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A Backward Method to Estimate the Dai-ichi Reactor Core Damage Using Radiation Exposure in the Environment

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ABSTRACT

The Fukushima accident resulted in the melting of the reactor core due to loss of supply of coolant when the reactor stopped from operating conditions. The earthquake and tsunami caused loss of electricity due to the flooding that occurred in the reactor. The absence of the coolant supply after reactor shutdown resulted in heat accumulation, causing the temperature of the fuel to rise beyond its melting point. In the early stages of the accident, operator could not determine the severity of the accident and the percentage of the reactor core damaged. The available data was based on the radiation exposure in the environment that was reported by the authorities. The aim of this paper is to determine the severity of the conditions in the reactor core based on the radiation doses measured in the environment. The method is performed by backward counting based on the measuring radiation exposure and radionuclides releases source term. The calculation was performed by using the PC-COSYMA code. The results showed that the core damage fraction at Dai-ichi Unit 1 was 70%, and the resulting individual effective dose in the exclusion area is 401 mSv, while the core damage fraction at Unit 2 was 30%, and the resulting individual effective dose was 99.1 mSv, while for Unit 3, the core damage fraction was 25% for an individual effective dose of 92.2 mSv. The differences between the results of the calculation for estimation of core damage proposed in this paper with the previously reported results is probably caused by the applied model for assessment, differences in postulations and assumptions, and the incompleteness of the input data. This difference could be reduced by performing calculations and simulations for more varied assumptions and postulations.

INTRODUCTION

The Fukushima Dai-ichi nuclear power plant (NPP) consists of six boiling water reactors (BWRs). The first unit is a 460-MWe BWR/3 that reached its first criticality in October 1970. The second unit is a 784-MWe BWR/4 that reached its first criticality on July 18, 1974. The third and the forth units are also 784-MWe BWR/4's but they reached their first criticalities on different dates. The third unit reached its first criticality on March 27, 1976, while the fourth unit reached first criticality on October 12, 1978. The fifth unit is also a 784-MWe BWR/4 and reached its first criticality on April 18, 1978. The last unit is a 1100-MWe BWR/5 that reached its first criticality on October 24, 1979. Those reactors use Mark I containments, except for the last unit which uses Mark II containment [1]

At the time of the April 2011 Fukushima earthquake, Units 1-3 were operating and Units 4-6 were in refueling/maintenance outages. All of the operating reactors (Units 1-3) were shutdown/ scram automatically after the earthquake [1]. The sequence of the subsequent events is as follows. In the early

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stages, early core degradation occurred with core heat-up due to the decay of fission products, followed by core material oxidation by steam, liquefaction and melting of core materials, release and transport of fission products, and loss of core geometry. Afterwards, inside the vessel, massive melt formation occurred in the core, followed by the relocation of the melt to the lower head, formation of molten pool with crust, gap cooling, thermal attack on vessel wall, and finally vessel failure. Then, outside the now-failed vessel, molten core-concrete interaction occurred, along with behavior change of concrete basement and cooling of the debris bed and pools. The resulting source term was transported in the cooling system, in the containment, and finally experienced containment bypass. Moreover, radiological contamination spread into the environment [2-4]. During the early phases of the accident, experts could not determine how severe the accident was. They could not measure the core damage percentage because the radiation level around reactor was very high. The available data consisted only of the radiation dose measured in the environment that was reported by the authorities.

Prior to this work, the failure of the core have been estimated and assessed by several experts. Several methods have been applied to find how large the damage of the reactor core was, because the accidents occurred in a complicated manner [5,6]. The method used by previous researchers was to estimate core damage by probabilistic and deterministic methods. The probabilistic method is a method for calculating the core damage frequency. The deterministic method is a method to calculate core damage based on certain assumptions and postulations on the initiating event and the type of accidents. This method requires detailed data on reactor condition. This method is time-consuming and involves intricate calculations in obtaining the source-term data.

The consequences and risks to the environment are calculated based on the source term. The advantage of this method is that it gives more accurate data on reactor conditions. The disadvantage of this method is that when it is used for assessment of severe accident management, such as for the Fukushima Dai-ichi accident, it takes more time. In a severe accident conditions, it is necessary to be fast in estimating the severity of the reactor accident, so that the operators can more quickly implement the Emergency Operating Procedures (EOP) or Severe Accident Management Guidelines (SAMGs).

This paper attempts to propose a method to obtain a first estimate that is obtainable early and rapidly, but also sufficiently accurate, of the severity of the conditions of the reactor core. The method is carried out by counting backwards, starting from the radiation dose measured in the environment and then regressing to determining the source term released from the containment. The backward method was applied to the calculation of core damage, because it made it possible for the result of the estimates to be compared to real-time conditions that occurred around the NPP location in Fukushima.

The goal of this assessment is to estimate the extent and severity of accidents or core damages based on the measured environment radiation dose. A case study is conducted based on the Fukushima accident data, by the method of counting backwards from measured doses associated with the fission products released to the atmosphere. The meteorological data of Fukushima and the source term of the core damage are used in this assessment.

The calculation starts by calculating the fission products released to the atmosphere based on radiation dose measurements [7]. The fission products release is calculated based on source term and meteorology data as input data. The source term for the Unit 1 reactor was estimated by using the severe accident postulation models, in which the core melt fraction is assumed to be in the 50-80% range.

The postulated Design Basis Accident (DBA) was used to calculate the source term for Units 2-3, for which their core damage fractions were assumed to be between 20% and 40%. Core damage fraction estimation results obtained using the backward method were compared to the estimations by other researchers.

EXPERIMENTAL METHODS

Assessment modeling

The assessment modeling in this paper uses the backward method, following the steps shown in Fig. 1. The calculation starts by calculating the fission products released to the atmosphere at Fukushima area based on the radiation dose which was measured in the environment (step 1). Using local meteorological data as input data, the activities of the fission products associated with the source term are estimated (steps 2-4). The postulated reactor accident and an estimate of the core melt severity were assumed, and the results of calculations based on the assumptions are compared to the known or reference data on the fission products dispersed in the atmosphere and in the reactor core (steps 5-8).

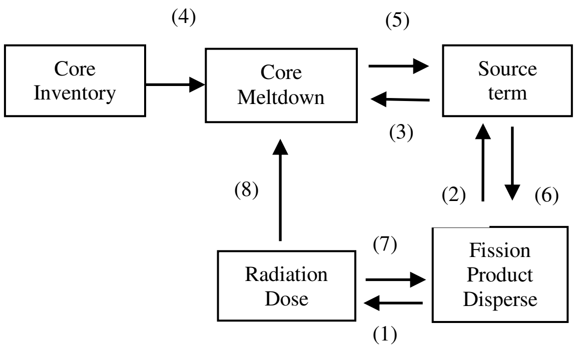

Fig. 1. Flowchart of assessment modeling.

Core inventory calculation

Based on the data in Table 1, the core inventory is calculated using Origen 2.2. Other inputs for the calculation are the amount and composition of uranium for each reactor, average burnup, conditions at the end of a full power cycle, irradiation time, and reactor power [7,8].

Table 1. Fukushima Dai-ichi Reactors Specifications [8]

Unit	Electric / Thermal Power (MW)	Type of Reactor	Number of fuel rods	
			Core	Spent fuel
Unit 1	460 / 1380	BWR/3	400	292
Unit 2	784 / 2381	BWR/4	548	587
Unit 3	784 / 2381	BWR/4	548	514

The fuel assemblies are about 4 m long. There are 400 assemblies in Unit 1, 548 in Units 2-5 each, and 764 in Unit 6. Each assembly consists of 60 fuel rods containing uranium oxide fuel enclosed by zirconium alloy cladding. Unit 3 has a partial core of mixed-oxide (MOX) fuel (32 MOX assemblies, 516 LEU). Normally, they all run at a core outlet temperature of 286°C under a pressure of 6930 kPa with a dry containment pressure of 115-130 kPa.

For estimating the core inventories, the ^{235}U enrichment is taken as 3.0% for Dai-ichi Units 2-3 and less than 3% for Unit 1. The burnups and fuel loads used are an average burnup of 30 000 MWd/tU and and a fuel load of 68 tU for Unit 1, and 23 000 MWd/tU and 94 tU for Unit 2 and Unit 3 [1,8]. A full power cycle is assumed as involving three years of irradiation. The result of the calculation is an estimation of the activity of the fission products which form in the fuel. The results of the calculations are shows in Table 2.

Table 2. Activities of Fission Products in Core Inventory [8]

Nuclide	Core Inventory Activity (Bq)		
	Unit-1	Unit-2	Unit-3
^{85}Kr	1.91E+16	3.34E+16	3.34E+16
^{85m}Kr	2.99E+17	5.18 E+17	5.18E+17
^{88}Kr	7.94E+17	1.37E+18	1.37E+18
^{133}Xe	2.48E+18	4.29E+18	4.29E+18
^{135}Xe	7.24E+17	1.25E+18	1.25E+18
^{131}I	1.27E+18	2.19E+18	2.19E+18
^{132}I	1.82E+18	3.15E+18	3.15E+18
^{133}I	2.55E+18	4.41E+18	4.41E+18
^{135}I	2.38E+18	4.12E+18	4.12E+18
^{132}Te	1.78E+18	3.07E+18	3.07E+18
^{134}Cs	3.08E+17	5.32E+17	5.32E+17
^{137}Cs	2.06E+17	3.56E+17	3.56E+17
^{90}Sr	1.36E+17	2.35E+17	2.35E+17
^{106}Ru	9.11E+17	1.57E+18	1.57E+18
^{140}Ba	2.17E+18	3.75E+18	3.75E+18
^{144}Ce	1.64E+18	2.84E+18	2.84E+18

Core damage estimation

Based on the released fission products data, the severity of the core damage is estimated by making assumptions of reactor accident type and severity, and comparing the estimates resulting from using the assumptions in the calculation, with the known data on the amount of fission products dispersed in the atmosphere and in the reactor core. Here, two types of accidents were assumed to have occurred, namely the postulated core meltdown by severe accident for Unit 1 and the DBA (Design Basis Accident) for Units 2 and 3, respectively.

Two severe accident postulations were chosen, namely a severe accident condition with the assumption of 50-80% core damage fraction used for reactor Unit-1, and the DBA condition for Unit-2 and Unit-3 with core damage fraction assumed to be 20-40% [6,7].

Fission product release (source term) estimation

The calculation of fission product release is represented as step 2 in Fig. 1. By assuming a severe accident [5], the source term calculation was carried out using the data in Table 1 and Table 2. The source term is calculated starting from the fission product release from the damaged core, to the cooling system, and then to the containment. The containment is equipped with spray safety systems. The fission product of ^{131}I is first retained in the containment, and partly released into the environment. Fission product release will be reduced by filtering system in the stack into the environment [9]. Based on the fission product release data with the postulated reactor accident, assumptions were made on the core melt severity.

The input data for this calculation are the activity of the fission product in core inventory, assumptions on core damage, release mechanism, and release fraction for each subsystem.

For Unit 1, the source term associated with the postulation was estimated by using the models based on the severe accident scenario, where the assumption of 50-80% core damage fraction is used. Other assumptions made were: the emergency core cooling system (ECCS) did not work; the containment integrity was maintained; the spray systems were not functioning; and: release through the stack occurred without filter system. The release fraction of fission products into the containment was 100% for noble gases, 50% for iodine, and 1% for other nuclides. The calculation was performed for assumptions of core damage fractions of 50%, 55%, 60%, 65%, 70%, 75%, and 80% [6,7]. The calculation's outputs, namely the source term activities associated with those assumptions, are shown in Table 3.

Table 3. Source term (Bq) for Dai-ichi Unit 1

Nuclide	Core damage fraction (%)						
	50	55	60	65	70	75	80
^{85}Kr	9.55E+15	1.05E+16	1.15E+16	1.24E+16	1.34E+16	1.43E+16	1.53E+16
^{85m}Kr	1.50E+17	1.64E+17	1.79E+17	1.94E+17	2.09E+17	2.24E+17	2.39E+17
^{88}Kr	3.97E+17	4.37E+17	4.76E+17	5.16E+17	5.56E+17	5.96E+17	6.35E+17
^{133}Xe	1.24E+18	1.36E+18	1.49E+18	1.61E+18	1.74E+18	1.86E+18	1.98E+18
^{135}Xe	3.62E+17	3.98E+17	4.34E+17	4.71E+17	5.07E+17	5.43E+17	5.79E+17
^{131}I	3.40E+16	3.48E+16	4.08E+16	4.42E+16	4.76E+16	5.02E+16	5.44E+16
^{132}I	2.28E+17	2.51E+17	2.73E+17	2.96E+17	3.19E+17	6.83E+16	3.64E+17
^{133}I	4.45E+17	4.90E+17	5.34E+17	5.79E+17	6.23E+17	6.34E+17	7.12E+17
^{135}I	3.18E+17	3.49E+17	3.81E+17	4.13E+17	4.45E+17	4.76E+17	5.08E+17
^{132}Te	4.55E+17	5.01E+17	5.46E+17	5.92E+17	6.37E+17	6.83E+17	7.28E+17
^{134}Cs	6.38E+17	7.01E+17	7.65E+17	8.29E+17	8.93E+17	9.56E+17	1.02E+18
^{137}Cs	5.95E+17	6.55E+17	7.14E+17	7.74E+17	8.33E+17	8.93E+17	9.52E+17
^{90}Sr	7.70E+16	8.47E+16	9.24E+16	1.00E+17	1.08E+17	1.11E+17	1.23E+17
^{106}Ru	5.15E+16	5.67E+16	6.18E+16	6.70E+16	7.21E+16	7.55E+17	8.24E+17
^{140}Ba	5.43E+17	5.97E+17	6.51E+17	7.05E+17	7.60E+17	7.63E+17	8.68E+17
^{144}Ce	4.10E+17	4.51E+17	4.92E+17	5.33E+17	5.74E+17	6.23E+17	6.56E+17

For Unit 2 and Unit 3, the models used were based on the DBA postulation with core melt fraction assumed to be 20-40%. Further assumptions were: the emergency core cooling system (ECCS) function was limited; containment vessel structural integrity was not compromised; spray systems were still functioning; fission product releases occurred through the stack; and: stack filter system was still functioning. In the containment, spray system reduced iodine nuclides by 46%. The efficiency of the filter in the reactor stack is 0% for noble gases, 99% for iodine (organic), and 99% for other nuclides (Te, Cs, Rb). The calculation was performed for core damage fraction assumptions of 50%, 55%, 60%, 65%, 70%, 75% and 80% [7]. The source term activities obtained under those assumptions are shown in Table 4.

Table 4. Source terms (Bq) for Dai-ichi Unit 2 and Unit 3

Nuclide	Core damage fraction (%)				
	20	25	30	35	40
^{85}Kr	6.68E+15	8.35E+15	1.00E+16	1.17E+16	1.34E+16
^{85m}Kr	1.04E+17	1.30E+17	1.55E+17	1.81E+17	2.07E+17
^{88}Kr	2.74E+17	3.43E+17	4.11E+17	4.80E+17	5.48E+17
^{133}Xe	8.58E+17	1.07E+18	1.29E+18	1.50E+18	1.72E+18
^{135}Xe	2.50E+17	3.13E+17	3.75E+17	4.38E+17	5.00E+17
^{131}I	4.70E+12	5.88E+12	7.05E+12	8.23E+12	9.40E+12
^{132}I	3.14E+13	3.93E+13	4.71E+13	5.50E+13	6.28E+13
^{133}I	6.14E+13	7.68E+13	9.21E+13	1.07E+14	1.23E+14
^{135}I	1.01E+16	1.26E+16	1.51E+16	1.76E+16	2.01E+16
^{132}Te	1.45E+16	1.81E+16	2.17E+16	2.54E+16	2.90E+16
^{134}Cs	2.03E+16	2.54E+16	3.04E+16	3.55E+16	4.06E+16
^{137}Cs	1.90E+16	2.37E+16	2.84E+16	3.32E+16	3.79E+16
^{90}Sr	1.06E+13	1.33E+13	1.60E+13	1.86E+13	2.13E+13
^{106}Ru	7.12E+12	8.90E+12	1.07E+13	1.25E+13	1.42E+13
^{140}Ba	7.50E+13	9.38E+13	1.13E+14	1.31E+14	1.50E+14
^{144}Ce	5.68E+13	7.10E+13	8.52E+13	9.94E+13	1.14E+14

Fission product dispersion and dose calculation

The calculations are based on the observed doses. The calculation of fission product release to the atmosphere was performed using PC-Cosyma code [7]. PC-Cosyma is a dose consequence assessment computer code, with segmented Gaussian diffusion model using source data derived from accident scenarios. This computer code can be used to calculate the following: hourly changes in meteorological conditions; horizontal and vertical dispersion parameter for various surface roughness as a release height function; plume rise; building-induced downwash, and: radioactive decay and daughter in-growth. The input data used in the calculation process are the source term, meteorological data, and the release height. The meteorological data consists of wind direction, wind speed (m/s), season (winter or summer), stability category, altitude at which the wind speed is measured, and surface roughness (smooth terrain or rough terrain).

Using local meteorological data, the fission product dispersion (air dispersion and deposition on the ground surface) and dose could be calculated for various pathways (cloud shine and ground shine) [10,11].

RESULTS AND DISCUSSION

Core inventory

Fission product activities in the inventory for the cores of the Unit 1, Unit 2, and Unit 3 reactors are shown in Table 2. Fission product activities in the core inventory are affected by the amount and composition of uranium fuel, reactor power or burnup, and irradiation time. Table 2 shows the inventory of fission products, such as noble gases (Kr and Xe), iodine isotopes, and metallic fission products (Sr, Cs, Ba), inside the core. As shown in Table 2, the activity of fission products in the Unit 2 and Unit 3 reactor cores are higher than in Unit 1's core. The core of Unit 2 and Unit 3 has 548 fuel assemblies each, while Unit-1 has 400 fuel assemblies. Fission product activities in the core are influenced by the weight of uranium; the higher the amount of uranium is, the higher the activity is.

Reactor source term

By assuming a severe accident, the source term calculations were carried out using the data in Table 3 and Table 4. Table 3 shows the calculation results of fission products release under severe accident scenarios, using data on Table 1 and Table 2. It shows that the source term of Unit 1 has higher activity than that of Unit 2 and Unit 3. From comparison of the activity of inventories in Table 2, it is seen that the source term in Unit 3 was the smallest one. The results of source term calculation depend on the core integrity and the occurrence of core failure. Since the source term for Unit 1 was estimated using the models based on severe accident where it is assumed that 50-80% of the core melts, even though Unit 1 has the smallest core inventory activity, it releases the most fission products to the air.

Calculations for Unit 2 and Unit 3 used models based on the DBA postulations where the core melt is assumed to be 20-40%. In addition, the containment integrity also influences the source term release. Containment integrity corresponds to the function of the stack HEPA filter. If the containment is damaged, it can be considered that the filter is not functioning properly, although in normal condition a HEPA filter could capture 90% of the iodine and 99% of other fission products. Source term calculation results depend on the postulations and assumptions on the magnitude of core damage. The level of confidence in the condition that occurs will also result in different calculations such as pessimistic calculations or optimistic calculations.

Fission product dispersion and radiation dose in the environment

Based on these radiological observations, the calculation of fission products releases in the atmosphere at Fukushima area was performed. As the basis for calculating the dose rate, the value of 50-400 mSv, obtained from dose monitoring on 15-16 March 2011 [6,8], was used. The assumed value of the dose was observed within a radius of 500 m from the Unit 1, Unit 2, and Unit 3 reactors. By using the meteorological data at the Fukushima area when the doses were measured, fission products dispersion has been estimated. Calculations can be performed for different core damages, and calculation based on data from experiments can produce a more accurate results; it will more accurately estimate the core damage and proper functioning of safety systems inside a reactor.

The dose calculations were performed for short-term individual effective dose and long-term individual effective dose for each radius [12]. Exposures in long-term individual doses were modeled through cloud shine and ground shine pathways, while the calculations for the long-term doses were modeled through ground shine pathway (via the food chain). The potential exposure situation for a nuclear reactor facility was not a typical accident affected by the fuel in the core which releases radioactive material to the environment [13]. Thus, the effects to the public and the types of consequences may be different.

The dose data in Table 5 indicates a short dose in the range of 24-48 hours after the accident and calculated for each unit. Dose calculation results at 800 m (exclusion area) for Unit 1 ranges between 140 to 470 mSv for the core damage fractions in the 50% to 80% range. The backward method was based on real-time measured dose to estimate the core damage. Based on the measured dose in the environment in the exclusion area of Unit 1, the core damage can be estimated. Based on Table 5 and Fig. 2 for real-time measured dose of 385 to 400 mSv, the core damage for Unit 1 was estimated to range from 50% to 70%. IAEA reported that core damage fraction in Unit 1 was 70% on the b sis of the measured dose of approximately 400 mSv [6,8,14]. It indicates that the backward method in this paper can estimate the core damage fraction and the severity of accident.

Table 5. Short term individual effective dose vs distance on various core damaged on Dai-ichi Unit-1

Distance (km)	Short term individual effective dose vs distance for various core damage fractions for Dai-ichi Unit-1 (mSv)						
	50%	55%	60%	65%	70%	75%	80%
0.5	1.48E+02	1.67E+02	3.49E+02	3.82E+02	4.01E+02	4.40E+02	4.69E+02
1	1.14E+02	1.29E+02	2.68E+02	2.93E+02	3.15E+02	3.38E+02	3.60E+02
3	5.89E+01	6.69E+01	1.39E+02	1.53E+02	1.64E+02	1.76E+02	1.87E+02
5	3.24E+01	3.67E+01	7.66E+01	8.38E+01	9.02E+01	9.67E+01	1.03E+02
10	1.16E+01	1.32E+01	2.75E+01	3.01E+01	3.24E+01	3.47E+01	3.70E+01
20	4.56E+00	5.18E+00	1.08E+01	1.18E+01	1.27E+01	1.37E+01	1.45E+01
30	3.09E+00	3.51E+00	7.31E+00	8.02E+00	8.62E+00	9.25E+00	9.84E+00
40	2.28E+00	2.60E+00	5.40E+00	5.93E+00	6.38E+00	6.84E+00	7.28E+00
50	3.52E+00	4.07E+00	8.26E+00	9.07E+00	9.75E+00	1.05E+01	1.11E+01
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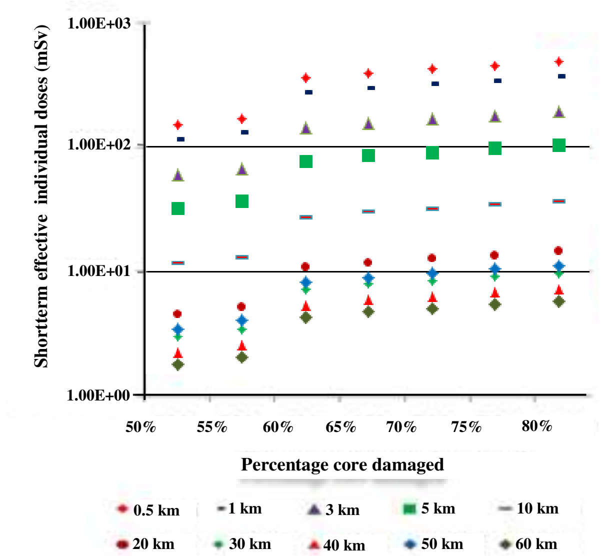

Fig. 2. Short-term effective dose vs distance for various core damage fractions for Dai-ichi Unit 1.

This method can also be used for determining the emergency response that should be taken to mitigate the consequences of this accident. Based on the data in Fig. 2, the countermeasures such as evacuation, relocation, and area decontamination can be estimated. The results obtained by simulation using the backward method in this paper showed no significant difference with the countermeasures actually taken by the authorities in Fukushima [6].

The determined long-term dose can be used to estimate the needed long-term countermeasures such as relocation and area decontamination. Figure 3 gives the magnitude of dose without decontamination action. The dose will decrease if the decontamination is intensive and massive. If decontamination has been performed, the area whose inhabitants are to be relocated and the duration of relocation will be reduced.

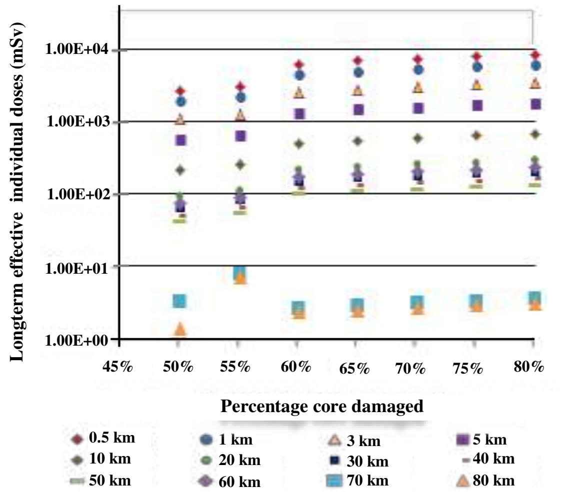

Fig. 3. Long-term effective dose vs. distance for various core damage fractions for Dai-ichi Unit 1.

The calculation of source term for Unit 2 and Unit 3 follows the postulates and assumptions of the Design Basis Accident (DBA). The accident postulated by the DBA is lighter than the postulation of severe accident. With a smaller source term (Table 4), the dose calculation results range from 80-103 mSv (exclusion area) for the core damage fractions of 20% to 40%.

Based on Table 6 and Fig. 4 for the reported dose at exclusion area were 80 to 100 mSv, the core damage fractions for Unit 2 and Unit 3 ranged from 20% to 40%. IAEA reported that core damage occurring in Unit-2 was 30%. From Table 6, the associated dose is 99.1 mSv [14]. In the same manner, for Unit 3 the core damage fraction was 25% for 92.2 mSv (Table 6 and Fig. 4). If we compare the results of backward calculation method, it is found that the results are still within the range measured dose. For Unit 2 or Unit 3, this observation indicates that the backward method can estimate the core damage fraction and the severity of the accident.

Table 6. Short term Effective dose (mSv) vs distance on various core damaged on Dai-ichi Unit 2-3

Distance (km)	Short term individual effective dose vs distance on various core damaged on Dai-ichi Unit 2-3 (mSv)				
	20%	25%	30%	35%	40%
0.5	8.53E+01	9.22E+01	9.91E+01	1.06E+02	1.06E+02
1	6.60E+01	7.21E+01	7.81E+01	8.42E+01	8.42E+01
3	3.42E+01	3.68E+01	3.94E+01	4.20E+01	4.20E+01
5	1.86E+01	2.02E+01	2.18E+01	2.34E+01	2.34E+01
10	6.69E+00	7.23E+00	7.77E+00	8.31E+00	8.31E+00
20	2.61E+00	2.78E+00	2.94E+00	3.11E+00	3.11E+00
30	1.93E+00	2.02E+00	2.11E+00	2.19E+00	2.19E+00
40	1.76E+00	1.85E+00	1.93E+00	2.02E+00	2.02E+00
50	1.30E+00	1.35E+00	1.39E+00	1.44E+00	1.44E+00
60	1.04E+00	1.07E+00	1.10E+00	1.13E+00	1.13E+00

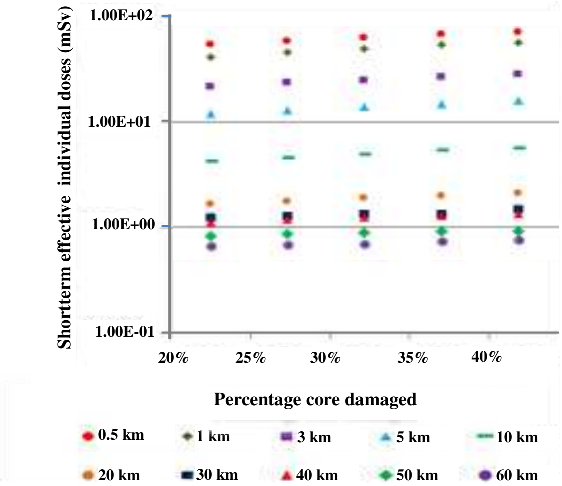

Fig. 4. Short-term effective dose vs. distance for various core damage fractions for Dai-ichi Units 2-3.

Figure 5 shows the long-term effective dose as a function of distance for various core damage fractions at Dai-ichi Units 2-3. From the data in Fig. 5, the emergency response needed to mitigate the consequences of this accident can be determined.

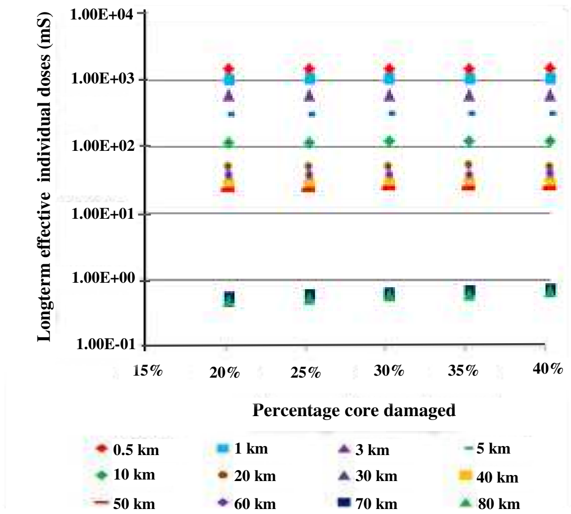

Fig. 5. Long-term effective dose vs distance for various core damage fractions for Dai-ichi Units 2-3.

Comparisons between the radiation doses estimated using the backward method and the results of measurements showed differences. The differences between the reports [6,8] and the present results may be caused by uncertainty which have not been accounted for in the data parameters. Among others, the uncertain parameters include the inaccuracies of dose measurements (data not accurate because of equipment damage by the tsunami and other reasons), the meteorological data (site conditions), the complexity of the accidents (multievent accident involving multiple reactors), the simplified postulations of the accidents, and the simplified assumptions on fission product release for each subsystem in the reactors.

If we base the calculations or estimations on official data using the model for backward calculations, the results obtained are similar to the assumptions used for the calculations of consequences for the severe accidents. This shows that the calculation model used in this study validated the results obtained. The advantage of the model is that it can estimate or predict severity of accidents, thus allowing operators to more quickly perform rescue activities following the EOPs (Emergency Operating Procedures) or SAMGs (Severe Accident Management Guidelines) standards used. Another advantage of the model is the reduction of the uncertainties in the postulations or model calculations which are caused by the complexity of the accident. However, this method also has disadvantages, including that to obtain a more accurate estimation, the counting backwards method requires more calculations and the use of proper assumptions and postulations. In addition, for complicated accidents, it is difficult to decide the postulation to be used and to subsequently obtain the estimates.

The uncertainties can be reduced by more accurate measurements of dose data, more complete and appropriate data on site conditions and meteorological conditions, use of more varied postulations for accident and assumptions for calculations, repetitions of simulations/calculations, and verification of the resulting assessment with calculations using previously existing methods (modelling using RELAP-SCDAP, MELCOR, or THALES) [15-17]

CONCLUSION

The core damage fraction in a severe accident can be determined based on radiological consequences by using the backward counting method. Dose calculation results for a radius of 800 m (exclusion area) for Unit 1 ranges for 140 to 470 mSv for core damage fractions of 50% to 80%, while for Unit 2 and Unit 3 the dose calculation results range from 80-103 mSv for core damage fractions of 20% to 40%. This method has advantages such as that it can allow faster determination of the severity of a reactor accident, thus allow operators to more quickly implement the EOPs or SAMGs. The disadvantage of this method is the poorer level of accuracy than what is obtained by the common method. The inaccuracy causing this uncertainty can be reduced by performing simulations for more varied postulations and repetitive calculations. This proposed method is used if a severe accident is extremely complex, as is the case for the reactor accident in Fukushima.

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