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Cost per severe accident as an index for severe accident consequence assessment and its applications

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ABSTRACT

The Fukushima Accident emphasizes the need to integrate the assessments of health effects, economic impacts, social impacts and environmental impacts, in order to perform a comprehensive consequence assessment of severe accidents in nuclear power plants. "Cost per severe accident" is introduced as an index for that purpose. The calculation methodology, including the consequence analysis using level 3 probabilistic risk assessment code OSCAAR and the calculation method of the cost per severe accident, is proposed. This methodology was applied to a virtual 1,100 MWe boiling water reactor. The breakdown of the cost per severe accident was provided. The radiation effect cost, the relocation cost and the decontamination cost were the three largest components. Sensitivity analyses were carried out, and parameters sensitive to cost per severe accident were specified. The cost per severe accident was compared with the amount of source terms, to demonstrate the performance of the cost per severe accident as an index to evaluate severe accident consequences. The ways to use the cost per severe accident for optimization of radiation protection countermeasures and for estimation of the effects of accident management strategies are discussed as its applications.

1. Introduction

Probabilistic risk assessment (PRA; or probabilistic safety assessment) is widely used as a method to assess the risks of a nuclear power plant. PRA is divided into three levels in order to sequentially assess the occurrence possibilities and the consequences of nuclear power plant severe accidents. Level 1 PRA and level 2 PRA calculate the core damage frequencies (CDFs) and containment failure frequencies (CFFs), respectively. Level 3 PRA assesses the consequences from the radioactive materials emitted in the wake of severe accidents.

A number of calculation codes: MACCS [1], Cosyma [2], OSCAAR [3,4], RSAC [5], HotSpot [6], etc., are developed to perform level 3 PRA. They simulate the dispersion of the emitted radionuclides in certain atmospheric conditions and estimate the individual or public dose or both of them. Most of the codes can take into account the radiation protection countermeasures. MACCS, Cosyma and OSCAAR also provide a function to estimate the costs regarding radiation protection countermeasures, decontamination and food intake restriction. There are many earlier studies [3,7–16] related to severe accident consequence assessment using these calculation codes. Most studies concentrate on the evaluation of acute and chronic doses. This is because the probabilistic safety criterion related to the consequence of severe accidents which is commonly used by the regulatory bodies and utilities in several countries is the dose (some of them do not even have a criterion for the consequence of severe accident but only have annual probabilities of occurrence, e.g., core dame frequency (CDF) or containment failure frequency (CFF)) [17].

Nevertheless, the accident at the Fukushima Daiichi Nuclear Power Station (Fukushima accident) showed that a severe accident wreaks tremendous economic, social and environmental impacts even though the health effects due to radiation exposures are unapparent. Three huge tsunamis attacked the Fukushima Daiichi Nuclear Power Station after the Great East Japan Earthquake (M 9.0) which led to station blackout (SBO). There were hydrogen explosions in the units 1 and 3. Reactor core melting and reactor vessel/containment vessel failures were strongly suspected in the units 1–3. More than 140,000 people were sheltered and evacuated [18] as there was a large amount of radioactive materials emitted from the power plants [19]. Most of them would not be able to return home for several years. The evacuees lost their incomes throughout the period of evacuation, and thousands of square kilometers of area needed decontamination. Only a few nuclear power plants in Japan could restart after all were shut

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down [20,21], and many Japanese decided to oppose the utilization of nuclear energy [22].

Circumstances after the Fukushima accident imply the need to include the evaluations of economic, social and environmental impacts into the consequence assessment of severe accidents. However, these impacts, together with the health effects due to the radiation exposures, have different characteristics and their evaluation results are shown in different ways. In order to comprehensively evaluate the consequences of severe accidents, various kinds of consequences must be converted into a common unit, and integrated to form a common index. The authors selected the cost per severe accident as a common index because previous studies [23–28] proved that it can cover a large scope of consequences and it is easy-understanding. In ExternE [23], Hirschberg et al. [24] and IAEA technical reports series no. 394 [25], many kinds of consequences, including health effects regarding radiation exposures, economic, social and environmental impacts, are evaluated in terms of monetary value, referring to the consequences of the Chernobyl accident. However, the objective of these studies was to perform a comparative consequence assessment of severe accidents among the electricity generation systems. Therefore, the consequences selected for the evaluation are the consequences that can be commonly evaluated in all systems, and there is a possibility for consequences particular to nuclear severe accidents to be overlooked. The aim of the study of Park et al. [26] is to estimate the total damage cost of the severe accidents in extreme conditions, and the main purpose of NUREG/BR-0058 Rev. 4 [27] and NUREG/BR-0184 [28] is to provide a guideline for the regulatory analysis. Hence their results cannot represent the consequences of severe accidents, though the methods to convert the consequences of severe accidents to monetary values can be adapted to the consequence assessment methodology discussed in Section 2.

The primary objective of this paper is to consider the severe accident consequence assessment methodology that can take into account various kinds of consequences. We introduce the methodology to convert consequences of severe accidents into monetary values, and integrate them to form a common index: the cost per severe accident (Section 2). The authors must emphasize that the aim is not to estimate the total damage cost of the accident itself but to extend the scope of the consequence assessment. As a case study, the methodology was applied to a virtual 1100 MWe boiling water reactor (Section 3). The calculated cost per severe accident was compared with the amount of source terms emitted in the severe accidents, another index for severe accident consequences, in order to demonstrate the performance of the cost per severe accident. The secondary objective is to consider the applications of the cost per severe accident calculated by the proposed methodology. The ways to use it for optimization of radiation protection countermeasures and for estimation of the effects of accident management strategies were discussed (Section 4).

2. Methodology

2.1. Overview of the calculation of cost per severe accident

The flow of the calculation of cost per severe accident is shown in Fig. 1. First of all, the type of the nuclear reactor and its location are determined. Then the severe accident sequences are defined in order to take into account all conceivable severe accidents. The accident sequences that do not proceed until the release of the radioactive materials from the containment vessel are excluded since their source term data are not provided. After that, the source term data of each sequence, including the release time, release duration and the amount of the released radionuclides are calculated or taken from the level 2 PRA results. If the amounts of the released radionuclides are shown in the form of the release ratios, the core inventory data is also needed. Also the radiation protection scenario is set. This includes the conditions of sheltering, evacuation, relocation and restriction of food intake. At this stage, containment failure frequencies (CFFs), i.e., the annual probabilities of the occurrence of containment failure, of representative accident sequences are calculated or taken from the level 2 PRA results. The CFFs are used to weight the accident sequences in the calculation of the average cost per severe accident (to be described in Section 2.5) in order to prioritize the accident sequences according to their probabilities of occurrence. The reason that the CFFs are chosen as indicators of the accident occurrence probabilities is that the CFFs are the probabilities that the containment fails to confine the radioactive materials which have stronger relations with the consequences of the accidents comparing with the core damage frequencies (CDFs). In the next step, the consequence analysis is performed using level 3 PRA code, OSCAAR (see Section 2.2). Before holding calculation of cost per severe accident of each accident sequence, the consequences which are able to be quantified and to be taken into consideration are determined (see Section 2.3). Then the results from the consequence analysis by OSCAAR, e.g., the expected values of the periods and the numbers of people involved in the radiation protection countermeasures and the collective dose of each severe accident sequence, are used as the input data to perform the calculation of the cost per severe accident of each accident consequence (see Section 2.4). Finally, the average cost

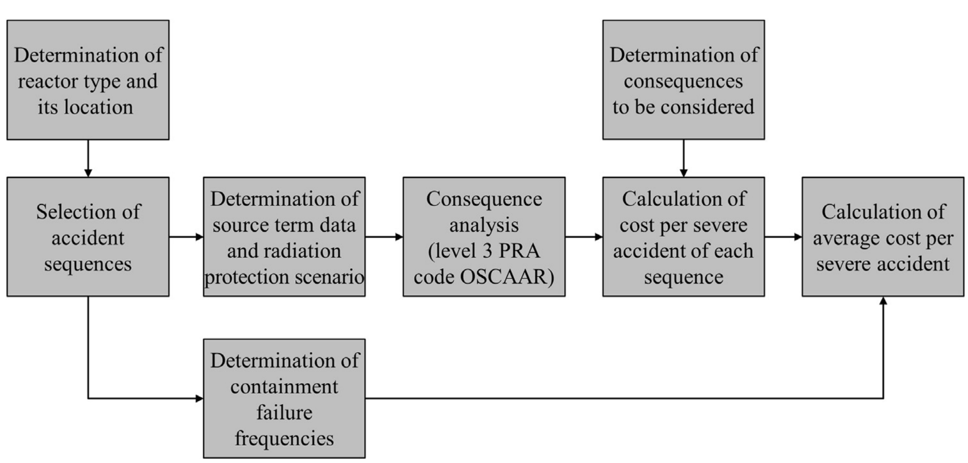

Fig. 1. Flow of calculation of cost per severe accident.