Analysis of factors influencing internal exposure by factors causing radioactive aerosols

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1. Introduction

Radioactive aerosols are caused by NPP decommissioning and unexpected severe accidents in NPPs, and lead to the internal exposure of NPP workers and ordinary citizens in the vicinities. The resulting internal exposure dose varies by the particle size of radioactive aerosols, nuclides and concentration, and these factors have different characteristics and nature depending on the cause of NPP decommissioning and severe accident. Accordingly, it is necessary to accurately predict damages due to internal exposure doses induced by different causes by analyzing the characteristics and nature of different causes. This study analyzed particle sizes and contained nuclides for each cause of radioactive aerosols, and showed them from a macroscopic point of view.

2. Main title

In general, aerosols are generated mostly by the nucleation of supersaturated vapor in a severe accident. As the radioactive vapor, evaporated from the high-temperature nuclear reactor core debris, spreads farther from the nuclear reactor core debris, it is supersaturated by the low ambient temperature, and aerosols are generated by homogeneous nucleation, i.e. the agglomeration of supersaturated vapor molecules, or non-homogeneous nucleation, i.e. agglomeration of supersaturated vapor molecules around heterogeneous particles. On the other hand, aerosols are generated by mechanical friction and evaporation mechanism during NPP decommissioning. If force is applied to a material that will be cut by the cutting machine, this force will cause friction and deform the material, and this delivery of energy generates aerosols, generated by mechanical friction, and aerosols, generated by the evaporation mechanism, appear when heat energy is used for cutting, e.g. the plasma arc torch and laser cutting machine. The factors, affecting the internal expose dose due to the above two causes, will be examined in the following subsection.

2.1. Particle Size

The log normal distribution was used to show the distribution of the sizes of radioactive aerosols, discharged into the air during the representative severe accidents, i.e. the Fukushima accident and the Chernobyl accident, in Table I. The size distribution data, observed in Helsinki, shows that the average size of the particles may differ depending on the type of radioactive materials. For instance, the size of most fuel particles was 1μm, but ^{131}I particles were smaller than other particles in general, and according to the data, measured in Tsukuba, the sizes of the particles remained almost constant, i.e. 2.6μm, for about a month.

Table I. Distribution of the sizes of radioactive particles during severe accidents

		Chernobyl	Fukushima
Location of collection		Helsinki	Tsukuba
Components	Nuclide	^{103}Ru ^{131}I ^{137}Cs	^{134}Cs ^{137}Cs
	Geometric mean particle size (μm)	0.63~0.83 0.33~0.57 0.63	0.53~0.64
	Geometric mean deviation	1.7~1.9 1.7~2.3 1.8	1.3~1.4
Concentration (mBq/m^3)		15~25 17~98 9	-

On the other hand, as it is rather difficult to measure the radioactive aerosols, generated during NPP decommissioning, during the actual decommissioning process, this study referenced the size distribution data of the radioactive aerosol particles, generated when the radioactive pipes, collected during the decommissioning process, were cut.

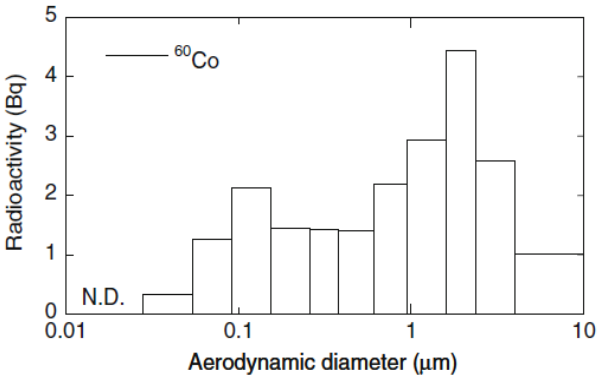

Fig. 1. Particle size distribution of ^{60}Co radioactivity for surface contaminated pipe

Fig. 1, illustrates the sizes of the radioactive particles of ^{60}Co, which is most considered during NPP decommissioning, and the two peaks, i.e. 2.38μm and 0.154μm, are shown in a dichotomous distribution.

2.2. Nuclide

Based on the results of the simulated experiments, which were conducted by the French Institute for Radiological Protection and Nuclear Safety from 1993 till 2004, the distribution of radioactive nuclides in a severe accident was examined. Among them, the result of the experiment, which used the boron carbide (B_4C) control rod like domestic NPPs, was cited.

The materials, discharged into the nuclear reactor building, weighed 13.6g in total excluding oxygen and inert gases, and the main components were Cs and Mo, which are nuclear fission components, B, which is a control rod component, and Sn, which is a coating material. Excluding I 87.7% of which existed in a gaseous state, all components existed as aerosols in most cases.

On the other hand, if the degree of radioactivation of the concrete and pipes, the structures that must be cut during NPP decommissioning, is analyzed, it will be possible to see the distribution of the nuclides of radioactive aerosols, generated during the decommissioning process.

To analyze the characteristics of the radioactive nuclides of the Bioshield concrete, US NRC collected samples from 12 NPPs, and analyzed them. In this study, the key radioactive nuclides, generated by radioactivation in the Bioshield concrete of a PWR-type NPP, considering deferred decommissioning, are permanent shutdown ^{3}H, ^{152}Eu, ^{41}Ca, ^{39}Ar, ^{63}Ni and ^{60}Co, and ^{65}Zn,^{55}Fe, ^{54}Mn and ^{14}C with a short half-life for 100 years after permanent shutdown. Among them, as ^{54}Mn and ^{65}Zn have a short half-life, 10 years or so after permanent shutdown, almost all of them disappear.

Element		Average	% S.D.(b)	Range	Range Factor(a)	No. of Measurements(a) Used
H	ppm	~6100				2
Li	ppm	20				Crustal Abundance
B	ppm	~20				2
N	ppm	~120				2
Na	ppm	7390 ± 7640	103	176 to 18940	108	11
Al	%	3.1 ± 2.9	67	0.53 to 6.1	11.5	11
Si	%	16.8 ± 9.5	57	3.9 to 32.4	8.3	12
P	%	<0.5				12
S	%	0.31 ± 0.10	32	0.20 to 0.46	2.3	12
Cl	ppm	45 ± 18	40	11 to 59	5.9	8
K	%	0.75 ± 0.67	89	0.047 to 2.5	53.2	12
Ca	%	18.3 ± 9.7	53	8.3 to 34.7	4.2	12
Sc	ppm	6.5 ± 6.3	97	0.73 to 17.4	23.8	11
Ti	ppm	2121 ± 2320	105	230 to 7900	34.4	12
V	ppm	103 ± 140	136	13.3 to 490	36.8	11
Cr	ppm	109 ± 159	146	29.0 to 540	28.4	11
Mn	ppm	377 ± 290	77	56 to 990	17.7	12
Fe	%	3.9 ± 6.4	172	0.50 to 24.0	48.0	12
Co	ppm	9.8 ± 10.3	105	1.1 to 31.0	28.2	11
Ni	ppm	38 ± 25	65	11.9 to 87.0	7.3	12
Cu	ppm	25 ± 17	68	10 to 60	6.0	12
Zn	ppm	75 ± 90	120	8.4 to 340	40.5	12
Ga	ppm	8.8 ± 6.4	73	1.05 to 20	19.1	12
As	ppm	7.9 ± 7.9	100	0.89 to 29	32.6	12
Se	ppm	0.92 ± 0.56	61	0.26 to 2.0	7.7	7
Br	ppm	2.4 ± 1.5	61	1.0 to 5.6	5.6	9
Rb	ppm	35 ± 44	127	2.5 to 170	68.0	12
Sr	ppm	438 ± 208	47	220 to 940	4.3	12
Y	ppm	18.2 ± 25.6	147	3.0 to 96	32.0	12
Zr	ppm	71 ± 44	62	27 to 160	5.9	12
Nb	ppm	4.3 ± 3.0	69	1.3 to 9.3	7.2	12
Mo	ppm	10.3 ± 10	104	1.6 to 36	10.0	12
Pd	ppm	<2				
Ag	ppm	<0.2				
Cd	ppm	~0.3				2
Sn	ppm	<7				
Sb	ppm	1.8 ± 3.7	202	0.16 ± 13.0	81.3	11
Cs	ppm	1.3 ± 1.8	139	0.32 ± 6.2	19.4	10
Ba	ppm	950 ± 1950	106	420 to 7060	353	12
La	ppm	13.0 ± 6.9	53	2.9 to 28	9.7	11
Ce	ppm	24.3 ± 13.5	55	6.2 to 52	8.4	11
Sm	ppm	2.0 ± 1.3	63	0.42 to 4.2	10.0	11
Eu	ppm	0.55 ± 0.38	69	0.11 ± 1.2	10.9	11
Tb	ppm	0.41 ± 0.24	59	0.11 to 0.78	7.1	11
Dy	ppm	2.3 ± 1.3	54	0.55 to 4.3	7.8	7
Ho	ppm	~0.9				R.E. Ratio
Yb	ppm	1.4 ± 0.9	63	0.38 ± 3.0	7.9	11
Lu	ppm	0.27 ± 0.13	48	0.15 to 0.50	3.3	11
Hf	ppm	2.2 ± 1.5	71	0.65 to 5.7	8.8	11
Ta	ppm	0.44 ± 0.31	70	0.092 to 0.90	9.8	11
W	ppm	1.4 ± 1.1	81	0.39 to 3.9	10.0	11
Pb	ppm	61 ± 158	258	5.4 to 560	104	12
Th	ppm	3.5 ± 3.0	85	0.75 ± 120	16.0	11
U	ppm	2.7 ± 0.9	36	1.4 ± 4.4	3.1	11

(a) Range factor is the ratio of the highest to lowest value measured.
(b) Relative standard deviation expressed as a percentage of the average value.

Fig. 2. Mean contents of Bioshield concrete components

3. Conclusion

This study analyzed the characteristics of the radioactive aerosols that are generated in a severe accident and during the NPP decommissioning process. As a result, the average particle size of the radioactive aerosols, generated in a severe accident, was 1um for Chernobyl, and 2.6μm for Fukushima, The particle size distribution was rather big, and as for nuclides, Cs, I and Co, similar to the radioactive aerosols generated during decommissioning, were discovered. On the other hand, the sizes of the radioactive aerosols, generated during the decommissioning process, ranged from 0.154μm to 2.38μm. The particle sizes, which showed differences by causes, greatly affect adsorption in the body, and if the particle is small, it will be adsorbed in the alveola and cause whole-body exposure. In general, 2.1~3.3μm tends to be deposited in the secondary bronchi, 1.1~2.1μm in the terminal bronchi, 0.6~1.1μm in the alveolar ductules, and 0.65μm or smaller radioactive aerosols in the alveola.

In relation to this, the internal exposure doses of radioactive aerosols by particle size, were assessed form comparison with the same absorption type and concentration as a random nuclide ^{60}Co, and the result showed that the internal exposure dose for 1um was 83% of that for 0.1μm, and 3um was 55%. Also, to increase the reliability of the result, the result of assessment with ^{131}I also showed similar levels.

In view of these results, the particle size of the radioactive aerosols, generated during the decommissioning process, rather than in a severe accident, had a greater influence on the internal exposure doses. If not only internal exposure doses, but also external exposure doses are compared, more reliable evaluation criteria will be provided.

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