Safety Assessment of Surrounding Areas after the Fukushima Nuclear Accident Using the RESRAD Code

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1. Introduction

At 14:46 on March 11, 2011, the Tohoku Regional Pacific Ocean earthquake occurred, and the Fukushima Daiichi Nuclear Power Plant was automatically shut down for nuclear safety. Afterwards, the emergency core cooling system operated normally, but the tsunami swept over the nuclear power plant, flooding the emergency diesel generator and all the power systems, resulting in a Station Black Out (SBO). The core temperature rose to 1200 Celsius as all the cooling water in reactors 1-3 were evaporated, and hydrogen gas was generated as the zirconium and water vapor in the fuel reacted. Hydrogen gas and water vapor, which were kept at high temperature and high pressure, eventually caused a hydrogen explosion, damaging the containment vessel, and radioactive are leakage began.

Following the accident, the spread of radionuclides into the atmosphere, soil, and water quality has led the Japanese government to designate areas as 20 km away from nuclear power plants and some areas 20-30 km away as planned evacuation areas. However, up to eight years after April 2012, some areas within 20 km have been converted into evacuation detention zones, restricted areas of residence, and difficult to return areas, and no sanctions have been imposed on other areas and areas outside 30 km. Therefore, it was necessary to find out if the residents could resettle in the de-restricted area and if the human beings lived, the annual dose is lower than the limit.

Using the Onsite code among RESRAD codes, the annual exposure dose was calculated by creating a hypothetical situation of living in an arbitrary area for one year. The area where want to study is Kawamata-cho, Fukushima Prefecture, we decided that the conditions we would like to conduct our research on were the best. As a guideline, this study was conducted based in the annual exposure allowance of 0.1mSv/yr, which is the standard for reuse of the site and remaining buildings after the dismantling of nuclear facilities [8]. This will determine if it is appropriate to release the evacuation zone and lower the boundaries for some areas when you live in the area where you intend to live. In addition, this study was conducted to find out whether it is appropriate to select 30 km of restricted area at the time of the accident.

2. Methods

2.1 Introduction of RESRAD-Onsite

The RESRAD family of Codes are developed at Argonne National Laboratory (ANL) to analyze potential human and biota radiation exposures from the environment contamination of residual radioactive materials [2]. In there, the RESRAD-Onsite is for assessing radiation exposures of a human receptor located on top of soils contaminated with radioactive materials. I chose this code because I thought that the research objectives and direction of the annual exposure dose in the villages around Fukushima and the validity of regulation and policy direction are very similar.

2.2 Main input parameter

First, according to the type and age if living around Fukushima, it was classified into cities, country areas, and adults and children. In conclusion, there are four categories: children living in cities, adults living in cities, children living in country areas, and finally, adults living in country areas. Second, depending on the age group, the amount of time spent in and outside the living area, depending on the environment, the intake of local agricultural and marine products and depending on the respiratory volume that can vary depending on the age, the annual exposure can be determined for these, so I did some research and calculations for that.

Respiratory volume according to age group is $8400m^2$ per year according to the code of RESRAD-Onsite. When the age range is different, the volume of breath can be different, so the survey shows that both children and adults have a volume of around $8400m^2$. Therefore, as shown in Table. 1, $8400m^2$ value was used regardless of age group [9].

For energy intake by age group, I compared the average energy intake of children under 18 teas of age with adults over age. And the average energy intake of a child is 82% of the average energy intake of an adult [3]. Therefore, when assigning variable values in relation to intake, I set the values so that only 82% of the adult's intake can be consumed by children living in the same living environment. In addition, meat intake and seafood intake can vary widely from country to country, so I surveyed Japanese annual meat and seafood intake. In the case of meat and poultry consumption is 39.7kg/year, case of fish consumption is 28.6kg/year, and other seafood consumption on numerical value is 20kg/year, these values are different with values in RESRAD-onsite code, so that only those values that were entered in the existing code were changed [4, 7].

There are two types of exposure pathways, depending on the living environment: rural and urban. In rural areas, both external exposure by gamma rays and internal exposure through other pathways were considered effective. However, in the case of cities, it was determined that they were more likely to eat agricultural products from other regions, and the internal exposure caused by digestion of meat and milk was considered invalid. Radon exposures were ruled out in both country and urban areas.

In Table. 1, the ratio of time spent living inside a house and working outside a residence is shown in Table. 1 that a person working in the city will have a lot of time working inside, so I expected the time to be small and left the ratio at 0.25. In the case of children, both country and cities, I entered the same value as an adult living in the countryside, expecting that they would have plenty of time to play outside.

In conclusion, the main input values to be input to RESRAD-Onsite can be summarized in Table. 1.

Table 1. Input parameters in RESRAD-Onsite related with the exposure path.

parameter	Unit	Resident Farmer(Adult)	Suburban Resident(Adult)	Resident Farmer(Kid)	Suburban Resident(Kid)
Exposure duration	yr	1	1	1	1
Inhalation rate	m^3/yr	8,400	8,400	8,400	8,400
Fraction of time indoors	-	0.3	0.5	0.3	0.3
Fraction of time outdoors	-	0.5	0.25	0.5	0.5
Contaminated Fractions of food	-				
Plant food	-	0.5	0.1	0.41	0.082
Milk	-	1	Not used	0.82	Not used
Meat	-	1	Not used	0.82	Not used
Aquatic food	-	1	0.5	0.82	0.41
Soil ingestion	g/yr	36.5	36.5	36.5	36.5
Drinking water(contaminated) intake	L/yr	510	100	420	82

For the other variable input values, the area of Kawamata-cho, Fukushima Prefecture, Japan was 127.70km^2, average wind speed 2m/s, and average precipitation 1193mm [1].

2.3. Exposure scenario

Since we intend to measure the current annual exposure over eight years after the Fukushima nuclear power plant accident, we did not consider radionuclides with a half-life of less than one year, resulting in only Cs-134 with a half-life of 2.06 and Cs-137 with a half-life of 30.2 years [6].

Firstly, when no action is taken eight years after the accident, annual doses will be calculated according to the living environment and age group. In this case, the thickness of the contaminated soil containing radioisotopes was 0 to 5 centimeters thick with a relatively high concentration of radionuclides. The average soil density in this section was 1.15g / cm^3, the average concentration of Cs-137 was 2399.12Bq/kg and the average concentration of Cs-134 was 2259.32 Bq / kg [5].

The second is to calculate the annual dose when the 5 centimeters thick soil, which had a relatively high concentration of radionuclides, was removed. Currently, the soil containing radionuclides was 5-12cm deep, and the average density of soil was 1.53 g / cm^3 and the average concentration of Cs-137 was 35.7 Bq / kg , Cs-134. The average concentration of was calculated as 35 Bq / kg [5].

3. Result and Discussion

Before deriving the results using the code, we will analyze the results by forging the annual exposure dose due to external exposure since the value of annual exposure dose due to external exposure is much larger than that of internal exposure.

3.1. Annual dose due to contaminated soil when no action is taken

In rural areas, the average annual dose for adults in 2019, eight years after the accident, was 0.6065mSv/year, represented on Fig. 2. Among them, the annual exposure dose due to internal exposure was 0.02528 mSv/year, and the annual exposure dose due to external exposure caused by gamma radiation was 0.5812 mSv/year.

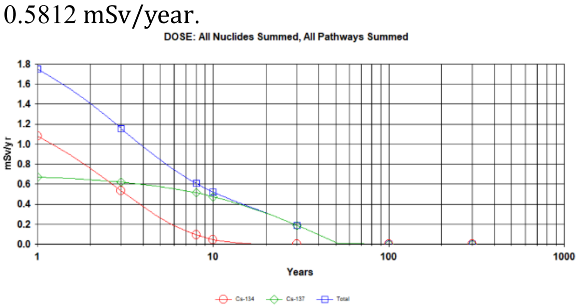

Fig 1. Annual dose for adults living in the countryside when no action is taken.

In same area, on countryside, the average annual dose for kids in 2019 was 0.593 mSv/year. From that, the annual exposure dose due to internal exposure was 0.01173 mSv/year, and the external exposure dose was 0.5813 mSv/year.

In urban areas, the average annual dose for adults in 2019, was 0.4923mSv/year. Among them, the annual exposure dose due to internal exposure was 1.149µSv/year, and the annual exposure dose due to external exposure caused by gamma radiation was 0.4912 mSv/year. And the average annual dose for kids in 2019 was 0.5820 mSv/year. From that, the annual exposure dose due to internal exposure was 0.7488 µSv/year, and the external exposure dose was 0.5813mSv/year.

Looking at the results derived from the first scenario, the annual exposure dose was calculated by dividing the living environment and the age group and found that the values ranged from 0.4923 mSv/year to 0.6065 mSv/year. This results in exceeding 10 μSv/year, a regulation on radioactive waste classification and self-disposal standards, and even 0.1 mSv/year, over six times, a standard for reuse of sites and remaining buildings after the dismantling of nuclear facilities. It was also confirmed that this annual dose would fall below the reused dose standard after more than 50 years. Considering this, it was concluded that humans could be at risk if they moved back to the area when they had not acted in some areas where restrictions on residence had been lifted or relaxed since 2012.

3.2. Annual dose values when 5 cm of soil is removed.

In rural areas, the average annual dose for adults in 2019, eight years after the accident, was 13.46μSv/year, represented on Fig. 2. Among them, the annual exposure dose due to internal exposure was 0.4251μSv/year, and the annual exposure dose due to external exposure caused by gamma radiation was 13.035 μSv/year.

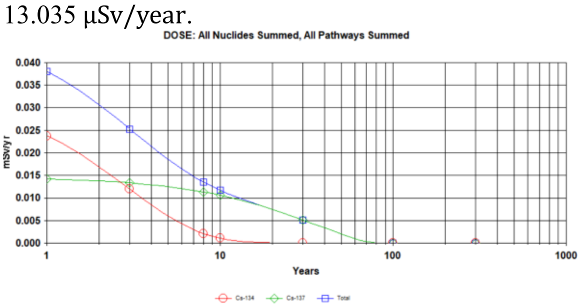

Fig. 2. Annual dose for adults living in the countryside when remove 5cm thick of dirt.

The average annual dose for kids in 2019 was 13.30 μSv/year. From that, the annual exposure dose due to internal exposure was 0.2616 μSv/year, and the external exposure dose was 13.038 μSv/year.

In urban areas, the average annual dose for adults in 2019, was 11.04μSv/year. Among them, the annual exposure dose due to internal exposure was 0.02562μSv/year, and the annual exposure dose due to external exposure caused by gamma radiation was 11.014 μSv/year.

And finally, in urban areas, the average annual dose for kids in 2019 was 13.06 μSv/year. From that, the annual exposure dose due to internal exposure was 0.02226 μSv/year, and the external exposure dose was 13.038 μSv/year.

Looking at the results derived from the second scenario, the annual exposure dose was calculated by dividing the living environment and the age group and found that the values ranged from 11.04μSv/year to 13.46μSv/year. This result is around 10 μSv/year, a regulation on radioactive waste classification and self-disposal standards. This annual dose value may fall below 10 μSv/year within 10 years from now.

4. Conclusion

The maximum annual dose was 0.6065 mSv/year on Table 2, when no action was taken using the values set in the input parameters, which was 6 times the 0.1 mSv/year limit annual dose. When 5 cm of soil is removed, the annual dose is shown to be 13.46 μSv/year, indicating that safety is assured when such work is performed.

Table 2. Comparing two scenario, general case and removing 5cm dirt, with reuse dose standard.

	General	Remove 5cm dirt	Reuse Dose Standard
External exposure (mSv/yr)	5.812E-01	**1.304E-02**	--
Internal exposure (mSv/yr)	2.528E-02	**4.251E-04**	--
Total exposure(mSv/yr)	6.065E-01	**1.346E-02**	**1.000E-01**

However, the Japanese government now ignores the annual doses that may be exceeded when exposed by contaminated soil and is also relieved that radionuclides have disappeared while easing regulations and eliminating regulations at all. It is. However, as a result of this study, if the polluted area around the Fukushima Daiichi Nuclear Power Plant was not removed, or if other forms of decontamination were not performed, the annual exposure dose beyond the reuse dose standard may be shown as the study results. We could have determined that a very long time of 50 years or more could be required to meet the criteria. Therefore, I think it is necessary to loosen regulations on areas contaminated with radioactive elements or reinforce those regulations in areas where regulations have been removed.

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