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Title

Cost per Severe Accident as an Index for Severe Accident Consequence Assessment and Its Applications

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Abstract (100 – 200 words)

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.

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- Cost per severe accident is used for severe accident consequence assessment.
- Assessments of health, economic, social and environmental impacts are included.
- Radiation effect, relocation and decontamination costs are important cost components.
- Cost per severe accident can be used to optimize radiation protection measures.
- Effects of accident management can be estimated using the cost per severe accident.

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 sheltered and evacuated [18] as there is a large amount of radioactive materials emitted from the power plants [19]. Most of them will not be able to return home for several years. The evacuees lose their incomes throughout the period of evacuation, and thousands square kilometers of area needs decontamination. Only a few nuclear power plants in Japan could restart after all were shut 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 1,100 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 per severe accident is calculated (see section 2.5) and this is the index that represents the consequences of severe accident.

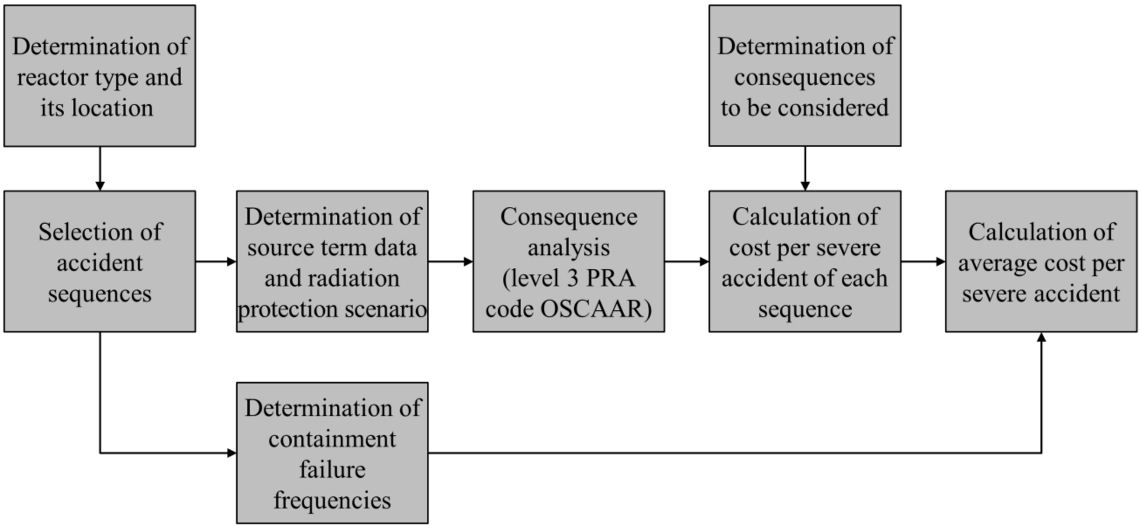

Fig. 1 Flow of calculation of cost per severe accident

2.2. Consequence analysis (level 3 PRA code, OSCAAR)

The consequence analysis is performed using the level 3 PRA code, OSCAAR (Off-Site Consequence Analysis of Atmospheric Releases of radionuclides) [3], which was developed by Japan Atomic Energy Agency (JAEA). OSCAAR estimates the periods and the numbers of people involved in the radiation protection countermeasures, e.g., sheltering, evacuation, relocation, etc. In addition, it calculates the individual early (or acute) and chronic doses, the collective dose, and the health effects regarding the radiation exposure. The calculation flow of OSCAAR is shown in Fig. 2 [3]. ADD module uses the source term information and meteorological data to simulate the advection and diffusion of the released radioactive materials and their deposition amounts. MS preprocessor code uses the bin sampling method [29] to pick up 248 representative sequences from 8,760 typical meteorological sequences to consider the effects of the meteorological conditions (8,760 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 take into account all kinds of weather conditions in a year from very moderate to very extreme. EARLY and CHRONIC modules use the input data from ADD module to calculate the individual early and chronic doses. Dose conversion factors for internal and external exposures used by these two modules are prepared in advance by DOSDAC preprocessor code. In PM module, the dose reductions resulted from the radiation protection countermeasures are considered, and the doses are reevaluated. Also PM module calculates the sheltered, evacuated and relocated populations and regarding periods. Distributions of population and agricultural products needed for calculation of collective dose are prepared by CURRENT code and the time needed for sheltering and evacuation are calculated beforehand by HINAN code. The outputs from PM module are passed to HE module in order to calculate the health effects regarding the radiation exposure. HEINPUT code is used to prepare inputs, such as lifetime risk per unit dose, the time-dependent probability of occurrence of health effects, and so on. In HE module, deterministic effects and stochastic effects (including hereditary effects) are evaluated. Also the collective dose is calculated here. Lastly, the economic impacts due to sheltering, evacuation, relocation and food intake restriction are evaluated using ECONO module. However, in this study, the ECONO module was not used. The economic impacts are estimated at the same time as other consequences, and those consequences are integrated to form the index: the cost per severe accident. The detail of the calculation of cost per severe accident is to be described in section 2.4. 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 value of the nth accident consequence EC_n are calculated by

$$EC_n = \sum_{k=1}^{a} C_{n,k} P_k \ , \tag{1}$$

where

$$\sum_{k=1}^{a} P_k = 1 \, . \tag{2}$$

Here, $C_{n.k}$ is the nth accident consequence of the kth meteorological sequence; P_k is the probability of occurrence of the kth meteorological sequence, and; a is the number of samples of meteorological sequences (in this case, a = 248). If the cumulative probability $CLP_{n,k}$ of the occurrence of meteorological sequences of the nth accident consequence is

$$CLP_{n,k} = CLP_{n,k-1} + P_k \tag{3}$$

and

$$CLP_{n,1} = P_1 \, , \tag{4}$$

when we put the nth accident consequence $C_{n.k}$ in the ascending order, the bth percentile value of the nth accident consequence is the accident consequence $C_{n.k}$ when the cumulative probability $CLP_{n.k}$ equals to b %. The stochastic uncertainty that arises from the different weather conditions which is a crucial component of severe accident consequence assessment can be evaluated by comparing these percentile values. However, the detailed discussion on this issue is out of the scope of this paper. The uncertainty from the different weather conditions in OSCAAR is discussed in detail elsewhere [30].

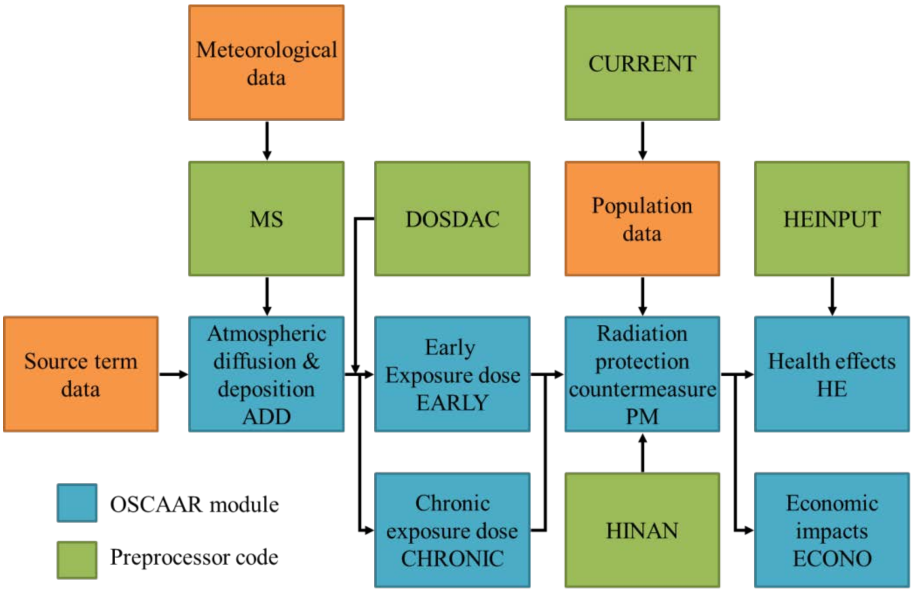

Fig. 2 Calculation flow of OSCAAR

2.3. *Determination of consequences to be considered*

It is stated in the fundamental safety principles of International Atomic Energy Agency (IAEA) that "*the fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation*" [31]. In order to fulfill this safety objective, the scope of the risk assessment, and also that of the consequence assessment, must cover all the risks and the consequences of the severe accidents to people and the environment. However, as the consequences of severe accidents have to be converted to monetary value and integrated to form the cost per severe accident, there are some consequences that cannot be included into the evaluation scheme. Consequences being included into or excluded from the evaluation scheme in this study and the reasons are discussed in this section.

Consequences of the severe accidents to people can be divided into health effects, economic impacts and social impacts. As for the consideration of health effects from radiation exposure, we adopt the concept of International Commission on Radiological Protection (ICRP) which 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 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*" [46]. Both effects are typically considered as the health effects from the radiological accidents [7-16]. However, we decided not to include the deterministic effects into the scope of assessment. This is because it is internationally recognized that full effort must be made to prevent the deterministic effects regardless of the cost of the measures [32]. This means we have to conduct every possible measure that can prevent the deterministic effects even though those measures can significantly increase other consequences of the accident. Therefore, there is no point to consider the deterministic effects together with other consequences. However, this does not mean that the deterministic effects are not important. We need to have a separate assessment for deterministic effects to complement the insights regarding the severe accident consequences obtained from the evaluation of the cost per severe accident. Apart from the health effects from radiation exposure, considering the anxiety of people about the effects from radiation exposure after the Fukushima Accident, the psychological effects to the people were also added into the health effect assessment.

For economic impacts, as the costs resulted from the radiation protection countermeasures, i.e., sheltering, evacuation, relocation and restriction of food intake, are estimated in ECONO [3], we included those costs into the economic impact assessment. In addition, referring to the report of the commission of management and financial survey of Tokyo Electric Power Company (TEPCO) [33] published after the Fukushima Accident, we included the cost of the alternative power source to replace the electric power supply of the power station where the accident happened. Though the health inspection costs and the costs spent for the evacuees to temporarily return home were mentioned in the report, they were not included in this study since they are negligibly minimal comparing with other costs.

The social impacts are very difficult to deal with because these impacts involve the responses of the human-being which make them specific to the accidents. The Three Mile Island Accident forced America to abandon the plan to build any new nuclear power stations, though it continued the operation of the existing power stations [34]. On the other hand, nuclear reactors in Japan and many other countries which shut down for inspection could not restart after the Fukushima Accident unless they pass the so-called stress tests [35]. The Japanese Government reviewed their energy policy and decided to move toward denuclearization [36]. Though these social impacts may be very important, they are different according to the situation in each accident. In addition, it is very difficult to convert them to monetary values. However, there is a piece of data of the cost regarding damages by harmful rumor after the Fukushima Accident obtained from the aforementioned report of the commission of management and financial survey of TEPCO [33]. The authors decided to include this cost to observe its fraction of the total cost per severe accident.

Consequences of the severe accidents to the environment can be divided into on-site and off-site consequences. The on-site consequences can be represented by the increase in decommissioning cost and the cost to decontaminate the land on which the power station is located. The off-site consequences can be quantified by summing up the costs for decontamination of the land contaminated by the released radioactive materials.

2.4. Calculation of cost per severe accidents of each accident sequences

According to the section 2.3, costs to be taken into consideration are costs regarding: health effects, economic impacts, social impacts and environmental impacts. The health effects consist of stochastic effects from radiation exposure and psychological effects. The costs regarding sheltering, evacuation, relocation and food intake restriction are estimated to evaluate the economic impacts. The cost resulted from harmful rumor is taken into account to represent the social impacts. And the environmental impact costs are calculated considering the increase in expenses for decommissioning and the land decontamination. Expected values of outputs of OSCAAR listed in Table 1 of each accident consequence are used to calculate the costs representing all the impacts stated above. We selected the expected values rather than any percentile values because it can better represent the whole picture of the calculation. The calculation methods for these costs are described below.

Table 1 Outputs of OSCAAR that are used for the calculation of cost per severe accident

No.	Outputs of OSCAAR
1	Sheltered population [person]
2	Evacuated population [person]
3	Relocated population [person]
4	Total area where relocated people lived [km^2]
5	Product of relocated population and relocated period [person·year]
6	Product of area where relocated people lived and relocated period [km^2·year]
7	Total weight of restricted milk [ton]
8	Total weight of restricted dairy products [ton]
9	Total weight of restricted beef [ton]
10	Total weight of restricted cereals [ton]
11	Total weight of restricted root vegetables [ton]
12	Total weight of restricted leaf vegetables [ton]
13	Collective dose [person·Sv]

2.4.1. Health effects

The cost regarding stochastic effects from radiation exposure is estimated by

$$SE = CD \times WTP \tag{5}$$

where *SE*, *CD* and *WTP* represent the cost regarding stochastic effects from radiation exposure [JPY], the collective dose [Sv] and the willingness to pay (WTP) per unit dose [JPY/Sv], respectively. A simple multiplication of the collective dose and the WTP per unit exposure is used to estimate the cost [37]. This is because the stochastic effects are supposed to be in linear relationship with the exposure dose according to the linear non-threshold hypothesis of ICRP [38].The willingness to pay (WTP) per unit exposure dose was determined referring to NUREG-1530 [39], and it is to be noted that the deterministic effects regarding the radiation exposures are not considered in the WTP estimation in NUREG-1530 which is consistent with the condition mentioned in section 2.3 that the deterministic effects are not included into the scope of the assessment. The collective doses for each accident sequence are calculated by OSCAAR.

The psychological effect cost is estimated by summing up the compensations regarding psychological effects resulted from sheltering, evacuation and relocation [40]:

$$PE = \sum_{x} POP_x \times T_x \times UPE \tag{6}$$

where x represents the radiation protection countermeasures: sheltering S, evacuation E and relocation R. Here, PE, POP, T and UPE are sequentially the psychological effect cost [JPY], the populations [person], the periods [year] and the psychological effect cost per unit [JPY/person · year]. The value of UPE is set according to the compensations in the Fukushima accident, and the compensation period for relocated people is reduced to a year if it is longer as there is no compensation over a year regarding the psychological effects from the Japanese government after the Fukushima Accident [41].

Finally, the summation of all the costs stated above forms the health effect cost HEC [JPY]:

$$HEC = SE + PE \ . \tag{7}$$

2.4.2. Economic impacts

Income losses, transportation costs, accommodation costs and capital utility losses of the sheltered, evacuated and relocated population are used to estimate the economic impacts of those countermeasures, referring to Homma et al. [3]. Income losses are included into the cost estimations of all countermeasures. Transportation costs and accommodation costs are included in the case of evacuation and relocation. Capital utility losses are considered only in the relocation cost calculation. The income losses IL_x [JPY] are calculated by

$$IL_x = POP_x \times T_x \times GDP \tag{8}$$

where GDP is the average gross domestic product (GDP) of the population [JPY/person · year].

$$TR_x = POP_x \times D_x \times UTR \tag{9}$$

is used to calculate the transportation costs TR_x [JPY]. Here, UTR is the unit transportation cost [JPY/person · km] and D_x is the travel distance [km]. Accommodation costs AC_x [JPY] are estimated by

$$AC_x = POP_x \times T_x \times UAC \tag{10}$$

where UAC represents the unit accommodation cost [JPY/person · year]. The capital utility losses include the losses of land capital utility LLC [JPY] and the losses of other capital utilities LOC [JPY].

$$LLC = A_R \times T_R \times CP_{Land} \times IR \tag{11}$$

calculates the former. and

$$LOC = POP_R \times T_R \times CP_{Others} \times (1 - DR) \times (DR - I) \tag{12}$$

calculates the latter. CP_{Land} is for the unit land capital costs [JPY/km^2], CP_{Others} is for the sum of other capital costs [JPY/person], A_R is for the relocated area [km^2], IR is for the investment recovery rate, DR is for the depreciation rate and I is for the interest rate.

Using the components stated above, sheltering cost SC [JPY], evacuation cost EC [JPY] and relocation cost RC [JPY] can be estimated using equations (13), (14) and (15), respectively:

$$SC = IL_S \ , \tag{13}$$

$$EC = IL_E + TR_E + AC_E \ , \tag{14}$$

$$RC = IL_R + TR_R + AC_R + LLC + LOC \ . \tag{15}$$

For the cost resulted from the restriction of food intake, the losses of the agricultural and livestock products LF_y [JPY] and the cost of waste management WM_y [JPY] are considered. The former is estimated by

$$LF_y = G_y \times M_y \times T_y \ , \tag{16}$$

and the latter by

$$WM_y = D_y \times M_y \times UTR + \frac{M_y}{VRF_y \times MVCF_y} \times UWM \ . \tag{17}$$

y represents the 6 types of the agricultural and livestock products: milk, dairy products, meat, leaf vegetables, root vegetables and grains. G is the gross value of the products [JPY/ton], M is the mass of the products [ton], *VRF* is the volume reduction factor [-] to indicate the volume reduction regarding the incineration of the wastes and the evaporation of moisture in the wastes, *MVCF* is the mass-volume conversion factor [-] and *UWM* is the unit cost for the radiation waste disposal [JPY].

Food intake restriction cost *FRC* [JPY] is estimated by summing the losses of the agricultural and livestock products LF_y [JPY] and the cost of waste management WM_y [JPY] of the 6 types of the agricultural and livestock products:

$$FRC = \sum_{y} \left(LF_y + WM_y \right). \tag{18}$$

The cost of the alternative power source *AP* [JPY] is calculated by

$$AP = T_A \times AF \times EP \times \left(UC_{Fossil} \times UC_{Nuclear} \right) \tag{19}$$

where T_A, *AF*, *EP* and *UC* represent the period of using the alternative power source [year], the available factor [-], the electric power of the target power plants [MW] and the unit cost of the power source [yen/MW · year], respectively. The subscripts *Fossil* and *Nuclear* represent the thermal power plants and nuclear power plants.

The summation of all the costs calculated above forms the economic impacts regarding the accident *EI* [JPY]:

$$EI = SC + EC + RC + FRC + AP\,. \tag{20}$$

2.4.3. Social impacts

Only the cost regarding damages by harmful rumor *HR* [JPY] is taken into account for the estimation of social impact cost *SIC* [JPY]:

$$SIC = HR\,. \tag{21}$$

The approximate value of *HR* was taken from the report of the commission of management and financial survey of TEPCO [33] as mentioned in section 2.3. Expenses resulted from harmful rumors in agricultural and livestock, tourist and service industries were included.

2.4.4. Environmental impacts

The on-site and off-site consequences are estimated by calculating the increase in the decommissioning cost and the decontamination cost, respectively. The increase in the decommissioning cost *DM* [JPY] is estimated by

$$DM = \frac{EP}{EP_{Fukushima}} \times DM_{Fukushima} \tag{22}$$

where the subscript *Fukushima* represents the values in the Fukushima Accident. $DM_{Fukushima}$ [JPY] refers to the report of the commission of management and financial survey of TEPCO [33] and $EP_{Fukushima}$ [MW] is equal to the total electric power of units 1 – 3 of the Fukushima Daiichi Nuclear Power Station.

The decontamination of the released radioactive materials is supposed to be done in the entire relocated area. The decontamination cost includes, the costs of the materials, equipment and labors spent DC_z [JPY] and the management costs of the wastes generated during the decontamination procedures WM_z [JPY]. The former are calculated by

$$DC_z = A_z \times UDC_z\,, \tag{23}$$

and the latter by

$$WM_z = D_z \times M_z \times UTR + \frac{M_z}{VRF_z \times MVCF_z} \times UWM\,\cdot \tag{24}$$

Here, *z* represents the targets of decontamination: houses and buildings, gardens and lawns, agricultural and farming lands, forests, and roads. *UDC* represents the total unit cost of the costs of materials, equipment and labors spent in the decontamination procedures of each target [JPY/m^2]. The decontamination methods of each target were selected based on the data from the decontamination demonstration project of JAEA [42] which evaluates those decontamination methods by considering their efficiencies and costs. We assumed using high pressure water and sandblast for roofs; wiping with clothes for walls; turning the soils upside down, eliminating the upper part of the soils or lawns and trimming the shrubs for gardens and lawns; turning the soils upside down and eliminating the upper part of the soils for agricultural and farming lands; eliminating the upper part of the soils and trimming the shrubs for forests; and high pressure water for roads [37]. The total unit costs of each decontamination method were calculated based on EURANOS report [43].

Decontamination cost *DCC* [JPY] is estimated by summing the costs of the materials, equipment and labors spent for the decontamination work DC_z [JPY] and the cost of waste management WM_z [JPY] of all decontamination targets:

$$DCC = \sum_z \left(DC_z + WM_z \right). \tag{25}$$

And the environmental impact cost *EIC* (JPY) is finally estimated by

$$EIC = DM + DCC\,. \tag{26}$$

2.4.5. Consideration of discount rate

Discount rate has important influences on results where there are long term effects [44]. Since there are many long term effects (longer than one year) included in the cost per severe accident, namely, the cost regarding stochastic effects from radiation exposure, some components of relocation cost: accommodation cost and capital utility loss, the food intake restriction cost, the alternative power source cost, the increase in the decommissioning cost and the decontamination cost, the discount rates of these components has to be discussed. We adopted the declining-balance method for the consideration of discount rates of each component which follows

$$CST_{Total,m} = \sum_{l_m=1}^{T_m} CST_{l,m} \times \left(1 - DCR\right)^{l_m - 1} \times DCR \tag{27}$$

where $CST_{Total,m}$, $CST_{l,m}$, DCR and T_m ($m = SE,R,FRC,DCC,AP$) represents the summation of the mth cost after consideration of discount rate [JPY], the mth cost generated in the l$_m^{th}$ year [JPY], the discount rate for all tlong term effects [-] and the length of the period in which the mth cost is generated [year].

The discount rate *DCR* shall be set in the range of 0% - 4.5% as ExternE suggested the usage of this range of discount rate for the calculation of the externalities of energy which also includes the calculation of the costs from the accidents that may occur in the energy generating facilities, e.g., accidents in nuclear facilities [23]. The period of consideration of the cost regarding stochastic effects from radiation exposure T_{SE} is set to 37 years which was obtained by subtracting the sum of the incubation period [3] and the average age of Japanese [45] from the average life-span of Japanese [45]. The relocated period T_R is taken from the results from OSCAAR. As OSCAAR does not provide the information on annual relocated population, annual relocated area, food intake restriction period and decontamination period, simple assumptions were adopted for these values. The relocated population and area are assumed constant every year. The food intake restriction period T_{FRC} and the decontamination period T_{DCC} are set the same as the relocated period. The period of consideration of the alternative power source cost T_{AP} is 30 years. The increase in the decommissioning cost is divided into short-term and long-term cost according to the report of the commission of management and financial survey of TEPCO [33], and the period of consideration of the long-term cost is set to 30 years. The influence of the discount rate is discussed in section 3.3.

2.5. Calculation of average cost per severe accident

All costs calculated in section 2.4 are finally summed up to obtain the cost per severe accident $CPSA_p$ [JPY] of each accident sequence:

$$CPSA_p = HEC + EI + SIC + EIC\,. \tag{28}$$

The calculated cost per severe accident of each accident sequence is then averaged using their CFFs as a weighting factor:

$$\overline{CPSA} = \frac{\sum_{p=1}^{q} CPSA_p \times CFF_p}{\sum_{p=1}^{q} CFF_p} \tag{29}$$

where $\overline{CPSA}$, CFF_p and q represents the average cost per severe accident [JPY], the CFF of the p$^{\text{th}}$ accident sequence [year^{-1}], and the total number of accident sequences (in this case q = 13).

3. Case study

3.1 Model plant and its calculation condition

The methodology was applied to a virtual 1,100 MWe boiling water reactor (BWR-5) which is located at the center of Tokai Research and Development Center (TRDC) of JAEA. Dominant severe accident sequences were selected, and the CFFs, release times, release duration times, and release ratios of those accident sequences were taken from the results of an open document of level 2 seismic PRA [46]. They are shown in Table 2. The reason that the seismic PRA was selected is that it covers the accident sequences initiated by both internal events and earthquakes. The CFFs obtained from the level 2 seismic PRA are the conditional CFFs assuming the probability of earthquake unity. The CFFs shown in Table 2 are the products of the conditional CFFs and the seismic probability of Ibaraki prefecture [47] where 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 taken from NUREG/CR-6094 [48].

Table 2 CFFs and source term data of each severe accident sequence

Accident sequence[1]	Release sequence number	CFF [year^{-1}]	Release time [hr]	Release duration [hr]	Release ratio to core inventory [-]							
					Noble gas 1	Organic I 2	Inorganic I 3	Cs-Rb 4	Te-Sb 5	Sr-Ba 6	Ru 7	La 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
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
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

1 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

The selected radiation protection scenarios are shown in Table 3. The periods and the dose levels of recommending sheltering and evacuation follow the recommendations by IAEA [49]. 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) [50]. The dose levels of 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 ICRP [51]. The times of starting the countermeasures refer to Homma et al. [3].

Table 3 Radiation protection scenarios

Countermeasure	Area and dose level	Time of starting the countermeasure	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

As the virtual BWR-5 was supposed to be located at the center of TRDC which is in Ibaraki Prefecture, the data of population, agricultural and livestock products and land utilization were taken from the statistical data of Ibaraki Prefecture [52,53].

3.2. Estimated cost per severe accident

The normalized costs per severe accident of each accident sequence are shown with their CFFs in Fig. 3. The costs per severe accident of each accident sequence are normalized using the average cost per severe accident.

$$NCPSA_p = \frac{CPSA_p}{\overline{CPSA}} \tag{30}$$

where $NCPSA_p$ represents the normalized cost per severe accident of the pth accident sequence. It is to be noted that many accident sequences with small CFFs gave large costs per severe accident. This figure shows both the occurrence probabilities (CFFs) and the consequences (costs per severe accident) which are significant indicators to assess the risk regarding severe accidents in nuclear power plants. 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 CFF and the cost per severe accident, 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.

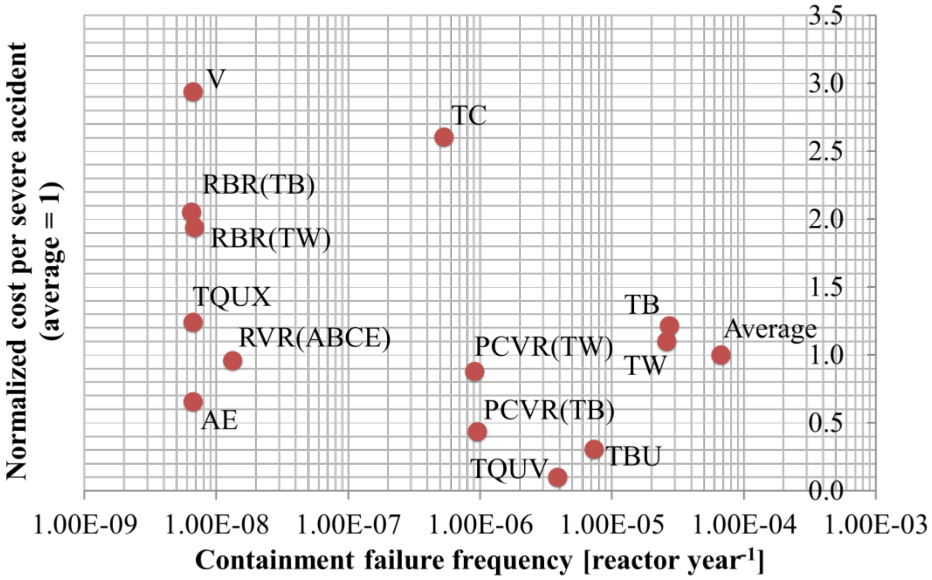

Fig. 3 Normalized costs per severe accident and CFFs of each accident sequence

The breakdowns which show the relative sizes of each component of the cost per severe accidents of each accident sequence are shown in Fig. 4. In the figure, accident sequences were sorted by their total cost per severe accident in ascending order. When the release is very small, like in the case of TQUV, all components estimated by using constant values, i.e., alternative source cost, harmful rumor cost and decommissioning cost, dominate the cost per severe accident. When the release is relatively small (PCVR(TB), AE, PCVR(TW) and RVR(ABCE)), the cost regarding stochastic effects from radiation exposure (radiation effect cost) dominates the cost per severe accident because the annual dose rates in most area are not high enough to trigger the relocation, and thus only limited area needs decontamination since the decontamination is assumed to be done only in the relocated area. When the release is moderate (TW, TB, TQUX, RBR(TB) and RBR(TW)), the radiation effect cost, the relocation cost and the decontamination cost are almost the same and the sum of these three costs cover 80 – 90% of the cost per severe accident. This is because the relocated area and the relocation period increase with the amount of source term released, which consequently enlarge the decontamination target area. When the release is relatively large (TC, V), the relocation cost and the decontamination cost dominate the cost per severe accident because the relocated area and the decontamination target area are significantly enlarged according to the increase of amount of source term while the increase of collective dose which determines the radiation effect cost is rather moderate.

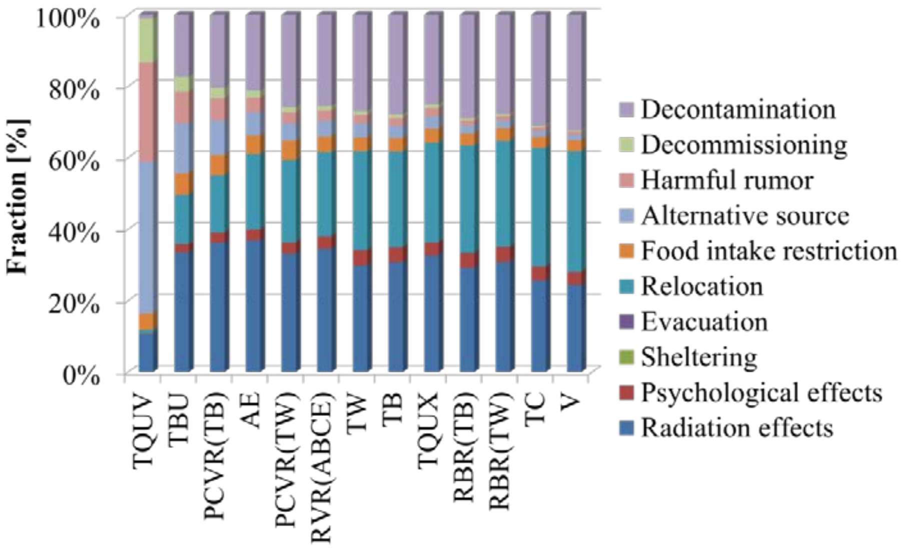

Fig. 4 Breakdown of cost per severe accident of each accident sequence

Fig. 5 shows the breakdown of the average cost per severe accident calculated by equation (29). The radiation effect cost accounts for the greatest proportion of the average cost per severe accident, followed by the decontamination cost and the relocation cost. One reason that the radiation effect cost was very high is the usage of WTP which normally leads to a more conservative result comparing with the human capital method. The radiation effect cost was less than one-fifth of the current result in Silva et al. [40] where the human capital method was used for the cost estimation. The reasons of the large relocation cost and decontamination cost are that the relocated population, relocated area and decontamination target area were very large, and the relocated period was relatively long, as stated above. Other costs were relatively small comparing with the three costs mentioned above. From Figs. 4 and 5, it can be concluded that the radiation effect cost, the decontamination cost and the relocation cost are the three components that dominate the cost per severe accident. Therefore, measures related to radiation protection, relocation and decontamination have to be carefully considered in the decision makings related to severe accident consequence management.

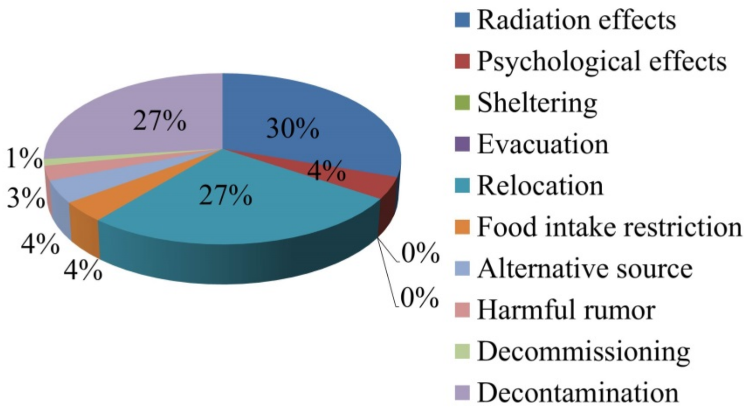

Fig. 5 Breakdown of average cost per severe accident

3.3 Influence of discount rate

As ExternE suggested a range of discount rate of 0% – 4.5% [23], four sets of calculations were performed where discount rates for components of the cost per severe accident that represents the long term effects were set to 0% (reference case), 1%, 3% and 5%. The changes of the fractions of each cost composing the cost per severe accident when the discount rates of 0%, 1%, 3% and 5% are shown in Fig. 6. It can be observed that in all cases the three important are still radiation effect cost, decontamination cost and relocation cost. However, the radiation effect cost significantly decreased and fell below the decontamination and relocation costs when the discount rate is more than 1%. As the average decontamination and relocation periods are relatively short comparing with the period of consideration of the radiation effects, the fractions of decontamination and relocation costs relatively increase with the discount rate. The changes of other costs were not significant as their percentages are relatively small. It can be concluded that the discount rate has a certain level of influence to reduce the radiation effect cost, though the radiation effect cost remains an important component of the cost per severe accident as well as the decontamination cost and relocation cost even in the case of 5% discount rate.

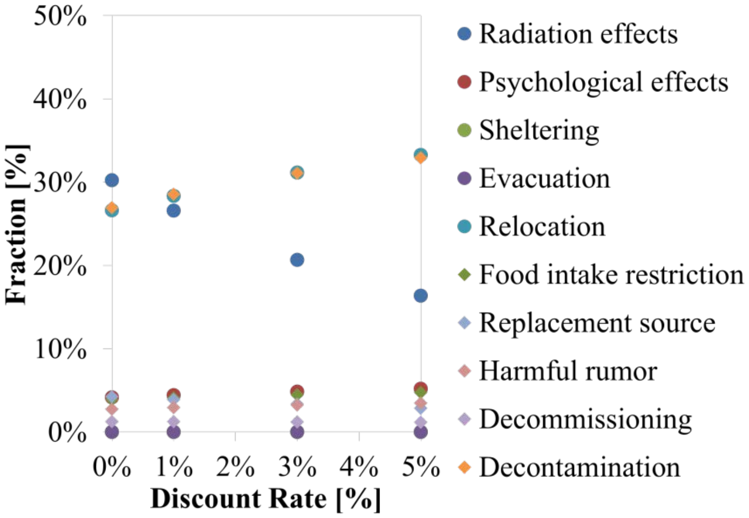

Fig. 6 Changes of the fractions of each cost composing cost per severe accident with different discount rates

3.4. Sensitivity analysis

Sensitivity analysis was performed in order to verify the influences of each parameter to the cost per severe accident. Ceteris paribus sensitivity analysis, where a single parameter is varied while all other parameters are fixed, was selected as it is simple and can be understood easily. We held the sensitivity analyses of following parameters.

1) Radiation effect estimation method
2) Exposure dose reduction factor
3) Psychological effect estimation method
4) Period of compensation for psychological effects
5) Dose level of recommending sheltering
6) Dose level of recommending evacuation
7) Dose level of recommending relocation
8) Dose level of returning home (for relocated people)

9) Period of loss of income
10) Dose of recommending restriction of food intake
11) Period of using alternative power source
12) Type of alternative power source
13) Estimation method of cost regarding harmful rumor
14) Waste management method (volume reduction factor)
15) Decontamination target area
16) Decontamination methods
17) Decontamination unit costs
18) Number of reactor units under consideration
19) Population density of the target site
20) Available factor

The dose levels of recommending relocation and returning home, the assumptions of the number of units under consideration, and the waste management methods, were among the most sensitive parameters. Their sensitivity analysis results are described below.

For the sensitivity analysis of the dose levels of recommending relocation, it was increased from 20 mSv/y (reference) to 100 mSv/year since it is the upper threshold of the reference level of emergency exposure recommended by ICRP [46]. The dose level of returning home was reduced from 20 mSv/y (reference) to 1 mSv/year or 5 mSv/year because 1 mSv/y is the lower threshold of the reference level of existing exposure recommended by ICRP [51] and 5 mSv/y is the lower threshold of the dose band of voluntary relocation in the Chernobyl accident [54]. The cost per severe accident was highly sensitive to both dose levels. It decreased by 40% when the dose level of recommending relocation was increased to 100 mSv/year, and increased by 30% and 180% when the dose level of returning home was decreased to 5 and 1 mSv/year, respectively. This is because the dose of recommending relocation determines the number of relocating population and the target area of relocation, and the dose level of returning home determines the period of relocation. If the dose level of recommending relocation is set higher, the area of which the integrated exposure dose reaches the dose level of recommending relocation will be smaller. Thus the relocation population becomes smaller. If the dose level of returning home is set lower, it takes time until the integrated exposure dose of the relocated area decreases to the determined dose level. Then the relocated population has to relocate for a longer period. This implies that the selection of these two dose levels is one of the most important task during the post-accident management since it can significantly increase or decrease the consequences of the accident.

Next sensitive parameter was the number of reactor units under consideration. As observed in 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 (including unit 1 – 4 of the Fukushima Daiichi Nuclear Power Station), a nuclear power station was assumed to possess 54/17 = 3.18 units. When assuming the same severe accident happening in all the reactor units located in the same site by multiplying the source term by 3.18 times, the cost per severe accident increased by 170%. It is to be noted that the cost per severe accident was not precisely proportional to the amount of the source term. The reason is that the relocation area and the relocation period which determine the two large components of the cost per severe accident: the decontamination cost and the relocation cost, are not in a linear relationship with the amount of the source term. The fact that this parameter is a sensitive parameter underscore the lesson learned from 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 in case this worst case scenario happens.

The waste management method (volume reduction factor) was also the parameter with high sensitivity. When the wastes were discarded without burning or evaporation to reduce their volumes (volume reduction factor = 1), the decontamination cost became 3.8 times the reference case. This led to a 110% increase in the cost per severe accident. This is because the unit waste management cost was calculated from the waste management cost of the extremely low level radioactive waste from the decommissioning of typical 1100 MWe BWR which is relative high [55] (this conservative assumption is adopted mainly because of lack of data and further discussion may be needed). Thus the waste management cost dominates the decontamination cost and have large influence on the cost per severe accident as the decontamination cost is an important component of the cost per severe accident. However, note that it is quite impractical to discard the wastes without burning or evaporation. This implies that the conditions must be carefully selected in the actual assessment. Note that these three parameters were the most sensitive parameters under specific conditions set by the authors based on the real situations observed in the Fukushima Accident and information obtained from literatures. Changing the conditions may change the order of importance of the three parameters, or other parameters might become more sensitive to the cost per sever accident. Sensitivity analysis and uncertainty analysis are among the issues on which further studies are needed.

3.5. Comparison of cost per severe accident and source term

Relations between the costs per severe accident and the amounts of source term of each accident sequence, which are sometimes used to estimate the consequence of the accidents without performing level 3 PRA, are plotted on Fig. 7. Amounts of source term of each accident sequence were obtained by adding the amounts of released iodine with 40 times of the amounts of released cesium, as determined in the International Nuclear Events Scale (INES) user's manual [56]. Each point of the graph corresponds to the each severe accident sequence and associated source term listed in Table 2. The costs per severe accident and the amounts of source term of each sequence are relatively in linear relationship ($R^2 > 0.95$). However, sometimes the cost per severe accident of one sequence is larger while the amount of source term is smaller than the other one, like in the case of the two accident sequences magnified in Fig. 7. This is also observed in Silva et al. [57]. This is because even though the amounts of source term are small, if the releases start very early or the release durations are very long, many costs, e.g., decontamination cost, relocation cost, radiation effect cost can rise. When the release starts early, the public can be exposed to the radiation before sheltering or evacuating, which consequently increase the radiation effect cost. Additionally, this early exposure will increase the annual exposure dose which is used to judge the relocation, and will finally raise the relocation cost and decontamination cost. In this case, if the release duration is very short, being sheltered until the release stops can avoid a great deal of the early exposure, and the cost per severe accident will not significantly rise. However, with long release duration, the public may be forced to evacuate during the release, which leads to large early exposure doses and higher radiation effect cost. From these facts, the cost per severe accident can be concluded more comprehensive than the amount of source term as an index to quantify the consequences of severe accidents. The reasons are: (1) the cost per severe accident can evaluate not only the amount of source term but also the release time and release duration, and (2) it can take into account the increase in the decommissioning cost, the alternative source cost and the damage by harmful rumor while the amount of source term cannot. Moreover, it provides the breakdown of the consequences of severe accidents (the relative sizes of each consequence) and shown in Figs. 4 and 5 which is a useful piece of information for severe accident consequence management. However, Fig. 7 implies that the source term is still a good index when one wants to approximately estimate the severe accident consequence. Indeed, the regulatory guide YVL 2.2 in Finland requires the release amount of Cs-137 below 100 TBq [58].

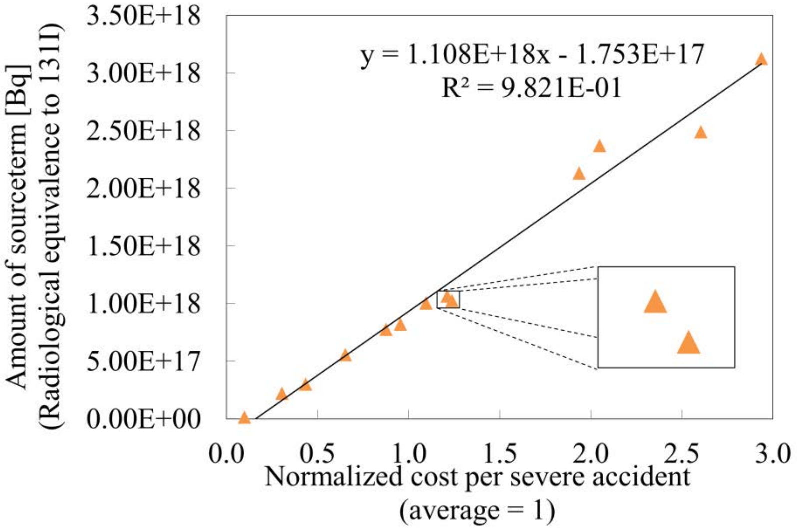

Fig. 7 Relations between costs per severe accident and amounts of source term of each accident sequence

4. Utilizations of cost per severe accident as risk information

4.1. Optimization of radiation protection countermeasures

In the conventional way, the countermeasures that can minimize the individual exposure dose have been selected as the optimum ones. Economic, social and environmental impacts resulted from severe accidents are not considered. Optimization of radiation protection countermeasures using the cost per severe accident which can take into account all consequences mentioned in section 2.3 is introduced in this section.

If the objective of the optimization is to minimize the individual exposure dose, the optimization will be carried out in each accident sequences. However, in actual situation, especially when the external events are the initiating events, there is a possibility of two or more different accident sequences occurring at the same time. In addition, there might be a chance of an occurrence of a severe accident beyond the scope of assumption. For these reasons, we selected the average cost per severe accident for the optimization of the countermeasures since it can represent the overall consequences of severe accidents. The dose levels of recommending sheltering, evacuation and relocation, and the dose level of returning home that minimize the average cost per severe accident were searched.

Table 4 shows the relative changes of each cost from the reference case when the dose levels of recommending sheltering, evacuation and relocation and the dose level of returning home are increased or decreased. The optimum dose levels of recommending the sheltering, evacuation and relocation, and dose level of returning home, which minimized the costs per severe accident in each case, were less than 1 mSv/week, less than 20 mSv/week, 100 mSv/year and 20 mSv/year, respectively, since they gave the lowest cost per severe accident.

For sheltering and evacuation, the cases with the lowest dose levels for recommending those countermeasures were optimum. The cost per severe accident decreased when the dose levels were lowered because the radiation effect cost provided a large proportion of the cost per severe accident and its slight decrease is much larger than the sum of the increases in all other costs. However, these levels do not significantly influence the total cost per sever accident partly due to no changes in the decontamination cost and the relocation cost.

For dose levels for recommending relocation and returning home, it can be concluded that the higher dose levels gave the smaller cost per severe accident. It was not the change in radiation effect cost but the changes in relocation cost and decontamination cost that dominated the change in the cost per severe accident. Following the recommendation by ICRP [51], the dose level of starting the relocation which is supposed to be used in the period of emergency exposure must not exceed 100 mSv/year, and the dose level of returning home which is supposed to be used in the period of existing exposure must not exceed 20 mSv/year. Therefore, the optimized dose levels of recommending relocation and returning home under such conditions were concluded 100 mSv/year and 20 mSv/year, respectively.

Table 4 Relative changes of each cost from reference case when dose level of recommending countermeasures were changed

Costs	Dose level of recommending sheltering (reference case: 10 mSv/week)		Dose level of recommending evacuation (reference case: 50 mSv/week)		Dose level of recommending relocation (reference case: 20 mSv/year)	Dose level of returning home (reference case: 20 mSv/year)	
	1 mSv/week	20 mSv/week	20 mSv/week	100 mSv/week	100 mSv/year	5 mSv/year	1 mSv/year
Radiation effect cost	-0.435%	0.276%	-0.771%	0.798%	22.7%	-16.5%	-34.2%
Psychological effect cost	0.0667%	-0.0157%	0.0747%	-0.0359%	-88.0%	0.00%	0.00%
Sheltering cost	221%	-51.8%	-41.2%	19.8%	0.00%	0.00%	0.00%
Evacuation cost	0.00%	0.00%	113%	-54.2%	0.00%	0.00%	0.00%
Relocation cost	0.00%	0.00%	0.00%	0.00%	-70.7%	112%	622%
Food intake restriction cost	0.00%	0.00%	0.00%	0.00%	-6.83%	108%	494%
Decontamination cost	0.00%	0.00%	0.00%	0.00%	-86.3%	0.00%	0.00%
Total cost per severe accident	***-0.117%***	***0.0794%***	***-0.215%***	***0.231%***	***-39.6%***	***29.9%***	***180%***

When these results are applied to the decision making of the radiation protection countermeasures, a number of people will be recommended to shelter and evacuate in order to minimize the radiation effect cost. One week later, people whose exposure doses are expected to exceed 100 mSv/year (the number will not be very large) will start relocation. As 20 mSv/year is used as the dose level of returning home, most people will move back to their homes soon.

It should be kept in mind that these results were achieved from the viewpoint of minimizing the cost per severe accident. Simulations must be performed in parallel to confirm that people are prevented from the deterministic effects regarding radiation exposure by all possible countermeasures. Furthermore, since the cost per severe accident was not calculated in the view point of individuals, there might be a problem of feeling of unfairness which may lead to public non-acceptance of the decisions made regarding the radiation protection. For example, a person whose expected exposure dose exceed 20 mSv/year but does not reach 100 mSv/year during the decision making of relocation cannot relocate. His/her exposure dose may exceed 20 mSv/year while those of the relocated people may not. There is no wonder that he/she will feel that the decision made is unfair and probably will not accept it. The issue of public acceptability of the post-accident radiation protection countermeasures was pointed out by Lochard et al. [59] considering the situations after the Chernobyl Accident. Further studies must be made to clearly identify the issue taking into account the situations after the Fukushima Accident and to find a solution toward it.

4.2. Estimation of effects of accident management strategies

CFFs and source term data used above are those without consideration of accident management (AM). This is because there is no assurance that the add-on equipment for the AM has adequate resistance to earthquake. As the AM is normally considered in the internal event PRA, it seems meaningful to try estimating the effects of the AM strategies by observing the reductions of the CFFs and the costs per severe accident. We assumed that all the systems related to AM are earthquake-proof. The AM strategies considered in level 1 and 2 internal event PRAs [60,61] were taken into consideration. In the level 1 PRA, many accident management strategies were considered, including alternative reactivity control, automation of reactor depressurization system, alternative water injection, high pressure resistance containment ventilation system and optimization of power supply system. In the level 2 PRA, the effects of the alternative water injection, the high pressure resistance containment ventilation system, recovery of residual heat removal system, recovery of power supply and ECCS were considered.

First, the reduction of the total CFF was estimated. We assumed that each accident management strategy reduces CFFs of related accident sequences at the same rate as those of the internal event PRA. The total core damage frequency (CDF) decreased by 74%, and finally the total CFF decreased by 82%. Note that the decrease of the total CFF regarding accident management shown above was determined under specific conditions, and large uncertainties which can affect the results remain.

Then the reduction of the cost per severe accident was estimated. In the cases of recovery of residual heat removal system and high pressure resistance containment ventilation system after core damage, even though the containment is intact, very small amount of radioactive materials can be released to the atmosphere. As Ishikawa et al. [62] provided the source term data of these cases, we selected the related accident sequences and held the consequence assessment. The breakdown of the cost per severe accident of the accident sequence TB with the high pressure resistance containment ventilation system successfully operated is shown in Fig. 8 as a sample result. Since the amounts of the source terms were smaller than the normal case by about one order for iodine and two orders for cesium, and the releases were controlled to be occurring in short periods (10 – 20 minutes), the consequent health effects were very little and very few people sheltered, evacuated and relocated.

Thus the costs regarding: radiation effects, psychological effects, sheltering, evacuation, relocation, food intake restriction and decontamination were nearly negligible. However, other costs, namely the increase in decontamination cost, the alternative power source cost and the cost regarding harmful rumor remained. This result implies that although the release of the radioactive materials is so small and controlled that the health effects and the impacts from radiation protection countermeasure can nearly be ignored, some consequences still exist. The cost per severe accident was finally reduced by 94%. The dominant cost were the costs regarding the alternative power source and harmful rumor while it had been the radiation effect cost, the decontamination cost and the relocation cost in the case without the consideration of accident management. The results in other accident sequences showed the same trend.

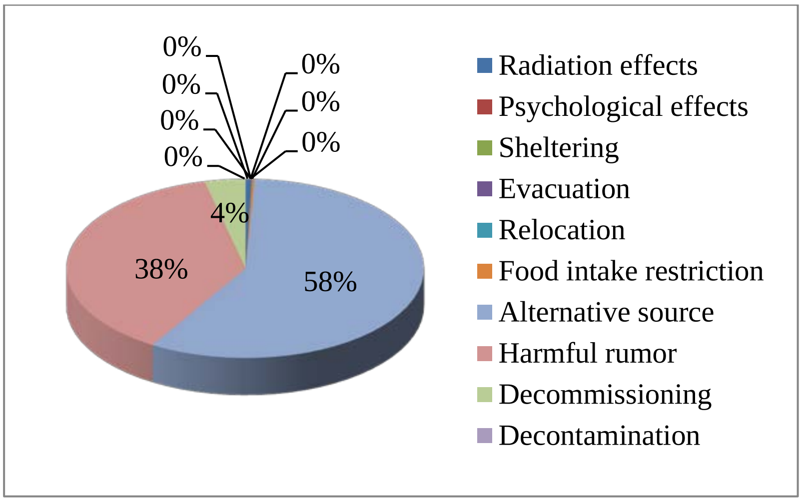

Fig. 8 Breakdown of cost per severe accident of accident sequence TB with consideration of high pressure resistance containment ventilation system

As the consequence assessment of the severe accident is enabled, not only the decrease of the CFFs but also the decrease of the cost per severe accident, i.e., the decrease of the consequences can be investigated. Having both the information of the decreases of CFFs and the decreases of the cost per severe accident may enable the cost-benefit consideration of various AM strategies. The accident management might also reduce the source terms even after the containment damage, though it is not considered in this study due to lack of source term data in such situations. If the reductions of the source terms by the accident managements after the containment damage are evaluated by experiments or simulations, the effects of the accident management strategies will be shown as more significant.

5. Conclusions

The cost per severe accident which is an index that can take into account various kinds of consequences of severe accidents and its calculation methodology was introduced.

- The methodology to convert various consequences of severe accidents into a monetary value, and integrate them to form the cost per severe accident was proposed.
- As a case study, the cost per severe accident of a virtual 1,100 MWe BWR-5 was calculated.
- The case study showed that the cost per severe accident can play an important role as an indicator to assess the risk regarding severe accidents in nuclear power plants along with CFFs.

- The cost regarding stochastic effects from radiation exposure (radiation effect cost), the relocation cost and the decontamination cost were the three largest components of the cost per severe accident.
- The discount rate has a certain level of influence to reduce the radiation effect cost, though the radiation effect cost remains as an important component of the cost per severe accident as well as the decontamination cost and relocation cost even in the case of 5% discount rate..
- The sensitive parameters to the cost per severe accident were the dose levels of recommending relocation and returning home, the assumptions of the number of reactor units under consideration, and the waste management method.
- The cost per severe accident was concluded more comprehensive than the amount of source term as an index to quantify the consequences of severe accidents.

In addition, the optimum dose levels of each radiation protection countermeasure were discussed based on the cost per severe accident as the risk information. The effects of the accident management strategies were estimated by observing the reductions of the CFFs and the costs per severe accident. Such approach may enable the cost-benefit considerations of various AM strategies.

One of the limitations of this research is that, the difference of various conditions/situations among individuals was neglected. This can cause a problem of unfairness and hence an additional psychological effect. This issue should be carefully considered when the cost per severe accident is used to optimize the radiation protection countermeasures. It may be solved by collaboration of multi-disciplinary professionals. In order to use the present methodology to estimate the effects of accident management strategies, not only the containment failure frequency but also the reduction of source terms by accident management after the failure of the containment should be provided as database.

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