A SIMPLE METHOD FOR SEVERE ACCIDENT CONSEQUENCE ASSESSMENT OF A NUCLEAR POWER PLANT USING RELEASE PARAMETERS

Kampanart Silva[1], Koji Okamoto[2]

[1] *Thailand Institute of Nuclear Technology (Public Organization) 16 Vibhavadi-Rangsit Rd., Latyao, Chatuchak, Bangkok, Thailand 10900 kampanarts@tint.or.th*
[2] *The University of Tokyo 7-3-1 Hongo, Bunkyo, Tokyo, Japan 113-8654 okamoto@n.t.u-tokyo.ac.jp*

The authors developed the simplified nuclear accident consequence index (simplified NACI) in the previous study, which can be used to assess the overall consequences of a severe accident to people and the environment. Though it can cover a large range of consequences, its assessment requires extensive resources. In this study, a simple method was developed by investigating the relations between the release parameters and the simplified NACI, in order to use the release parameters for the consequence assessment instead of the simplified NACI. The simplified NACI escalates significantly when the release amount is increased, whereas the influences of the release period and the release starting time are nearly negligible. Relation between the release amount and the simplified NACI follows a simple power function ($y = ax^b$), *in which the exponent b is the key of the relation. The exponent b is around 0.8 – 1.0 when the release amount is smaller than 100 TBq, and increases to around 1.3 – 1.4 when the release is equal to or larger than 100 TBq. The correlation between the release amount and the simplified NACI was used to perform an example calculation, where it was found that the consequences are limited when the release amount is maintained at 100 TBq or smaller.*

I. INTRODUCTION

The International Atomic Energy Agency (IAEA) sets as its fundamental safety objective to protect “people” and “the environment” from harmful effects of ionizing radiation[1]. Various consequences to people and the environment caused by the accident at the Fukushima Daiichi Nuclear Power Station (hereinafter referred to as 1F accident)[2] support this concept of radiation protection where not only “people” but also “the environment” need to be protected from all possible adverse effects from the utilization of radiation sources including nuclear power plants.

However, based on the report of the Japanese Government regarding the 1F accident[2], the efforts were mostly put on the protection of people from the excessive exposure to the radiation. One reason behind this is that preceding studies on severe accident consequence assessment tended to focus on assessment of direct consequences of radiation on people in the forms of acute and chronic doses[3-5]. Recognizing the necessity to include consequences other than direct effects from radiation exposure to people and consequences to the environment into the severe accident consequence assessment scheme, our previous study introduced the Nuclear Accident Consequence Index (NACI) which can include quantifiable consequences of a nuclear power plant accident on both people and the environment. As shown in Fig. 1, the NACI can take into account various types of consequences, including radiation effects, psychological effects, sheltering, evacuation, relocation, food intake restriction, alternative source cost, harmful rumor, decommissioning and decontamination. Since these consequences adopt a common unit called Accident Consequences Unit (ACU), the optimization of the protective measures, i.e. the minimization of overall consequences of an accident, is possible. Detailed calculation scheme of the NACI and the background for the adoption of ACU as a common unit can be referred to in our previous papers[6-8].

Despite the comprehensiveness of the NACI, the NACI assessment requires a great deal of information and its process is time-consuming. On the other hand, it was found that three dominant components of the NACI, namely radiation effect index, decontamination index and relocation index, which totally cover approximately nine-tenths of the whole NACI for most accident sequences. The authors thus simplified the assessment by using the three components to evaluate the overall consequences of a severe accident, and renamed the sum of the three indices to simplified NACI[7].

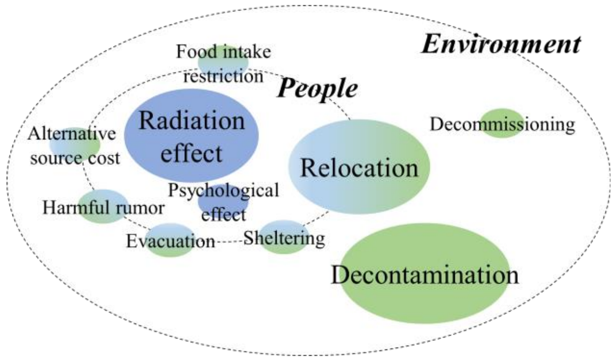

Fig. 1. Consequences of a severe accident on people and environment in the framework of Nuclear Accident Consequence Index (NACI)[7].

This simplification significantly reduced the time and resources spent on the assessment. Nonetheless, the assessor would still need to acquire a large amount of meteorological and other local data, and perform a probabilistic assessment in order to thoroughly consider the uncertainties in all factors. It would be worthwhile for an owner of a nuclear power station to perform such assessment if he wants to obtain the detailed information in each type of consequences and design an optimized accident management and emergency response measures. However, at the time when the construction of the power station has not been concluded, e.g. reactor design approval stage, he may think of securing the resources for some other urgent purposes. In addition, if the reactor has not yet been constructed, much of the information related to the site and the reactor may not be available or its disclosure may not be allowed. Therefore, an assessment which can provide an overview of all consequences of a severe accident to people and the environment but does not require extensive resources in terms of data, time and personnel, would be useful for those owners.

Release parameters, namely release amount, release period and release starting time, can be assessed with just the data of the nuclear power plant itself, thus their assessments could be performed without spending massive resources. If the relations between these release parameters and the overall consequences of a severe accident (which can somehow be represented by the simplified NACI) are quantified, the severe accident consequence assessment could theoretically be simplified from the evaluation of the NACI to the evaluation of the release parameters. Therefore, the objective of this study is to investigate the relations between the release parameters and the simplified NACI, in order to develop a simple method for severe accident consequence assessment where the assessor can just evaluate the release parameters.

II. METHODOLOGY

II.A. Flow of the Assessment

The flow of the assessment is shown in Fig. 2. First, the inputs and calculation conditions are determined. Then they are input to the HotSpot Health Physics Code Version 2.07.2[9] to evaluate the land contamination and the radiation exposure dose resulted from the radioactive material release after a severe accident. Two types of outputs from the code: the distributions of the amount of the deposited radioactive materials and the distribution of the radiation exposure dose are used to calculate the simplified NACI. Then the release parameters: release amount, release period and release starting time, are varied in order to investigate the relations and correlations between each parameter and the simplified NACI.

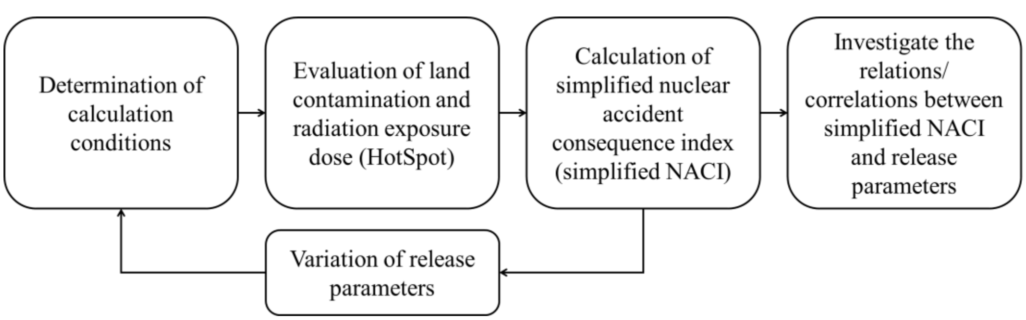

Fig. 2. Flow of the assessment.

TABLE I. Calculation Conditions[8]

Parameters	Values
Release characteristics	
Radionuclide taken into consideration	cesium 137
Release amount [TBq]	10 – 100,000
Release period [hrs]	1 - 24
Release starting time [hrs]	0 - 24
Effective release height [m]	40
Airborne fraction	1
Respirable fraction	1
Receptor characteristics	
Pathways taken into account	cloudshine, groundshine, inhalation 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	
Meteorological data taken into account	wind speed, wind direction, stability class, rainfall
Observation point of the meteorological data	Tsukuba Meteorological Station, Ibaraki Prefecture (2014)
Source of local data for calculation of relocation index and decontamination index	Documents of Ibaraki Prefecture

II.B. Calculation Conditions

Calculation conditions are shown in TABLE I. Realistic assumptions are adopted when firm evidence or background knowledge is available. All else conservative assumptions or the values recommended by the HotSpot code are adopted. Cesium 137 is the only radionuclide taken into account even though it was pointed out in the 1F accident that the release from a severe accident consists of three main radionuclides, namely iodine 131, xenon 133 and cesium 137. This is because the conversion factor for radiological equivalence to iodine 131 of cesium 137 in the INES user's manual is 40, while that of xenon 131 is so small that it is negligible. Release amount, release parameters and release starting time are varied in order to investigate the influence of the release parameters. The release amount is varied from 10 TBq to 100 PBq (100,000 TBq) since 10 TBq seems to be small enough for the consequences to be insignificant[7], and the inventory of cesium 137 of a typical 1,100 MWe boiling water reactor (BWR) is about 300 PBq[10]. The release period is varied from 1 to 24 hours, since the atmospheric dispersion model adopted by the HotSpot code is not suitable for a longer period of time. The release starting time is varied from 0 to 24 hours in order to get in line with the release period. It will be found in the following section that the release starting time does not significantly affect the simplified NACI. The dose levels for starting relocation and for decontamination target area setting are set based on the recommendation of ICRP[11]. Detailed reasons for the adoption of other conditions can be found in Silva and Okamoto (2016)[8].

III. RESULTS

III.A. Relations between Simplified NACI and Release Parameters

Simplified NACI and its components (radiation effect index, relocation index and decontamination index) when the release amount, the release period and the release starting time is varied are shown in Fig. 3A – 3C, respectively. Simplified NACI and its components increased significantly when the release amount is enlarged. The simplified NACI increased by approximately 1.5 orders of magnitude when the release amount is enlarged by an order. In contrast, when the release period lengthens, the simplified NACI and its components gradually decreased at a specific rate. It can be seen from the graph that the simplified NACI reduces by about half when the release period is lengthen from 1 to 12 hours. As for the release starting time, the simplified NACI and its components hardly change when the release starting time is varied. However, the release starting time has a potential to exert larger influence when radionuclides other than cesium 137 are considered. This will be further discussed in the following section.

It can be seen from Fig. 3A – 3C that the influences of the release period and the release starting time are insignificant when compared with the influence of the release amount. Thorough investigation will thus be done solely for the correlation between the simplified NACI (and its components) and the release amount.

III.B. Correlation between Simplified NACI and Release Amount

Fig. 4 shows the simplified NACI and all its components (radiation effect index, relocation index and decontamination index) at different release amount, along with the correlations between the simplified NACI and the release amount. It can be seen from the graphs that all relations follow power functions ($y = ax^b$). The key to the relations between the simplified NACI and the release amount is the exponent of the power function (constant b). If the exponent of the power function is determined, the assessor can make a rough estimation of the simplified NACI (which could represent the overall consequence of an accident) for every release amount between 10 and 100,000 TBq by estimating the value of the simplified NACI at a specific release amount and substitute it into the function.

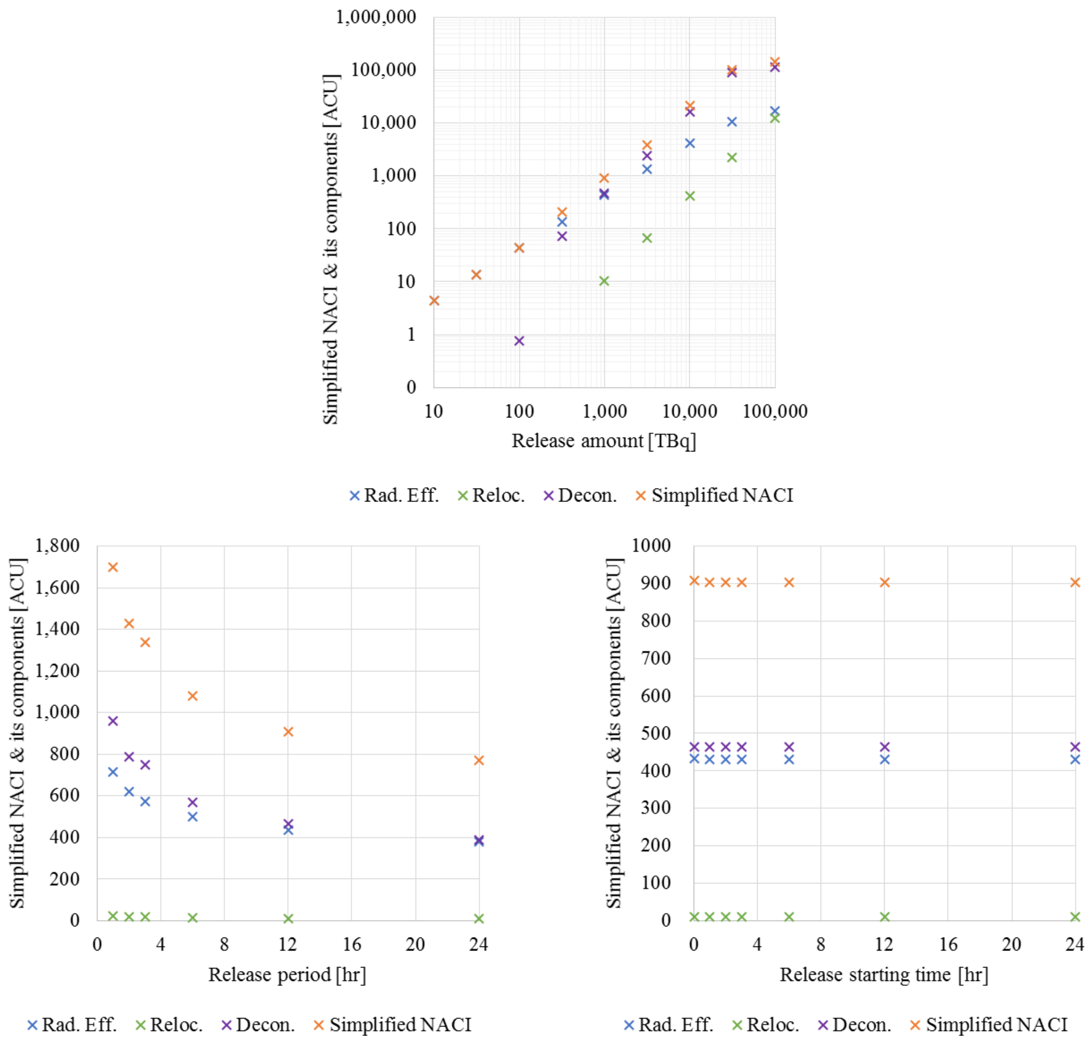

Fig. 3A. (top) Simplified NACI and its components when the release amount is varied from 10 - 100,000 TBq.
Fig. 3B. (bottom-left) Simplified NACI and its components when the release period in varied from 1 – 24 hours.
Fig. 3C. (bottom-right) Simplified NACI and its components when the release starting time is varied from 1 – 24 hours.

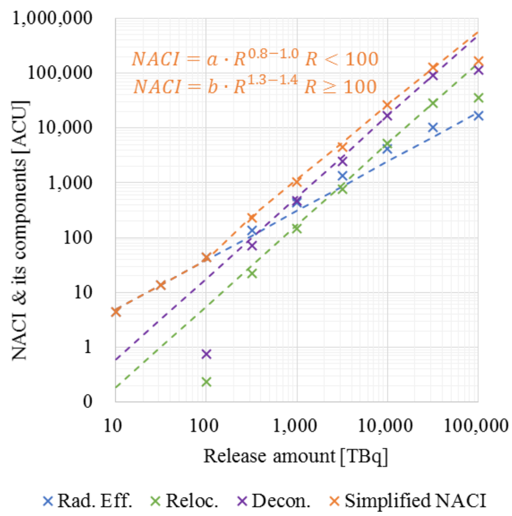

Fig. 4. Relations between simplified NACI/its components and release amount, and correlations between simplified NACI and release amount.

It is observable from the graph that when the release amount is smaller than 100 TBq, the relocation index and the decontamination index are zero, which means there are neither relocation nor decontamination. The radiation effect index remains as the index to determine the simplified NACI. It can be seen from the blue dotted line that the relation between the radiation effect index and the release amount is very close to a linear function. The reason to this is as follow. As the meteorological conditions are unchanged for all release amount, the amount of cesium 137 deposited on the target area is proportional to the total cesium 137 release amount. Next, the collective dose, and consequently the radiation effect index, are proportional to the amount of cesium 137 deposited. Thus the relation between the release amount and the radiation effect index would be a linear function. However, as radiation protective measures are more widely applied in a situation with large release, the exponent becomes slightly smaller than 1. Therefore, the exponent for the relation between the radiation effect index and the release amount, which is also the exponent for the relation between the simplified NACI and the release amount when the release amount is smaller than 100 TBq, is within the range of 0.8 – 1.0. On the other hand, when the release is equal to or larger than 100 TBq, the slope of the graph is closer to those of the relocation index and the decontamination index, whose the exponents are around 1.4 – 1.5. The reason to the values of the exponents of the two indices are not as straightforward as the case of radiation effect index. As the two indices have many variables that are area-dependent, it should be proportional to the square of the release amount (exponent = 2). However, the exponents are much smaller than 2. This is because of: (1) the characteristics of the dose levels for starting relocation and for decontamination target area setting, and (2) the consideration of meteorological conditions. The dose levels for starting relocation and for decontamination target area setting are set to 100 and 20 mSv/year, respectively. Therefore, when the dose of a specific area does not exceed this dose level, relocation and decontamination are not implemented. Additionally, the calculation takes into account the influences of wind and rain, thus the distribution of the released cesium 137 is not homogeneous, and cesium 137 may concentrate only in some directions. Relocation and decontamination will not be implemented in the area of which the annual dose does not exceed the aforementioned dose levels. This would suppress the escalation of the two indices, and keep the exponent in the range of 1.4 – 1.5. When the radiation index is added to the relocation index and the decontamination index to form the simplified NACI, the exponent for the relation between the simplified NACI and the release amount when the release amount is equal to or larger than 100 TBq becomes approximately 1.3 – 1.4.

Finally, the correlation between the release amount and the simplified NACI can be expressed by

$$NACI = a \cdot R^{0.8-1.0} \qquad (R < 100), \qquad (1)$$

$$NACI = b \cdot R^{1.3-1.4} \qquad (R \geq 100), \qquad (2)$$

where *NACI* and *R* stands for simplified NACI [ACU] and release amount [TBq]. The constants a and b can be determined if the simplified NACI of a specific release amount is estimated, and the calculated simplified NACI is substituted back to the equation.

IV. DISCUSSION

IV.A. Influences of Simplification of the Assessment

A number of assumptions have been made in order to simplify the methodology for the assessment, each of which can affect the results in some ways. First, dose levels for starting relocation and for decontamination target area setting were set to single values though it was shown in our previous studies[6,12] that they significantly influence the NACI. In this study, the authors adopted the highest dose levels within the dose bands recommended by the ICRP[11]. If smaller dose levels were adopted, the relocation index and the decontamination index will significantly increase. However, these escalation would be true for all release amounts, thus would affect only the constants a and b of Eq. 1 and 2, not the exponents. Next is the period of exposure which is set to one year. This is relatively short for the consideration of cesium 137. However, the period of exposure would also affect all release amounts equally, thus it will not affect the exponents. The boundary of the target area which was set to 200 km due to the limitation of the HotSpot code, is also too small to consider the release larger than 10 PBq (1,000 TBq). The authors attempted to extrapolate the results to the radius of 500 km in the previous study[8], and found that the exponents are still within the range specified in Eq. 1 and 2. However, further assessment is recommended by the calculation code that can take into account a larger target area (e.g. OSCAAR, MACCS), if the information needed is available. The next assumption is the disregard of the dose reduction due to decontamination. However, this again would not significantly affect the correlations between the simplified NACI and the release amount, as it was pointed out by our previous study[12] that the association between the decontamination index and the radiation effect index is very weak, i.e. the decontamination of the area would not really reduce the exposure dose, even though the main objective of decontamination is to reduce the radiation exposure to the public. In addition to all assumptions above, local data of Ibaraki Prefecture was used for the entire area, though the target area covers several prefectures. Nonetheless, any changes in the local data will not change the order of magnitude of any indices composing simplified NACI, thus would not significantly affect the exponent of the equations. The last assumption, which is one of the most important one, is the assumption that cesium 137 is used to represent all released radionuclides. In fact, iodine 131 is another important radionuclide, since it dominates the short-term consequences (while cesium 137 dominates the long-term consequences). Yet it brings down consequences for just few weeks, hence it is suitable for the consideration of severe accident effects on an individual in terms of acute dose, rather than the overall consequences like in this study. Since iodine 131 was not taken into account, the effects of large and early release which are dominated by the short half-lived radionuclides can be underestimated. This is the reason that the simplified NACI was not sensitive to the release starting time. Further study using iodine 131 may be necessary to investigate the influence of short half-lived radionuclides.

Though a number of assumptions made to simplify the assessment could influence the results of the assessment, those influences are either insignificant, or can be solved by further investigation. Therefore, the correlations presented in this paper are representative, and can be used for a simple assessment of severe accident consequences.

IV.B. Implementation of the Simple Method: An Example

As mentioned in the Introduction, this simple method can be used at the time when the construction of the power station has not been concluded e.g. reactor design approval stage. Calculations can be made to prove that the consequence from all anticipated accidents will be limited, and the results can be included to the safety assessment in order to support the reactor design approval.

In this study, the simplified NACI of the release amount at 1 PBq (1,000 TBq) was 908 ACU (see Fig. 4). The relocation boundary (the furthest distance where relocation is implemented) was 3 km which is quite small, while the decontamination boundary was 10 km which implied that the contaminated area was rather large. This also implied that the first year annual dose can go up to 100 mSv at the distance of 3 km, and up to 20 mSv at the distance of 10 km, which means the radiation effects are not negligible. When the simplified NACI of 908 ACU and the release amount of 1 PBq are substituted into Eq. 2 (the exponent was set to median = 1.35), the constant b becomes 0.081. Eq. 2 can be rewritten to

$$NACI = 0.081 \cdot R^{1.35} \qquad (R \geq 100). \qquad (3)$$

Here, when the release amount of 100 TBq is substituted into Eq. 3, the simplified NACI becomes 40.6 ACU. This should mainly be the contribution of the radiation effect index. Moreover, as the release is relatively small, annual doses in most area would be in the order of 1 mSv or lower. As 1 mSv/year is the recommended dose limit for the public, most of the radiation effects may be negligible. Therefore, it can be assumed that the consequences from an anticipated accident is limited if the release amount of 100 TBq or lower. Actually, this can also be observed from Fig. 3, where 100 TBq is the point that the exponent changes from 0.8 – 1.0 to 1.3 – 1.4. Consequences of a severe accident are dominated by the radiation effects, and increases linearly with the release amount until 100 TBq. Therefore, the extent of the consequences is controllable. However, when the release amount exceeds 100 TBq, the consequences increase exponentially following Eq. 2 which makes it difficult to control the consequences. Thus it is better to keep the release amount of cesium 137 from any anticipated accidents under 100 TBq.

V. CONCLUSIONS

Relations between the release parameters, namely release amount, release period and release starting time, and the consequences of a severe accident represented by the simplified NACI were investigated. It was found that:

- Simplified NACI escalated significantly when the release amount was increased, while the influences of the release period and the release starting time on the simplified NACI were nearly negligible when compared to the influence of the release amount.
- Relation between the release amount and the simplified NACI follows a simple power function (y = ax^b), and the exponent b of the function is the key of the relation.
- The exponent in the correlation between the release amount and the simplified NACI was around 0.8 – 1.0 when the release amount is smaller than 100 TBq, as it is dominated by the radiation effect index whose relation with the simplified NACI nearly follows the linear function.
- The exponent in the correlation between the release amount and the simplified NACI was around 1.3 – 1.4 when the release amount is equal to or larger than 100 TBq, as its trend is similar to those of the relocation index and the decontamination index, whose exponents were around 1.4 – 1.5.
- The correlation between the release amount and the simplified NACI enables an assessment of the consequences of a severe accident by a simple evaluation of the release amount of anticipated accidents.
- The simple method can be used for the consequence assessment at the time when the construction of the power station has not been concluded e.g. reactor design approval stage. It was found in the example calculation that the consequences are limited, when the release from an anticipated accident is maintained at 100 TBq or smaller.

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