resources. Section 4.2 will discuss the applicability of "100 TBq cesium 137 release into environment" as a safety criterion at reactor design approval stage. Simplified NACI which covers consequences to both people and the environment is used to assess the limitedness of the consequences resulted from the 100 TBq cesium 137 release. If the limitedness of the consequences are proved, confirming that the release of cesium 137 from any anticipated accidents of which the likelihood of the occurrence exceed a specific value could indirectly prove the limitedness of the consequences of those accidents. Section 4.3 even investigates further. It attempts to generalize the relations between release parameters, namely the release amount, the release period and the release starting time, and the consequences of a severe accident represented by the simplified NACI and its components, namely the radiation effect index, the relocation index and the decontamination index. The link between the simplified NACI and the release parameters would provide the information of consequences for respective types of release, without spending extensive resources to assess the simplified NACI.

4.2 Applicability of 100 TBq Cesium 137 Release as a Safety Criterion[10]

4.2.1 Motivation of using 100 TBq cesium 137 release as a safety criterion

The main reason that "100 TBq cesium 137 release into environment" is selected as the target of which the limitedness of the consequences are to be assessed is that, the Finnish Government is currently using this release as a safety criterion regarding consequences of a severe accident in the nuclear regulation of the country [4.2]. This release can be evaluated using solely the data of the nuclear reactor which is owned or can be obtained easily by the vendor or the operator. In addition, it does not require a lot of resources to perform the assessment.

There are two Finnish studies that evaluated the applicability of the 100 TBq cesium 137 release into environment as a safety criterion by showing that both acute and chronic health effects resulted from the release are limited [4.3, 4.4]. However, there was unfortunately no discussions on the impacts to the environment. Thus a more comprehensive discussion which is presented later in this subsection, is needed.

4.2.2 Calculation Conditions

The estimations of the nuclear accident consequence index which represent the consequences of a severe accident to people and the environment is done using the combination of HotSpot Ver. 2.07.2 [4.5] and a Microsoft Excel worksheet. The HotSpot code is used to estimate the radiation dose at respective distances and directions. Then the results from the HotSpot code are used to calculation the simplified nuclear accident consequence index (simplified NACI) using the Excel worksheet which is prepared based on the calculation schemes of the radiation effect index, the relocation index and the decontamination index introduced in Subsection 2.4.3 and modified in Subsection 3.3.2.

In order to evaluate the consequences from the 100 TBq cesium 137 release into environment, conditions shown in Table 4.1 are employed for the calculations of the HotSpot code. Realistic conditions are adopted whenever possible. Conservativeness is maintained for other conditions in order to avoid any underestimations. The amount of cesium 137 being release is set to 100 TBq and no other radionuclides are taken into account. As for the

[10] The content of this section is based on the paper: Silva K, Okamoto K. Applicability of 100 TBq cesium 137 release into environment as a safety criterion for consequence assessment at reactor design approval stage. J Nucl Sci Technol. DOI: 10.1080/00223131.2015.1018363 [4.1].

release period, a longer one (12 hrs) seems to be more appropriate since the 100 TBq cesium 137 release can be classified to a relatively small release which tend not to be a pulse release. The effective release height is 40 m which represents the leakage near the top of the power plant. Airborne and respirable fractions are fixed to 1 to maintain the conservatism. 3 m/s and D are selected as the wind speed and the stability class, since they are around the average values of the two parameters. The wind direction is fixed to a single direction since it will give a higher individual dose which would eventually lead to a larger health effect. All pathways available in the HotSpot code: cloudshine, inhalation, groundshine and resuspension are included in the calculation of the exposure dose. Since the annual dose is used to determine the decontamination and the relocation, the exposure duration is set to a year. The values recommended in the manual of the HotSpot code are adopted for the receptor height and the breathing rate. Only dry deposition is used to

Table 4.1. Calculation conditions for the calculations of the HotSpot code.

Parameters	**Values**
Release characteristics	
Amount of cesium 137 being released [TBq]	100
Release period [hrs]	12
Consideration of other radionuclides	none
Effective release height [m]	40
Airborne fraction	1
Respirable fraction	1
Meteorological characteristics	
Wind speed [m/s]	3
Wind direction	single direction
Stability class	D
Receptor characteristics	
Pathways	cloudshine, inhalation, groundshine and resuspension
Exposure duration [year]	1
Receptor height [m]	1.5
Breathing rate [m^3/s]	3.33×10^{-4}
Others	
Deposition type	dry deposition
Consideration of radiation protective measures	no

estimate the deposition of the radionuclides, since all radioactive materials will deposit near by the site if we assume wet deposition, which may lead to underestimation of the spatial effects. No radiation protective measures are considered in this assessment in order to be conservative.

Regarding the calculation of the simplified NACI using the Excel worksheet, a number of assumptions are made to keep the calculation simple. The area where the annual dose is larger than 100 mSv is set to the relocation target area, and the area where the annual dose is larger than 20 mSv is set to the decontamination target area. These dose levels correspond to the upper thresholds of the reference dose levels recommended by the ICRP for emergency exposure (between 20 and 100 mSv/year) and for existing exposure (between 1 and 20 mSv/year), respectively [4.6]. Upper thresholds are chosen since it was shown in the Chapter 2 that they give smaller NACI. The fractions of respective land use types out of the entire decontamination area refer to the fractions of land use types of Ibaraki Prefecture, Japan [4.7], in which the target plant is located. Suitable decontamination techniques for different land use types refer to the detail in Table 3.1. In order to take into account different decontamination techniques in respective land use types, the fraction for application of the tth decontamination technique for the lth land use type $F_{l,t}$ of each decontamination technique is assumed to be equal to each other, e.g. $F_{H,B} = F_{H,HPW} = 0.5$, where H stands for houses, B and HPW stands for brushing and high pressure water, respectively. The unit decontamination procedure indices and the unit waste management indices are the median values of the distributions used in Chapter 3. In regard to the relocation index, the number of relocated people is calculated by multiplying the number of population per square kilometer of the relocation target area. The relocated period is set to one year. All other values refer to the values used in Chapter 2.

4.2.3 Confirmation of limitedness of consequences due to 100 TBq cesium 137 Release into Environment

4.2.3.1 Estimated nuclear accident consequence index

First, in order to observe the trend of the simplified NACI when the release amount increases. The simplified NACI of 100 TBq release is compared with those of 1 PBq and 10 PBq releases. 10 PBq release of cesium 137 corresponds to the order of the total cesium 137 release at the Fukushima accident estimated by TEPCO [4.8]. The results are shown in Figure 4.1 along with the relocation and the decontamination boundaries which indicate the boundaries of the areas from which people relocate and of which is decontaminated in the form of distance from the center of the target plant. It can be seen from the figure that, while the amount of release is increased by 1 and 2 orders of magnitude, the simplified NACI rise by approximately 1.5 and 3 orders of magnitude, respectively. This implies that the consequences of a severe accident increase in an exponential manner with the release amount, thus it is better to keep the release as small as reasonably achievable. In the case of 100 TBq release, there is no relocated people and the decontamination boundary is 2 km, which shows that the consequences of the release are limited. Judging from these results, it seems reasonable to use 100 TBq cesium 137 release as a safety criterion for consequences resulted from an accident accompanying radioactive material release.

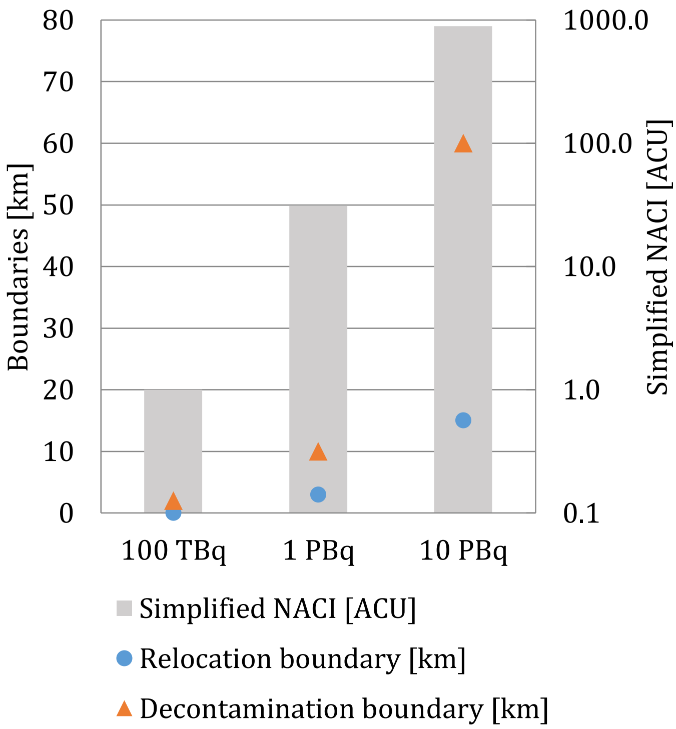

Figure 4.1. Simplified NACI, relocation boundary and decontamination boundary of different release amounts.

4.2.3.2 Parameter survey

Parameter survey is done by varying the parameters to the values shown in Table 4.2. The results are shown in Figure 4.2. Under all conditions, the simplified NACI does not rise above 5 ACU, which means the impacts of the 100 TBq cesium release can still be considered as limited. Even in the case that the wind speed is set to 1 m/s which gives the largest simplified NACI (4.26 ACU), the relocation and decontamination boundaries are 1 and 4 km, respectively. These boundaries show that the area being affected by the accident is very limited, and consequently show that the consequences resulted from the release are limited.

Table 4.2. Variation of parameters for parameter survey in the evaluation of the simplified NACI of the 100 TBq cesium 137 release into environment.

Parameters	**Values**
Release characteristics	
Amount of cesium 137 being released [TBq]	50, **100**, 200
Release period [hrs]	6, **12**, 24
Consideration of other radionuclides	**none**, iodine
Effective release height [m]	10, **40**, 100
Airborne fraction	1
Respirable fraction	1
Meteorological characteristics	
Wind speed [m/s]	1, 2, **3**, 5, 10
Wind direction	single direction
Stability class	A, B, C, **D**, E, F, G

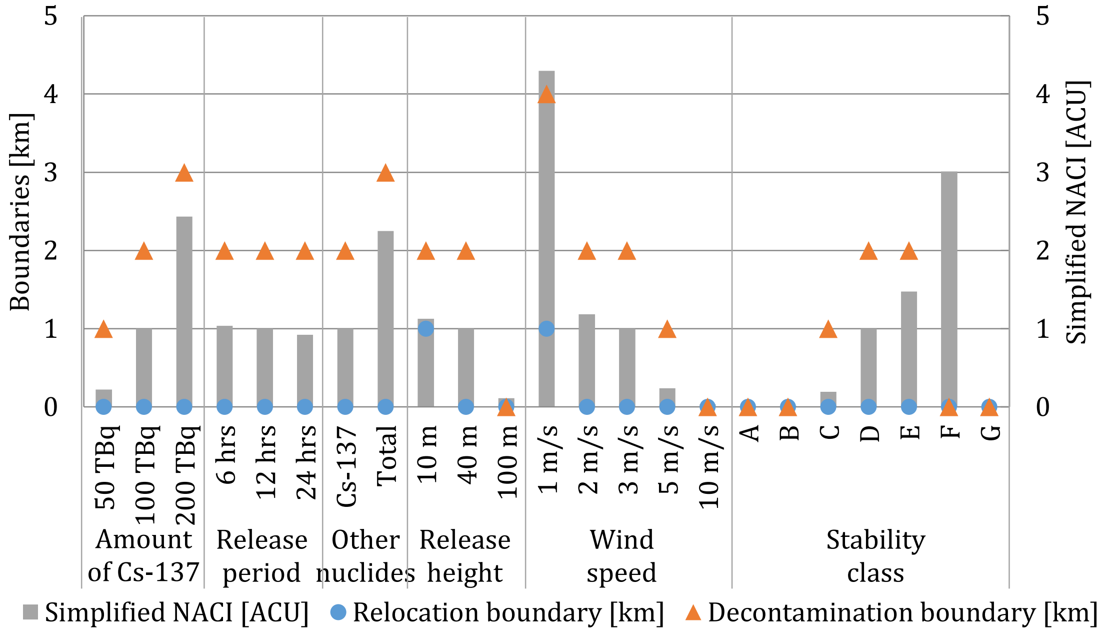

Figure 4.2. Simplified NACI, relocation boundary and decontamination boundary of the 100 TBq cesium 137 release estimated with different conditions.

4.2.3.3 Consideration of differences in meteorological conditions

The simplified NACI when differences in meteorological conditions is taken into account is estimated. The example meteorological input file provided in the HotSpot code which contain the hourly data of the wind speed, wind direction and rainfall for one year is used in the calculation. The calculation is done for all meteorological sequences and the 50th percentile values are used to represent the results. The case that the hourly changes in meteorological conditions are taken into account is less conservative in the evaluation of individual exposure dose, since the change of the wind direction every hour would reduce the concentration of the cesium in the plume or the amount of cesium deposited on a specific location, comparing to the case of single wind direction and wind speed. However, it can be seen from the results in Figure 4.3 that this case seems to give larger simplified NACI that the case of single wind direction and wind speed. This is because, although the changes of wind direction can reduce the cesium concentration at a specific location, it enlarges the area being contaminated by cesium. If the annual dose of the enlarged contaminated area exceeds the dose levels for determinations of relocation target area and decontamination target area (100 and 20 mSv/year, respectively), those areas would be larger than the case of single wind direction and wind speed though even though the relocation or decontamination boundaries are smaller. This is attributed to the contamination in various directions within the boundaries. As a result, the simplified NACI will be higher than the case of single wind direction and wind speed. On the other hand, if the annual dose of most area does not reach these dose levels, the simplified NACI would be extremely small. The case that gives largest simplified NACI is the case that amount of cesium 137 is set to 200 TBq where the simplified NACI is yet only 7.6 ACU. Therefore, it can still be concluded that the consequences of a 100 TBq cesium 137 release to people and the environment is limited even when differences in meteorological conditions are taken into account.

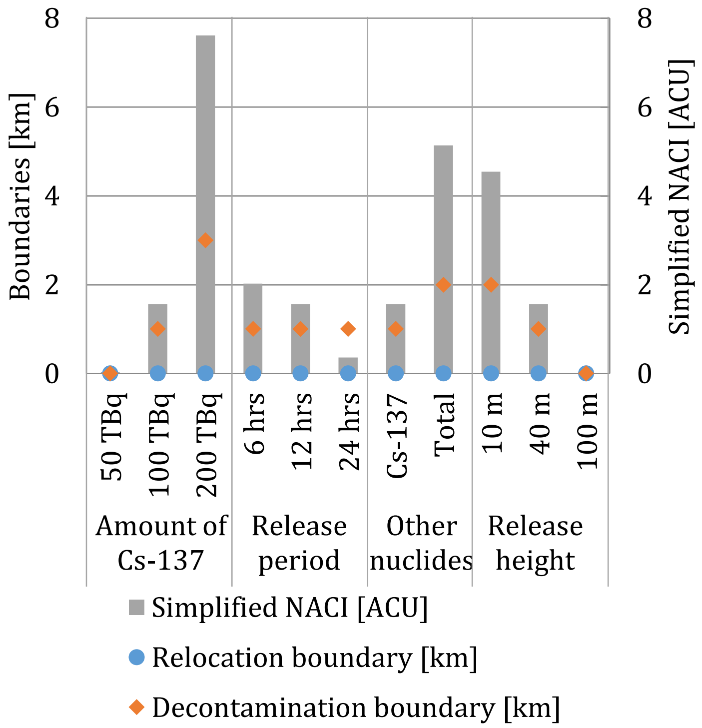

Figure 4.3. Simplified NACI, relocation boundary and decontamination boundary of the 100 TBq cesium 137 release when the differences in meteorological conditions are taken into account.

4.2.3.4 Consideration of differences in radiation protective dose levels

As it is shown in Chapters 2 and 3 that the dose levels that are used to determine the long-term radiation protective levels, i.e. dose level for starting relocation and dose level for decontamination target area setting, have large influence on the NACI (and also the simplified NACI), the influences of these dose levels are investigated. Based on the reference dose levels recommended by the ICRP [4.6], the dose level for starting relocation is set to 100 and 20 mSv/year, and the dose level for decontamination target area setting is set to 20, 5[11] and 1 mSv/year. The results are shown in Figure 4.4. It is obvious from the figure that the dose level for decontamination target area setting has a very large influence on the decontamination boundary and consequently the simplified NACI. Especially, when it is set to 1 mSv/year, the simplified NACI is even larger than that of 1 PBq cesium 137 release with baseline conditions. On the other hand, when the release is as small as 100 TBq, the influence of the dose for starting relocation on the simplified NACI is quite limited.

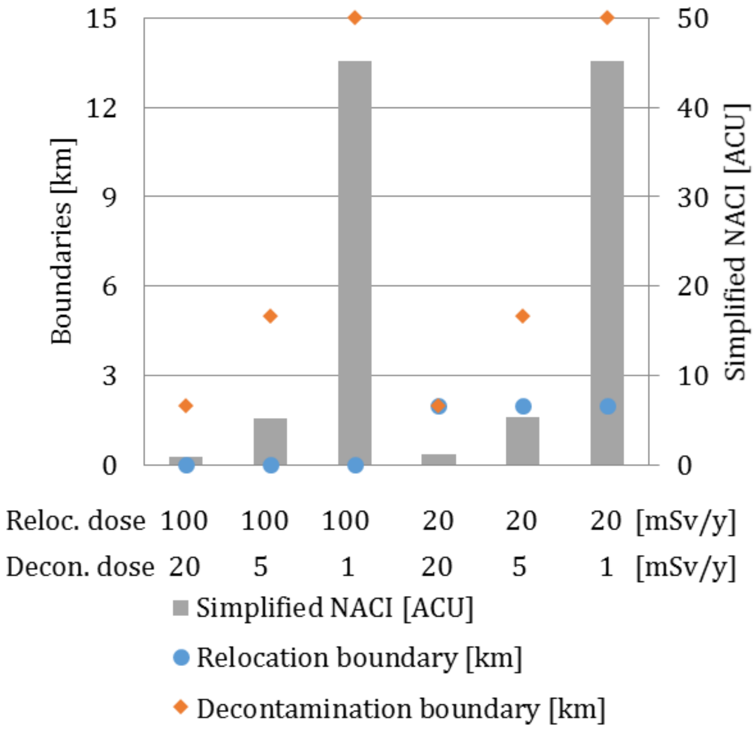

Figure 4.4. Simplified NACI, relocation boundary and decontamination boundary of the 100 TBq cesium 137 release when the differences in radiation protective dose levels are taken into account.

11 This was the target dose level for the decontamination in the Chernobyl accident [4.9].

4.3 Relations between Release Parameters and Consequences of a Severe Accident

4.3.1 Calculation conditions

Conditions in Table 4.3 are used for the calculations in this entire subsection. Most are the same as those in Table 4.1 with some exceptions. The amount of cesium 137 being released is changed from 100 TBq to 1 PBq in order for it to be large enough to observe the differences when other parameters are varied. Hourly meteorological data taken from the Tsukuba Meteorological Station, Ibaraki Prefecture, of the year 2014 [4.10] were organized in the manner that can be used in the HotSpot code. Evacuation, relocation and decontamination are taken into account, and the relevant dose rates and other conditions are shown in the table. Local data used for the calculation of relocation index and decontamination index are taken from documents of Ibaraki Prefecture [4.7]. It is to be noted that all parameters shown in italic letters will be vary in the following subsections to confirm its influence to the simplified NACI.

Though the HotSpot code can output the results from 50th to 99.99th percentile values, the author selected only the 50th percentile values from the outputs of the HotSpot code to use for further calculations. This is because the aim of this study is to understand the characteristics of the simplified NACI and its components when the release parameters are changed, and the 50th percentile value which is the median of the distribution of the results would be the value that can best represent the results.

4.3.2 Release amount versus simplified NACI

Simplified NACI and its components, i.e. the radiation effect index, the relocation index and the decontamination index, when the release amount of cesium 137 is varied from 10 TBq (10^{13} Bq) to 100 PBq (10^{17} Bq) are shown in Figure 4.5 in log-log scale. The simplified NACI and its components increase drastically when the release amount is increased. The simplified NACI, the relocation index and the decontamination index increase approximately 1.5 orders of magnitude when the release amount is enlarged by an order. On the other hand, the radiation index has a nearly linear relation with the release amount. The growth of the simplified NACI and its components seems to decelerate over 10 PBq. This is mainly because the HotSpot code can calculate the contamination and the radiation dose in the area just within a 200-kilometer radius, which seems not to be adequate to take into account the consequences of a release larger than 10 PBq. The detail on the relation between the release amount and the simplified NACI and its components will be discussed in Subsection 4.3.5.

Table 4.3. Conditions for the calculation of relations between release parameters and simplified NACI (and its components) using the HotSpot code.

Parameters	Values
Release characteristics	
Amount of cesium 137 being released [PBq]	*1*
Release period [hrs]	*12*
Release starting time [hrs]	*0*
Consideration of other radionuclides	none
Effective release height [m]	40
Airborne fraction	1
Respirable fraction	1
Meteorological characteristics	
Data taken into account	wind speed, wind direction, stability class, rainfall
Data point	Tsukuba Meteorological Station, Ibaraki Prefecture
Year	2014
Receptor characteristics	
Pathways	cloudshine, inhalation, groundshine and resuspension
Exposure duration [year]	1
Receptor height [m]	1.5
Breathing rate [m^3/s]	3.33×10^{-4}
Radiation protection dose rates	
Dose level for starting relocation [mSv/year]	100
Dose level for decontamination target area setting [mSv/year]	20
Evacuation characteristics	
Evacuation delay time [hr]	2
Effective radial evacuation speed [km/hr]	4
Local data	
Local data for calculation of relocation index and decontamination index	Documents of Ibaraki Prefecture

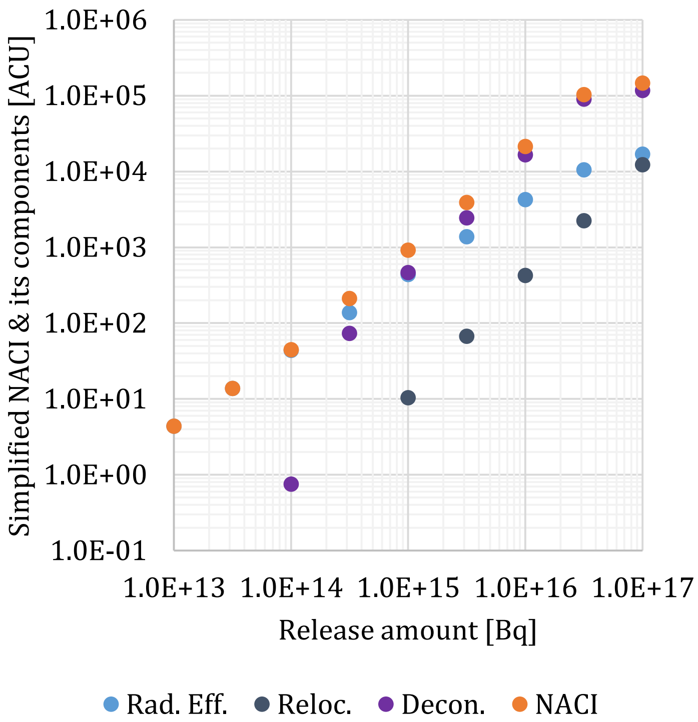

Figure 4.5. Simplified NACI and its components when the release amount is varied from 10 TBq to 100 PBq.

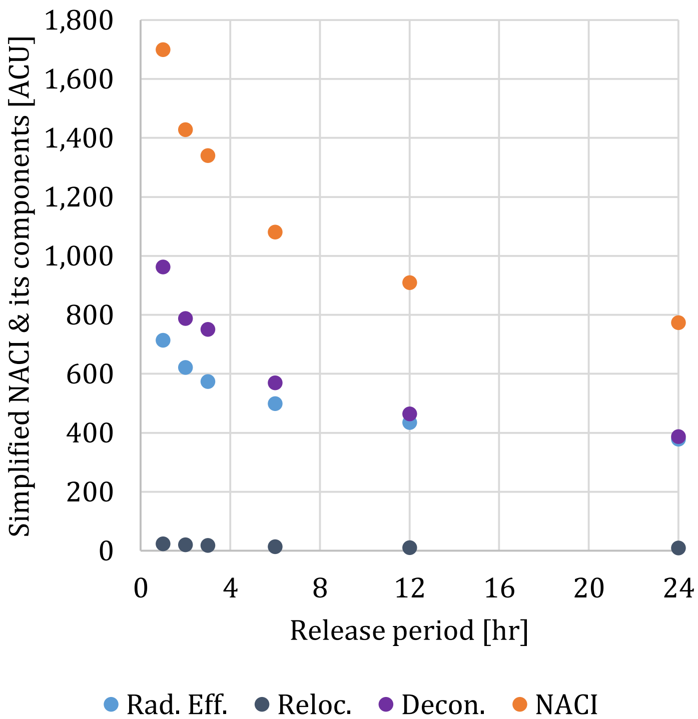

Figure 4.6. Simplified NACI and its components when the release period is varied from 1 hour to 24 hours.

4.3.3 Release period versus simplified NACI

Simplified NACI and its components when the release period is varied from 1 hour to 24 hours are shown in Figure 4.6. When the release period is increased from 1 hour to 2, 3, 6, 12 and 24 hours, the simplified NACI and its components gradually decrease at a specific rate. It is noticeable from the graph that the simplified NACI and its components reduced by about half when the release period is lengthen from 1 hour to 12 hours. It seems that they follow a negative power function (with power factors of approximately -0.6 to -0.3).

4.3.4 Release starting time versus simplified NACI

Simplified NACI and its components when the release starting time is varied from 1 hour to 24 hours are shown in Figure 4.7. When the release starting is changed from 1 hour to 2 and 3 hours, the simplified NACI and its components slightly decrease. However, after 3 hours, there is no significant changes in the values of the simplified NACI and its components. It could be concluded that the influence of the release starting time on the simplified NACI and its components are nearly negligible.

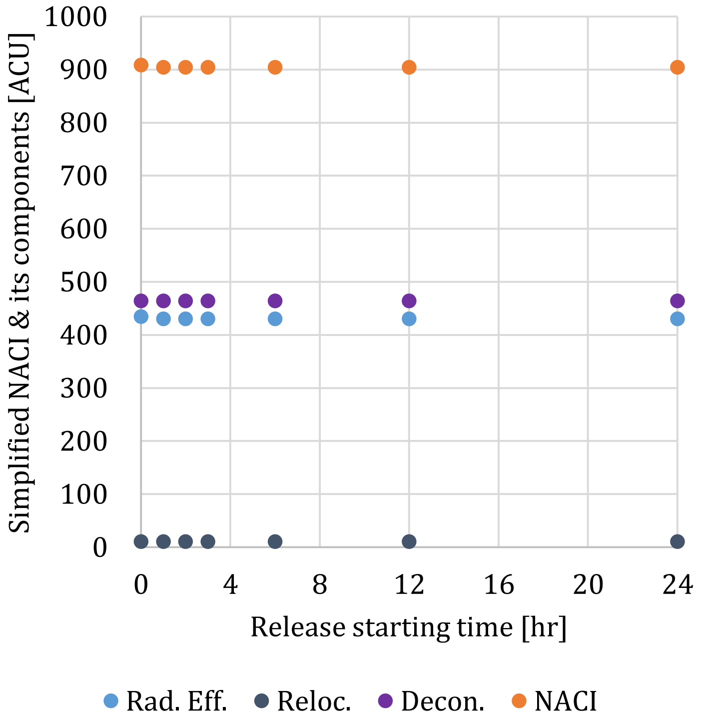

Figure 4.7. Simplified NACI and its components when the release starting time is varied from 1 hour to 24 hours.

4.3.5 Correlation between release amount and simplified NACI

It can be seen by comparing Figure 4.5 to Figures 4.6 and 4.7 that the influences of the release period and the release starting time on the value of the simplified NACI and its components are nearly negligible when compared with the influence of the release amount. Therefore, thorough investigation will only be made for the correlations between the release amount, and the simplified NACI and its components since they account for the major part of the influences of the release parameters on the value of the simplified NACI, i.e. the consequences to people and the environment resulted by the release of radionuclides (cesium 137) after a severe accident.

4.3.5.1 Radiation effect index

The baseline case of the relation between the release amount and the radiation effect index is shown in pale blue squares in Figure 4.8. All other cases are presented here in order to make an effort to represent the radiation effects to people accurately and to get closer to the actual situation. The cut off case (grey horizontal dashes) shows the radiation effect index when the people within the target area (200-km-radius) of which the annual dose do not exceed 1 mSv are not taken into account, i.e. the collective dose *CD* in Equation 2.1 is the sum of the dose to the people living within 200-km-radius whose the exposure are more than 1 mSv/year. Since the recommendation for the dose limit from a source to the public for normal situation is 1 mSv/year [4.6], the dose to the public from the accidental release must be considered negligible when it does not exceed 1 mSv/year. As the low-dose exposures are cut off, only serious exposures resulted from the accidental release will be focused. If we are to determine the radiation protective measures based on this results, we can apply reasonable measures than would really contribute to the reduction of the radiation effects to the public rather than apply any measure that would only slightly reduce the low doses to the people in wide area. All other three cases are cases when the target area is increased from 200-km-radius to 500-km-radius. It is necessary to enlarge the target area to 500-km-radius because the dose at the 200 km boundary is still high in cases of large release, which means the maximum target area of the HotSpot code (200-km-radius) is not adequate for the consideration of the total radiation effects. The author use manual extrapolations to determine the dose for the areas further than 200-km-radius since the HotSpot code cannot handle any area larger than that. The author is aware of the inaccuracy of using the extrapolations for this kind of calculations. However, this seems to be the best way to cope with this issue using the HotSpot code which is a free software and can be easily accessed by the developing countries. Functions used to extrapolate the dose for the areas further than 200-km-radius are (1) constant (all are same as the dose at 200-km-radius), (2) exponential function, and (3) power function. The results are shown in orange circles, yellow diamonds and blue triangles, respectively.

The data points of the radiation effect index of different release amount for respective cases are fitted using MATLAB Curve Fitting Toolbox [4.11]. The power function ($y = ax^b$) can best fit the data points for all cases. Constants a and b of the power function and the fitting parameters which represent the degree of fitness of the fitting equations for respective cases are shown in Table 4.4. The fitted graphs are shown in Figure 4.8. The light blue, grey, orange, yellow and blue dotted lines represent the fitted graphs of the baseline, cut off, constant, exponential function and power function cases, respectively. It can be seen from the fitting parameters in Table 4.4 that all fitted graphs could fit quite well with the data points. However, it can be observed from Figure 4.8 that all fitted graphs overestimate the radiation effect index when the release amount is relatively small, though they fit very well with the data points in the region of larger release. The exponents vary from around 0.8 to 1.0, which means the relation between the release amount and the radiation effect index follows a power function that is very close to a linear function (exponent = 1.0).

The reason that this relation follow a nearly linear function is simple. A black line in Figure 4.8 represents the radiation effect index when no radiation protective measures are applied. As the meteorological conditions of all release amounts are the same, the amount of cesium 137 deposited in the target area is proportional to the total cesium 137 release amount. Then the collective dose and consequently the radiation effect index is proportional to the amount of cesium 137 deposited in the target area. Therefore, the relation between the release amount and the radiation effect index follows a completely linear function. However, in actual situations, radiation protective measures are applied to reduce the exposures of the people to the radiation when the release is large, thus the radiation effect index in the range of large release would give a smaller value than the linear function. It can also be seen from Figure 4.8 that the extrapolations using the constant and the power function slightly overestimate the radiation effect index, i.e. the values are higher than the case that no radiation protective measures are taken into account. The actual radiation effect index would be somewhere between the case of exponential function and the case without consideration of radiation protective measures.

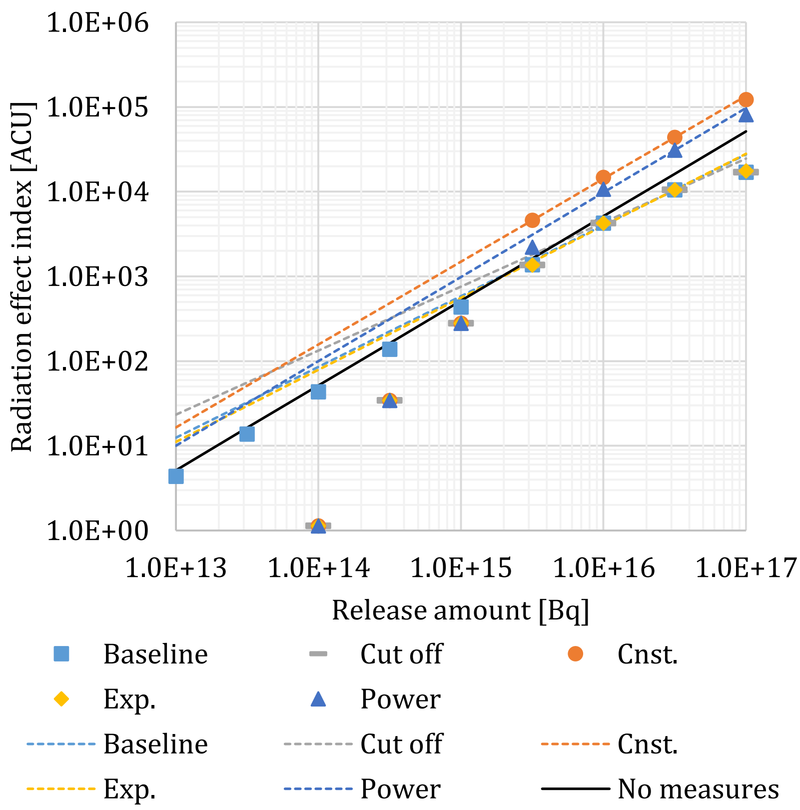

Figure 4.8. Correlations between release amount and radiation effect index for respective cases.

Table 4.4. Constants a and b of the power function $y = ax^b$ of the radiation effect index and the fitting parameters for respective cases.

Cases	**a**	**b**	**SSE**	**R^2**	**Adjusted R^2**	**RMSE**
Baseline	1.673E-10	0.8363	1.081E+05	0.9989	0.9987	134.2
Cut off	3.415E-09	0.7564	1.032E+05	0.9987	0.9978	185.4
Constant	3.141E-12	0.9785	1.916E+06	0.9987	0.9984	692.1
Exponential	9.801E-11	0.8504	2.066E+05	0.9976	0.997	227.3
Power	1.092E-12	0.9971	2.102E+06	0.9972	0.9965	724.8

It is quite obvious from Figure 4.8 and preceding paragraphs that the key to the relation between the release amount and the radiation effect index is the exponent of the fitted graph. As mentioned above, the exponents for this relation vary around 0.8 to 1.0. Figure 4.9 shows the verification of the correlation between the release amount and the radiation effect index. Three different exponents: 0.8, 0.9 and 1.0 are used to determine the correlation. The calculated value of radiation effect index of the release amount of 10 PBq is assigned to the variable *y* of the power function ($y = ax^b$) to obtain the value of a. It can be seen from the figure that all graphs fit quite well when the release amount is over 1 PBq, though they overestimate the radiation effect index of a smaller release amount. If the relation of the release amount smaller than 1 PBq and the radiation effect index is needed, another set of correlations of which the parameter a is obtained by assigning the calculated value of radiation effect index of small release amount (10 TBq or 100 TBq) to the variable *y* may be needed.

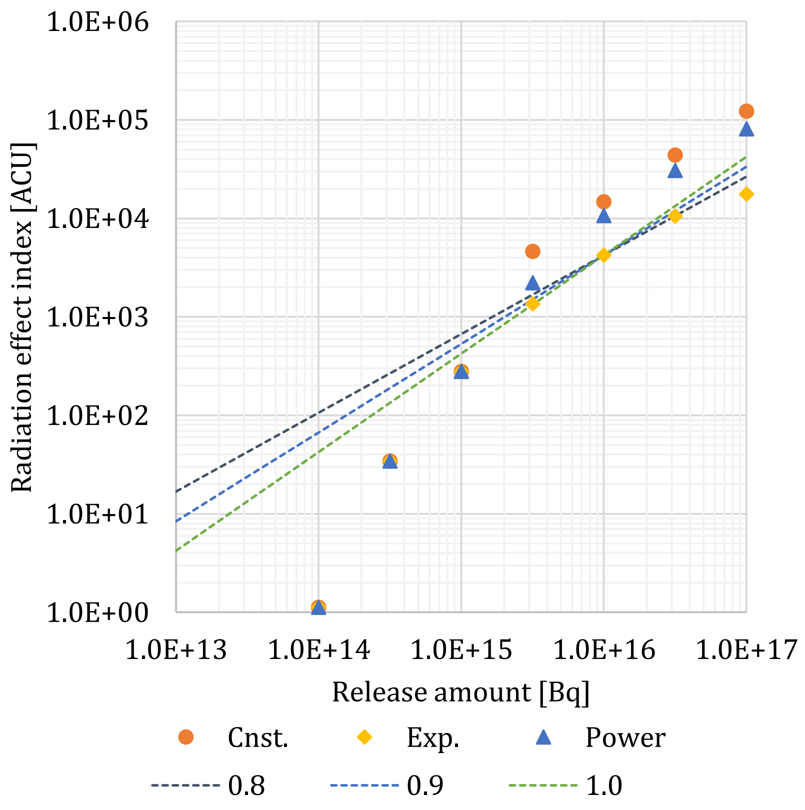

Figure 4.9. Verification of correlation between release amount and radiation effect index.

4.3.5.2 Relocation index

The baseline case (the dose for starting relocation = 100 mSv/year) of the relation between the release amount and the relocation index is shown in pale blue squares in Figure 4.10. The results of all other cases: cut off, constant, exponential function and power function cases are not presented since they are the same as the baseline case. The case that the dose for starting relocation is set to 20 mSv/year is also presented in Figure 4.10 since the reference level for emergency exposure recommended by the ICRP [4.6] is between 20 and 100 mSv/year. The relocation index of the two cases differ by approximately one order. Constants a and b of the power function and the fitting parameters for the two cases are shown in Table 4.5. It is obvious from the figure and the table that the fitting equation can fit very well with the data points of the case of 100 mSv/year. As for the case of 20 mSv/year, the fitted graph overestimate the relocation index of small release amount which is similar to the case of radiation effect index. Also the value of the relocation index when the release amount is 100 PBq is much lower that the fitted curve. However, this is not an over-estimation of the curve. The value of the relocation index when the release amount is 100 PBq does not follow the trend since the target area is limited to 200-km-radius. If the dose is correctly extrapolated, the value would probably follow the fitted graph.

As is the case for radiation effect index, the exponent of the fitted graph seems to be the key of the relation. The exponent of the two cases is within the range of 1.4 to 1.5. Unfortunately, the reason that the value of the exponent is within this range is not as simple as in the case of the radiation effect index. The best place to start is that the relocation index has many variables that are dependent to the area. Therefore, it would rather be proportional to the square of the release amount than being proportional to the release amount itself. (When you increase the radius of a circle from x to $2x$, the area increases from πx^2 to $2^2\pi x^2$.) However, the exponent in this case is much smaller than 2. There are two things that possibly contribute to the difference of the exponent. One is the characteristic of the dose for starting relocation, the other is the meteorological conditions taken into account. The dose for starting relocation is set to 100 mSv/year (or 20 mSv/year). Therefore, when the dose of a specific area does not exceed this dose level, the calculation code assume that there is no relocation of the people out of this area. On the other hand, this calculation takes into account the influence of wind and rain. Therefore, the distribution of the radionuclides at the same distance is not homogeneous. The release cesium 137 may concentrate only in some directions, but scarcely distribute in some other directions. For this reason, the exponent is decreased from 2 to around 1.4 to 1.5.

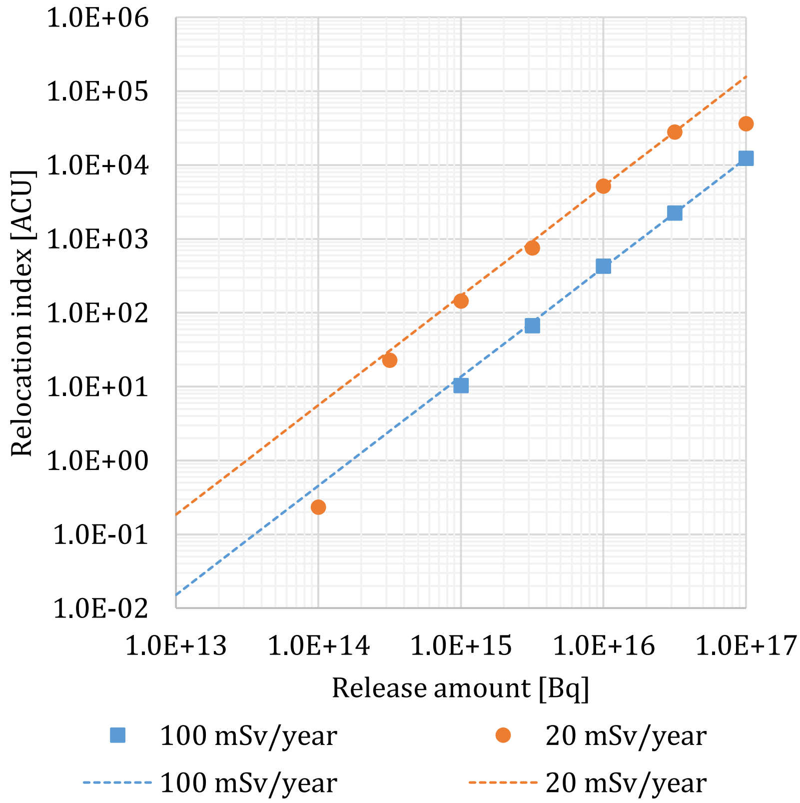

Figure 4.10. Correlations between release amount and relocation index when the dose for starting relocation is set to 100 mSv/year and 20 mSv/year.

Table 4.5. Constants a and b of the power function $y = ax^b$ of the relocation index and the fitting parameters for different dose for starting relocation.

Dose for starting relocation	**a**	**b**	**SSE**	**R^2**	**Adjusted R^2**	**RMSE**
100 mSv/year	9.555E-22	1.477	333.4	1	1	10.54
20 mSv/year	9.979E-21	1.482	3.182E+04	0.999	0.999	89.19

Figure 4.11 shows the verification of the correlation between the release amount and the relocation index. As the exponent of the two cases is within the range of 1.4 to 1.5, three different exponents: 1.4, 1.45 and 1.5 are used to determine the correlation. The calculated value of radiation effect index of the release amount of 10 PBq is assigned to the variable y of the power function ($y = ax^b$) to obtain the value of a. The fitted graphs of both cases fit very well with the data points, except for the release amount of 100 PBq. Therefore, it can be concluded that this exponent can be used to represent the relation between the release amount and the relocation index.

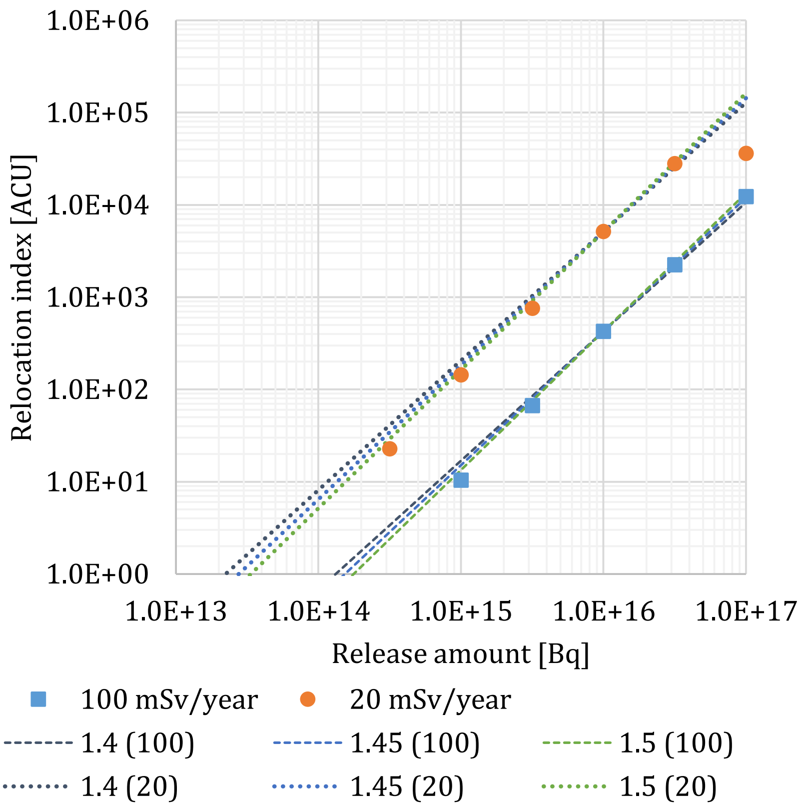

Figure 4.11. Verification of correlation between release amount and relocation index.

4.3.5.3 Decontamination index

The baseline, constant, exponential function and power function cases of the relation between the release amount and the decontamination index are shown in pale blue squares, orange circles, yellow diamonds and blue triangles, respectively, in Figure 4.12. The cut off case is not presented since the values are same as the baseline case. The fitted graphs of the baseline, constant, exponential function and power function cases are shown in the figure in pale blue, orange, yellow and blue dotted lines, respectively. Constants a and b of the power function and the fitting parameters for respective cases are shown in Table 4.6. All fitted graphs are almost identical except for the constant case where the fitting did not go very well. Alike the previous two indices, the fitted curves overestimate the decontamination index in the region of small release amount.

As are the cases for radiation effect index and relocation index, the exponent of the fitted graph seems to be the key of the relation. The exponent of all cases, except for the constant case where the fitted graph seems not to fit the data points, is within the range of 1.4 to 1.5. The decontamination index also has many variables that are dependent to the area, the value of the index is determined based on the dose for decontamination target area setting, and is influenced by the meteorological conditions. Hence, the reason that the exponent is in the range of 1.4 to 1.5 should be similar to that of the exponent of the relocation index.

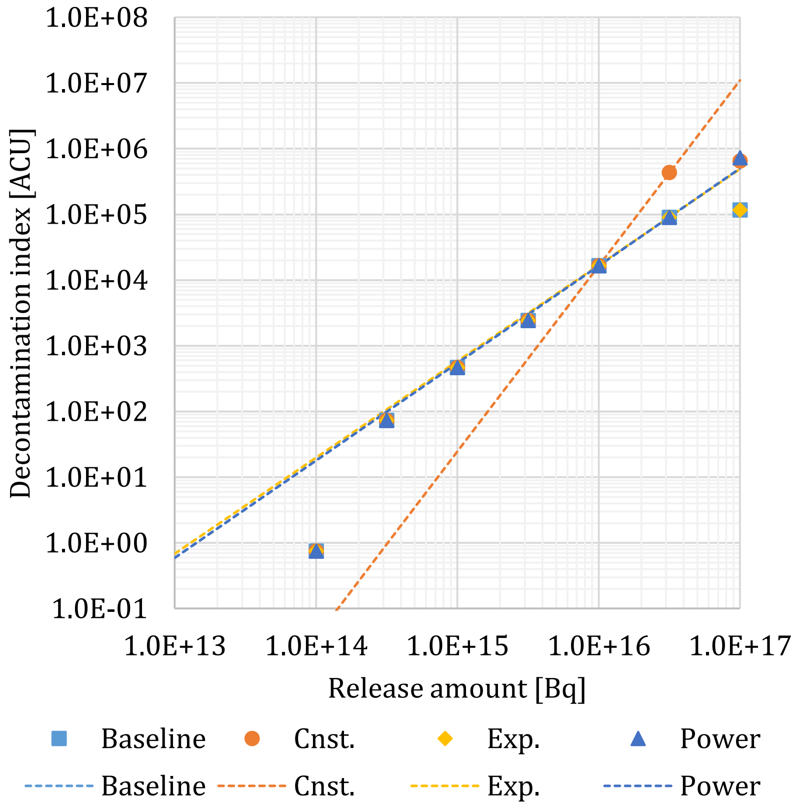

Figure 4.12. Correlations between release amount and decontamination index for respective cases.

Table 4.6. Constants a and b of the power function $y = ax^b$ of the decontamination index and the fitting parameters for respective cases.

Cases	**a**	**b**	**SSE**	**R^2**	**Adjusted R^2**	**RMSE**
Baseline	3.217E-20	1.482	3.306E+05	0.9999	0.9999	287.5
Constant	1.001E-41	2.826	3.433E+06	1	1	926.4
Exponential	6.58E-20	1.463	5.821E+05	0.9999	0.9999	381.5
Power	3.216E-20	1.482	3.306E+05	0.9999	0.9999	287.5

Figure 4.13 shows the verification of the correlation between the release amount and the decontamination index. As the exponent of all cases, except for the constant case, is within the range of 1.4 to 1.5, three different exponents: 1.4, 1.45 and 1.5 are used to determine the correlation. Again, the calculated value of radiation effect index of the release amount of 10 PBq is assigned to the variable y of the power function ($y = ax^b$) to obtain the value of a. The fitted graphs fit relatively well with the data points where the release amount are larger than 100 TBq. On the other hand, it overestimate the decontamination index when the release amount is smaller. However, it seems that the power function with the exponent around 1.4 to 1.5 can represent the decontamination index in a relatively good manner.

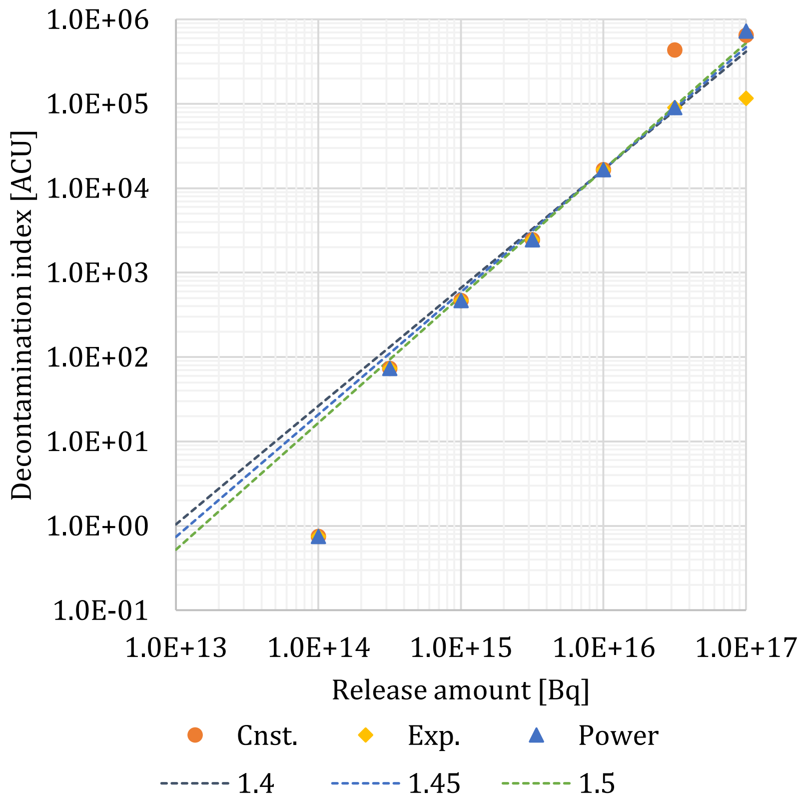

Figure 4.13. Verification of correlation between release amount and decontamination index.

4.3.5.4 Simplified NACI

The baseline, cut off, constant, exponential function and power function cases of the relation between the release amount and the simplified NACI are shown in pale blue squares, grey dashes, orange circles, yellow diamonds and blue triangles, respectively, in Figure 4.14. The fitted graphs of the baseline, cut off, constant, exponential function and power function cases are shown in the figure in pale blue, grey, orange, yellow and blue dotted lines, respectively. Constants a and b of the power function and the fitting parameters for respective cases are shown in Table 4.7. The fitted graphs of the cut off case and the exponential case are totally identical and very close to the baseline case. Their exponents are between 1.3 and 1.4. The fitting graph of the power function case seems not to be very bad from the figure. However, its SSE and its RMSE are significantly large, which indicates that the fitting is not going very well. As the simplified NACI is the summation of the radiation effect index, the relocation index and the decontamination index, its exponent must not be smaller than that of the radiation effect index, and must not be larger than that of the decontamination index. Therefore, it can be claimed that the fittings of the constant case and the power function case did not go well, and their fitted graphs may not be valid.

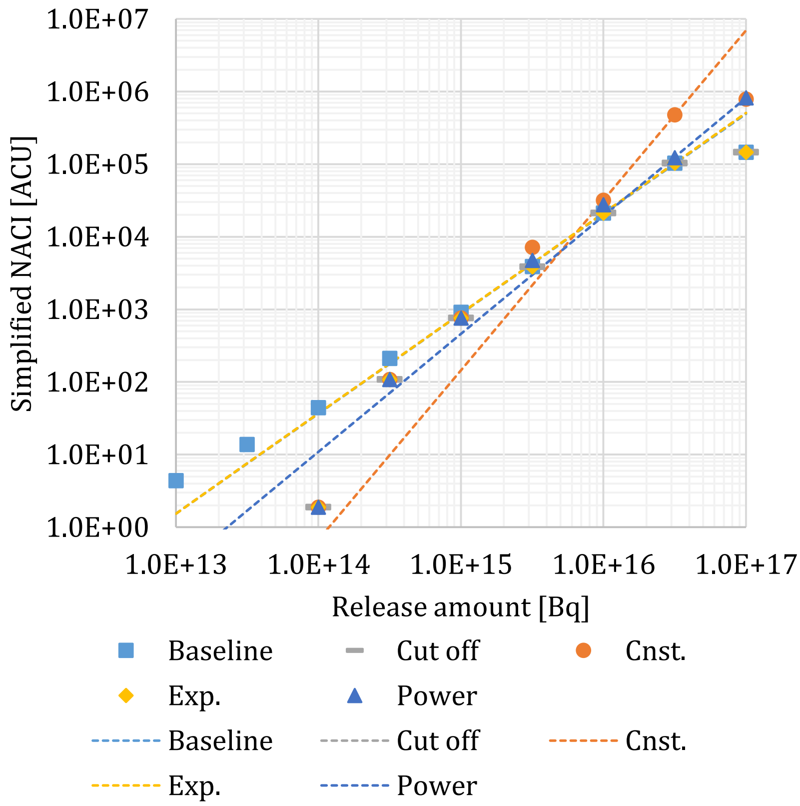

Figure 4.14. Correlations between release amount and simplified NACI and its components for respective cases.

Table 4.7. Constants a and b of the power function $y = ax^b$ of the simplified NACI and the fitting parameters for respective cases.

Cases	**a**	**b**	**SSE**	**R²**	**Adjusted R²**	**RMSE**
Baseline	1.925E-18	1.377	2.184E+05	1	1	190.8
Cut off	1.82E-18	1.379	2.514E+05	1	1	250.7
Constant	1.155E-33	2.34	2.508E+07	0.9999	0.9998	2504
Exponential	1.82E-18	1.379	2.514E+05	1	1	250.7
Power	1.933E-22	1.625	7.838E+07	0.9999	0.9998	3959

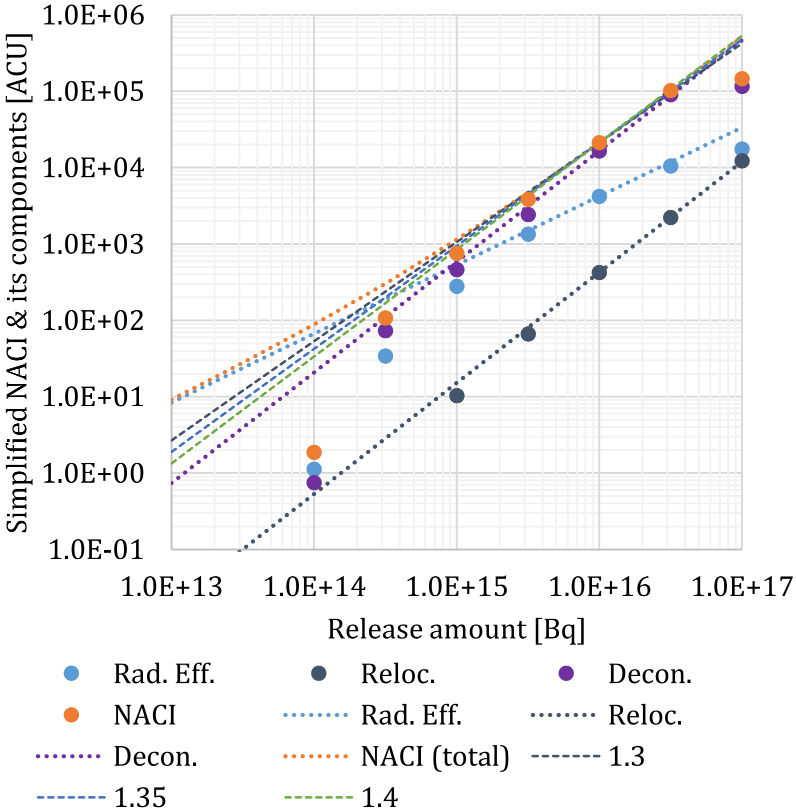

Figure 4.15. Verification of correlation between release amount and simplified NACI.

Figure 4.15 shows the verification of the correlation between the release amount and the simplified NACI. Apart from the simplified NACI which is shown in the figure in orange circles, the radiation effect index, the relocation index and the decontamination index are also shown with their fitted graphs in pale blue, dark green and purple, respectively. The orange dotted line which show the approximate values of the simplified NACI obtained by adding up the fitted graph of all the components of the simplified NACI, namely the radiation effect index, the relocation index and the decontamination index. In addition, as the exponent of all valid cases is within the range of 1.3 to 1.4, three different exponents: 1.3, 1.35 and 1.4 are used to determine the equation of the fitted graphs. Same as other cases, the calculated value of radiation effect index of the release amount of 10 PBq is assigned to the variable y of the power function ($y = ax^b$) to obtain the value of a. All fitted graphs are shown in dashed lines in the figure. All fitted graphs fit quite well with the data points of simplified NACI when the release is over 1 PBq, including the graph that is obtained by adding up the fitted graph of all the components of the simplified NACI (the orange dotted line). The main shortcoming of all fitted graphs are that they overestimate the simplified NACI in the small release amount region.

4.3.6 Discussion on assumptions made in the calculation model

Relations between the release parameters (mainly the release amount) and the simplified NACI (including its components, namely radiation effect index, relocation index and decontamination index) discussed in Subsection 4.3 are based on the evaluation using the HotSpot code and simple Microsoft Excel worksheets. These limitations of the tools force the author to make a number of assumptions within the calculation model, which would cause inaccuracy in the results. Followings are the assumptions that were made and some recommendations on how we could change those assumptions to obtain better results.

The first assumption is the assumption of all dose levels that are used to determine the radiation protective measures. It is obvious from Chapter 2 that dose levels related to sheltering, evacuation and food intake restriction would not really contribute to the value of the NACI and its components. On the other hand, the dose level for starting relocation, dose level for returning home and dose level for decontamination target area setting could provide significant influences on the NACI. In the assessments above, difference in dose level for starting relocation were taken into account in Subsection 4.3.5.2, though others are not mentioned. The relocated period is set to one year, thus the dose level for returning home is not applicable to this calculation model. The dose level for decontamination target area setting is set to 20 mSv/year, and no sensitivity analysis of the value of this dose level is made. If these dose levels are applied using very small values, the relocation index and the decontamination index can significantly increase. However, this is true for all release amount. Therefore, the author believe that the only thing that would change is the constant a of the power function ($y = ax^b$) not the exponent b which is the key parameter of this study.

The second assumption is the period of exposure which is set to one year. This is definitely short comparing to the half-life of cesium 137. However, same as the cases of dose levels for relocation and decontamination, the period of exposure would affect every release amount equally, thus it could change only the constant a not the constant b.

The third assumption is the size of the target area of which the exposure of the people to the cesium 137 are taken into account. The HotSpot code can take into account the target area within only 200-km-radius which is very small comparing to the release amount taken into account in this study. The author attempted to extrapolate the results to 500-km-radius, but extrapolation using a single function is actually not accurate enough. In addition, when the release amount reach 100 PBq, even the target area as large as 500-km-radius is too small to cover the whole affected area. However, the inventory of cesium 137 of a typical 1,100 MWe BWR is about 300 PBq [4.12], and it is very unlikely that more than 10% of the cesium inventory could be released to the environment even in a very severe accident. Therefore, it might not be very necessary to try to further enlarge the target area of the calculation.

The fourth assumption is that the dose reduction due to the decontamination is not taken into account. Even though one of the objectives of the decontamination is to reduce the exposure of the people to the radiation, the study in Chapter 3 has already indicated that the correlation between decontamination index and the radiation effect index is very weak, i.e. the decontamination of the contaminated area would not significantly reduce the exposure dose.

The fifth assumption is the assumption of the local data used in the calculation of respective indices. Most local data are taken from the documents of Ibaraki Prefecture. The local data may affect the results, especially when a wealthy city or a city with large population exists. Nonetheless, the author believe that any changes in this assumption will not change the order of magnitude of all the indices composing the simplified NACI, thus it would not significantly affect the exponents of the correlations above.

The last assumption is the assumption of the type of the radionuclides. There are a number of radionuclides which are released after a severe accident. However, this study focuses on the cesium 137 because it is the radionuclide that can represent the overall long-term consequences of a severe accident [4.13]. Iodine 131 is also a very important radionuclide, but it could cause consequences for only few weeks, and it is suitable for the consideration of consequences on an individual, rather than the overall consequences like in this study. Uranium and plutonium can also be emitted from the reactor if there is an explosion after the accident. However, these elements cannot disperse very far, thus they can influence only limited area very close to the power plant.

In spite of the shortcomings of the calculation model caused by the assumptions mentioned above, the author believes that all results presented above are accurate enough to represent the trend of all consequences resulted from a severe accident. The author also believe that the readers could use this piece of information to establish the safety criterion regarding consequences of a severe accident, or to determine the radiation protection scheme in order to minimize the overall consequences to the people and the environment.

4.4 Summary of Findings

The applicability of "100 TBq cesium 137 release into environment" as a safety criterion at reactor design approval stage is investigated using simplified NACI.

- ✓ The overall consequence to people and the environment of the 100 TBq cesium 137 release into environment were small enough for it to be used as a safety criterion regarding consequences of a severe accident at reactor design approval stage. It gives small simplified NACI in all calculation conditions, and under variation of meteorological conditions.
- ✓ Though the assumption of single wind direction and wind speed is conservative for the assessment of individual acute and chronic doses, it can be less conservative in the assessment of simplified NACI. Although the consideration of the changes in the wind direction and the wind speed can reduce the cesium concentration at a specific location, it enlarge the total area being contaminated by cesium.
- ✓ It is important to carefully select the dose level for decontamination target area setting, since it has large influence on the simplified NACI.

Relations between release parameters, namely the release amount, the release period and the release starting time, and the consequences of a severe accident represented by the simplified NACI and its components, namely the radiation effect index, the relocation index and the decontamination index were investigated.

- ✓ Simplified NACI and its components increased drastically when the release amount is increased. On the other hand, the influences of the release period and the release starting time on the simplified NACI and its components are nearly negligible when compared with the influence of the release amount.
- ✓ Relations between the release amount and the simplified NACI and its components can be fitted by a simple power function ($y = ax^b$). The exponent of the fitted graph seems to be the key to the relations.
- ✓ The exponent of the relation between the release amount and the radiation effect index was around 0.8 to 1.0. It follows nearly linear function because the relation between the release amount and the collective dose when the radiation protective measures are not taken into account follows a completely linear function.
- ✓ The exponent of the relation between the release amount and the relocation index was around 1.4 to 1.5. This is because the relocation index has many variables that are dependent to the area, and the spatial distribution of the cesium 137 is affected by the meteorological conditions. The exponent of the relation between the release amount and the decontamination index was identical with the same reason.
- ✓ The exponent of the relation between the release amount and the simplified NACI was around 1.3 to 1.4.

4.5 References

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Chapter 5 Conclusions

5.1 Conclusions

The nuclear accident consequence index (NACI) which is an index that can include all anticipated and quantifiable consequences of a severe accident to people and the environment was developed.

- ✓ The radiation effect index which represent the consequences to people, the decontamination index which represent the consequences to the environment and the relocation index which cover both consequences to people and the environment are the three important components which dominate the NACI of most accident sequences and the average NACI.
- ✓ The three abovementioned components can represent the consequences of a severe accident to people and the environment in the form of simplified NACI.
- ✓ A robust decontamination model for the severe accident consequence assessment using simplified NACI was developed.
- ✓ The dose for decontamination target area setting, the waste disposal scheme and the number of workers involving in the decontamination work were highly influential to the decontamination index and the simplified NACI.
- ✓ The decontamination index calculated by the newly developed decontamination model increased its importance notably. It emphasizes the findings above that we have to pay great attention to the determinations of dose level for decontamination target setting and the waste management process.
- ✓ The applicability of "100 TBq cesium 137 release into environment" as a safety criterion at reactor design approval stage was demonstrated using simplified NACI. The 100 TBq cesium 137 release gave small simplified NACI in all calculation conditions, and under variation of meteorological conditions.
- ✓ Relations between the release amount and the simplified NACI and its components can be fitted by a simple power function ($y = ax^b$). The exponent of the fitted graph seems to be the key to the relations.
- ✓ The exponent of the relation between the release amount and the radiation effect index/the relocation index/the decontamination index/the simplified NACI were around 0.8 to 1.0, 1.4 to 1.5, 1.4 to 1.5 and 1.3 to 1.4, respectively.

As the NACI can cover both consequences to people and the environment, it would consequently contribute to the protection of people and the environment, as stated in the safety objective of the IAEA.

5.2 Proposal for Further Research

In order to indicate the challenges for the future, the best thing to do is to return to the Section 1.3, final goal and necessary research components. There are two research components which are necessary to achieve the final goal: (1) development of severe accident consequence assessment scheme, and (2) applications of severe accident consequence assessment scheme. The author believe that the first piece of research is quite complete since all anticipated and quantifiable consequences can be assessed by the NACI developed in Chapter 2 and modified in Chapter 3, and non-quantifiable consequences can also be discussed in the manner that matches the local requirements. As for the second research components, the NACI was used to confirm the safety of a nuclear power plant in regard to the consequences of a severe accident in Chapter 4. It is confirmed that if the release of the cesium 137 can be limited to 100 TBq, the consequences of the release could be nearly negligible. In addition, the relation between the release parameters and the NACI was investigated in order to be used to confirm the safety of a nuclear power plant without spending a lot of resources. Regarding the second part of the second research component, though a number of clues to the establishment of emergency response scheme which can potentially minimize the overall consequences of a severe accident to people and the environment were provided in Chapters 2 to 4, though there is no dedicated research on this issue in this thesis. Therefore, one proposal for further research is to establish an optimized emergency response scheme based on the evaluated NACI which can minimize the overall consequences to people and the environment. To do this, detailed emergency response scheme including all factors that determine the radiation protective measures has to be modeled in the calculation scheme of the NACI, and effort has to be made to find the sets of parameters that minimized the NACI.

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