Study on Public Exposure Risk Assessment for Dismantling of Radioactive Components in Decommissioning Phase of Nuclear Reactor Facilities

Taro Shimada[a*], Kazuhiko Kabata[a], Shizuka Takai[a], Seiji Takeda[a]
[a]Nuclear Safety Research Center, Japan Atomic Energy Agency, Tokai-mura, JAPAN

Abstract: Nuclear regulatory inspections during the decommissioning phase of nuclear power plants need to be conducted based on risk information, but a method for quantitatively evaluating this risk has not been developed. Therefore, in this study, an event tree of accident events that may occur in the decommissioning phase has been developed, and a code DecAssess-R has been developed to evaluate the exposure risk, which is expressed as the product of the exposure dose and probability of occurrence according to the accident sequence for each equipment to be dismantled. In particular, we have taken into account that the amount of mobile radioactivity that may accumulate in HEPA filters and be released all at once during an accident varies temporally and spatially with the progress of dismantling work. The event tree was constructed based on the results of the survey of domestic and international trouble information in the decommissioning phase and similar dismantling and replacement operations. The event frequencies are based on information from general industries, and the event progression probabilities are based on the equipment failure probabilities in the operation phase. The safety functions to be reduced with the progress of decommissioning were taken into account according to the dismantling work schedule. As a result of the exposure risk assessment for dismantling operations of BWRs and PWRs in Japan, the exposure risk for fire events was the largest. In particular, the exposure risk was greater for the dismantling of components in the reactor building by airborne cutting than for the dismantling of reactor internals, which has the greatest radioactivity in underwater dismantling.

Keywords: Decommissioning, Exposure Risk, Event Tree, Public Exposure, Initiating Event, Mobile Inventory,

1. INTRODUCTION

In approving the decommissioning plan, it was confirmed that the public exposure doses at the accident was within the dose criteria of 5 mSv. On the other hand, it is necessary to develop a risk assessment method for nuclear power plants in the decommissioning phase so that the equipment to be dismantled and the work process to be inspected can be selected depending on the risk in the nuclear regulatory inspection [1] at the decommissioning phase in Japan. At the decommissioning phase, after the spent fuels are carried out of the facility, the radioactivity inventory in the facility will be greatly reduced to approximately 10^{17} Bq which is still larger than safety target [2] of atmospheric release of 10^{14} Bq of Cs-137. As the decommissioning work such as equipment removal and waste transportation progresses, the radioactive inventory in the facility will decrease, and the equipment related to the containment function of radioactive materials will also be removed in sequence. Furthermore, different from the operation stage, unsteady dismantling works are carried out in multiple areas in parallel, and radionuclides fixed in the equipment to be dismantled are scattered as radioactive dust by cutting and accumulated in filters. Mercurio et al. [3] carried out Level 1 – Level 2 decommissioning probabilistic risk assessment for spent fuel in the storage pool, but the risk during dismantling activities was out of the scope. Iguchi et al. [4] developed the risk assessment methodology where exposure dose as consequence of accidents during dismantling activities including nuclear fuel cycle facilities and their frequencies. Studies on project risks during decommissioning activities had been conducted for management [5]. However, a methodology for evaluating temporal change of exposure risk according to dismantling work process has not been established. Therefore, we started developing a methodology and code to evaluate the temporal change of exposure risk [6]. The authors defined exposure risk as the product of the public exposure dose and the probability of consequence in the event tree including frequency of the event occurrence due to an accident that is assumed to occur during the decommissioning phase. In addition to the above characteristics, the duration of the decommissioning project is long for 30 years or more after a maximum of 60 years of operation in Japan. There is a possibility of expanding the contamination area via groundwater by leakage of radioactive liquid wastes from the basement of the building due to damage of the liquid waste storage tank by aging. Moreover, the radionuclides released into the atmosphere in the form of dusts may be deposited on the ground surface. Therefore, the accumulation of mobile inventory up to the occurrence of the accident, the progression of the accident from the occurrence of the initiating event, the release of radioactive materials into the atmosphere or underground, the subsequent transfer to the public exposure, and the above accident should be considered for dose evaluation. An overall picture of radiation exposure risk assessment was constructed to comprehensively assess the accident occurrence probability in consideration of progress. Therefore, the authors studied that initiating events were identified based on the results of Failure Mode Effects Analysis (FMEA), and an event tree by fire event was developed. A risk assessment code for dismantling activities, DecAssess-R [7] was developed based on DecDose [8, 9] and DecAssess [6]. In addition, temporal change of the exposure risk according to dismantling work process was evaluated for reference BWR by a fire event. However, no evaluation has yet been made for initiating events other than fire. It is also necessary to evaluate the exposure risk for PWR. In this paper, event trees were created for all assumed attributable events, and the frequencies of event occurrence and progression probabilities were constructed. Furthermore, the radiation exposure risk for dismantling of components at the reactor building of BWR and PWR were evaluated by using DecAssess-R.

2. METHODOLOGY OF RISK ASSESSMENT DURING DISMANTLING ACTIVITIES

2.1. Basic Concept

In this study, exposure risk is defined as the product of public exposure dose (mSv) and the probability of the exposure (1/y) by consequence of the event during dismantling activities. Public exposure is caused by radioactivity released at the accident, and the quantities of radionuclides depends on mobile inventory accumulated at HEPA filters, which are attached at contamination control enclosures. Dismantling activity for contaminated components and structures are usually conducted in the contamination control enclosure. Mobile inventory such as radioactive particles and easy-to-remove surface contamination is generated during cutting activities of radioactive components. The quantities of mobile inventory depend on the cutting tools, and in-air thermal cutting tools generate more mobile inventory. The mobile inventory is calculated based on the cutting length, kerf width, surface contamination density, dispersion ratio and filtration efficiency of the HEPA filter. Because the accumulated quantity of mobile inventory change daily, exposure dose risk also changes daily.

2.2. Initiating Events and Their Frequencies of Occurrences

Initiating events during dismantling activities were extracted by using FMEA [7]. In addition, the authors investigated trouble information regarding decommissioning activities and similar activities such as periodic inspection stored in Nuclear Information Archives of Japan [10], NUCIA. Table 1 shows initiating events and their frequency of occurrence during dismantling activities. Frequency of the occurrence of initiating events was calculated, based on the number of occurrences counted in the archives and suspension period of 626 reactor years. For the initiating events with no occurrence, the frequency was assumed to be 10^{-3}/y because sufficient data had been obtained .

2.3. Event Trees

For each initiating event, an event tree was constructed so that the accident sequence would branch at a mitigation measure that prevented the event from progressing, and the event would progress to the next mitigation measure if the mitigation measure failed. The containment vessel will be maintained until the radiation control area is released. However, its airtightness is not ensured at the accidental situation. Emergency power supply such as diesel power generator will be maintained until stored spent fuels are transported out of the building or sufficient cooling period. The function of diesel generator will be removed after that. Figure 1 shows the event trees for all initiating events considering the above safety functions during dismantling activities.

2.4. Probability of Event Progress

Failure of mitigation measures causes the event progress to reach the release of radionuclides to the environment. The event progression probabilities were established by extracting equipment failure rate from the JANSI report [11] and CRIEPI reports [12, 13] that are applicable to the decommissioning phase. Table 2 show the probabilities of failure for the mitigation measures in the event trees.

2.5. Calculation of Mobile Inventory

The mobility inventory is calculated as the amount of dispersed radioactivity that accumulates on the filter, the amount suspended in the air, and the amount adhered to the filter. The quantity of radionuclide dispersed from activated object A_{vi} is expressed as

$$A_{Vi} = V_1 \times c_i \times a_i \tag{1}$$

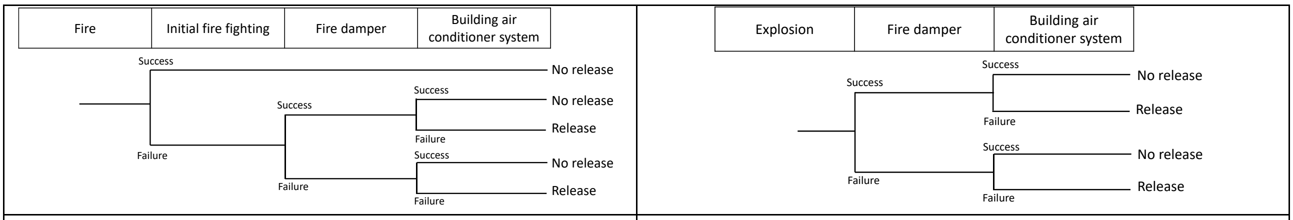
where V_{11} is the kerf volume, c_i the radioactive concentration nuclide i in the object and a_i the dispersion ratio nuclide i for activated object. The quantity of radionuclide dispersed from surface contaminated object A_{Si} is expressed as

$$A_{Si} = S_1 \times f_i \times b_i \tag{2}$$

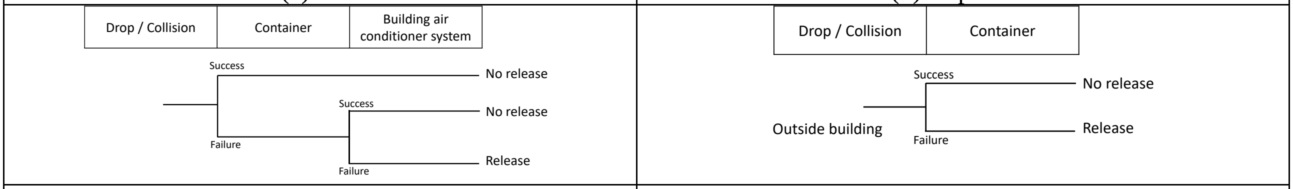
where S_1 is the kerf area, f_i the surface density of nuclide i on the surface and b_i the dispersion ratio nuclide i for surface contaminated object. Filter accumulation is controlled by differential pressure and is replaced when a certain amount of dust accumulates.

Table 1. Selected initiating events by human error and equipment failure and their frequency

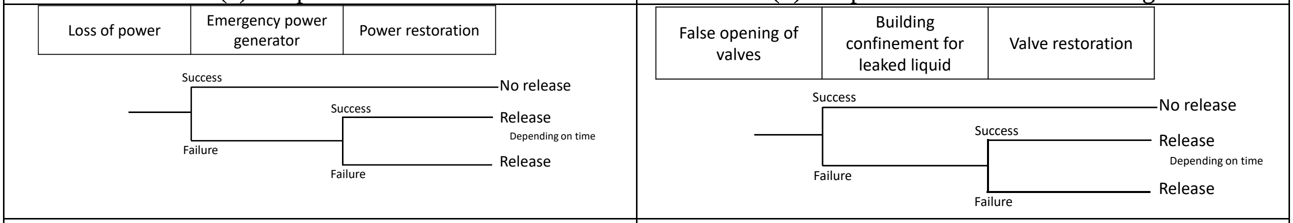
Initiating events		**Failure mode**	**Example of accidents**	**Number of occurrences**	**Frequency**
Category	**Subcategory**				
Human error	Fire	Spark, catch fire to combustible material by dross	Spark and dross generated during thermal cutting, welding etc.	12	1.92E-02
	Explosion	Unplanned explosion, Explosion of flammable gas	Acetylene gas, Explosion of accumulated hydrogen gas generated by underwater cutting	0	1.00E-03
	Drop / Collision	Damage of equipment including contaminants	Drop or collision of heavy equipment into the other equipment with contaminants by maloperation	2	3.19E-03
	Loss of power	Incorrect cutting of power system	Incorrect cutting of power cable	5	7.99E-03
	False opening of valves	Leakage of liquid or gas by false opening	Leakage by false opening of valves or false ceasing of pumps	6	9.58E-03
	Damage of equipment and piping	Damage of equipment and component by incorrect cutting	Incorrect cutting of contaminated piping and tanks including radioactive liquid	6	3.19E-03
Equipment failure	Fire	Fire by short circuit or earth fault	Fire from equipment in operation	8	1.28E-02
	Drop / Collision	Damage of equipment including contaminants	Drop or collision of heavy equipment into the other equipment with contaminants by aging	1	1.60E-03
	Loss of power	by short circuit or earth fault	Loss of power by equipment failure	3	4.79E-03
	Damage of equipment and piping	Damage, breaking of wire	Damage of filters, piping and tank including radioactive liquid	18	2.88E-02
	Cease of active equipment	Short circuit, earth fault, loss of function, breaking of wire, failure of continued operation	Failure of air conditioner by aging	1	1.60E-03
	Malfunction of valves	Misopening, misclosing, failure of opening and closing and blockage	Valves are not closed or opened completely by malfunction	50	7.99E-02



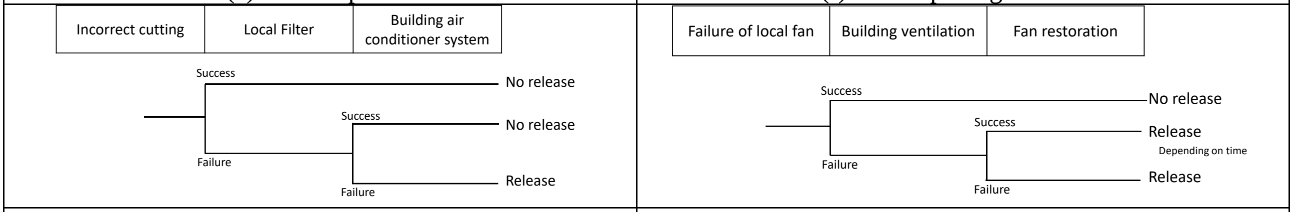
(a) Fire (b) Explosion



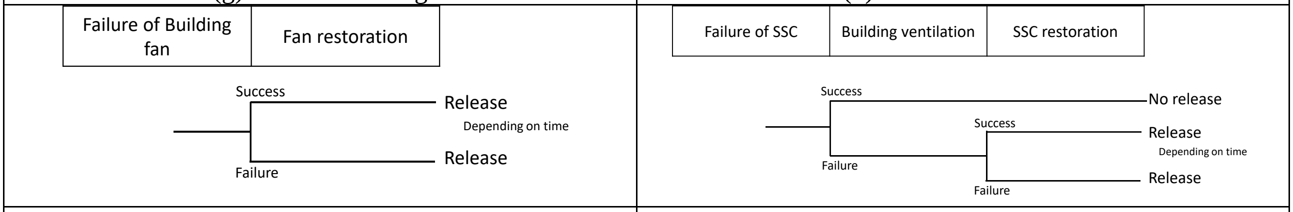
(c) Drop / collision (d) Drop / collision outside building



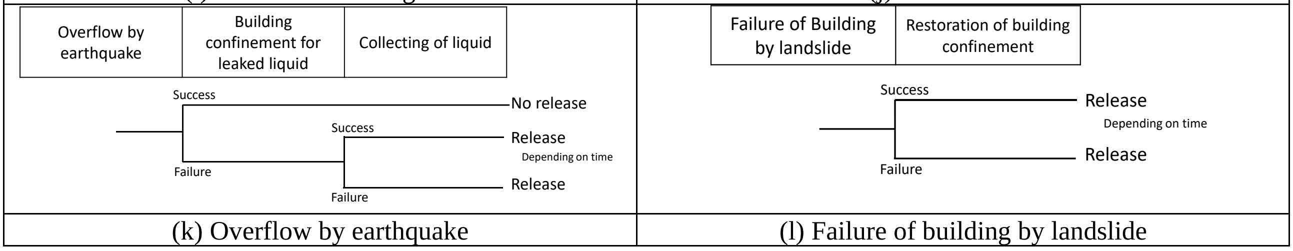
(e) Loss of power (f) False opening of valves



(g) Incorrect cutting (h) Failure of local fan



(i) Failure of building fan (j) Failure of SSC



(k) Overflow by earthquake (l) Failure of building by landslide

Figure 1. Event trees during decommissioning activities

Table 2. Probabilities of failure for the mitigation measures in the event tree

Initiating event	**Progress**	**Probability**
Fire	Initial fire fighting	0.3
Fire	Fire damper	0.00011
Fire/ explosion/ drop/ volcanic eruption	Building air condition system	$6.32 \times 10^{-6} \times$ (Decommissioning period) (h)
Drop	Container	0.01
Loss of external power	Emergency power generator	0.01
Loss of external power	Power restoration	0.01
Cease of active equipment	Local fan restoration	0.01
Failure of building confinement	Restoration of building confinement	0.01
Failure of component	Restoration of component or piping	0.01
Landslide	Restoration of building confinement	0.01
Volcanic eruption	Restoration of air supply filter	0.01

3. CALCULATION OF PUBLIC EXPOSURE RISK DURING DISMANTLING ACTIVITIES

3.1. Calculating Conditions

3.1.1. BWR

Table 3 show the main components of BWR (BWR-5, Mark II improved) in Japan, of which object and radiological was created based on the NUREG report [14]. Reactor internals and a reactor pressure vessel are segmented underwater plasma arc cutting. For evaluating exposure risk in BWR, each operation proceeds one at a time, and the order of dismantling is set so that no more than two operations are performed at the same time.

Table 3. Main components at the reactor building of BWR

	Number	Activated (Bq)	Surface contaminated (Bq/cm^2)	Weight (t)	Diameter (m)	Height / Length (m)
Core shroud	1	2.3×10^{17}	1.33×10^{6}	32	5.6	6.7
Core support plate	1	2.4×10^{13}	1.33×10^{6}	18.5	5.0	0.7
Jet pump assembly	10	7.4×10^{13}	1.33×10^{6}	0.606	0.2	13.0
Steam separator riser	1	3.5×10^{13}	1.33×10^{6}	42	6.2	4.9
Top fuel guide	1	1.1×10^{15}	1.33×10^{6}	2.3	5.2	0.4
Control rod	185	3.6×10^{13}	1.33×10^{6}	0.107	0.125	4.0
Incore instrument strings	55	7.4×10^{12}	8.51×10^{3}	0.019	0.25	1.0
Reactor pressure vessel (cladding)	1	1.6×10^{13}	8.51×10^{5}	6.66	6.66	22.23
Reactor pressure vessel (shell wall)	1	6.3×10^{13}	0	6.71	6.71	22.23
Contaminated piping (Carbon steel)	-	0	1.33×10^{6}	794	-	-
Contaminated piping (SUS)	-	0	2.22×10^{5}	44	-	-

3.1.2. PWR

Table 4 show the main components of 4-loops PWR in Japan, of which object and radiological data was created based on the NUREG report [15]. Reactor internals and a reactor pressure vessel are segmented underwater plasma arc cutting. For evaluating exposure risk in PWR, dismantling works in parallel for the components surrounding the reactor.

Table 4. Main components at the reactor building of PWR

	Activated (Bq)	Surface contaminated (Bq/cm^2)	Weight (t)	Width / diameter (m)	Height / Length (m)
Core shroud plate	1.27×10^{17}	8.51×10^{3}	13.6	13.0	4.2
Reactor lower barrel	2.41×10^{16}	8.51×10^{3}	31.67	3.9 dia in	4.1
Reactor upper grid plate	8.99×10^{14}	8.51×10^{3}	5.1	3.7	0.076
Reactor upper barrel	3.70×10^{13}	8.51×10^{3}	3.0	3.9 dia	2.74
Thermal shield	5.41×10^{15}	0	11.5	3.74	0.91, 1.22
Lower support column	3.70×10^{14}	0	3.7	-	2.93
Reactor vessel	3.70×10^{11}	8.51×10^{3}	308	4.4 dia	13.4
Steam generator	0	8.51×10^{5}	312	4.47	20.63
Pressurizer	0	1.48×10^{5}	97.5	-	-
Reactor cooling system piping	0	3.81×10^{6}	-	0.737 dia in	445
Piping (except RCS)	0	2.22×10^{5}	148	0.0051 to 0.254	-

3.1.3. Segmentation conditions

The exposure risk was calculated under the condition as follows.

- Components and piping were segmented by in-air plasma cutting of which dispersion ratio a_i into air was 10.7% for activated component [16].
- Surface-contaminated components and piping were segmented by in-air plasma cutting of which dispersion ratio b_i was 70% [16].

- Reactor internals and reactor pressure vessel were segmented by underwater plasma arc cutting of which dispersion ratio of radionuclides into air was 0.0036% for the activated part and 0.0236% for the surface contaminated part.
- Cutting width by both cuttings was assumed to be 1 cm.
- HEPA filter was assumed to be used continuously.
- Collecting efficiency of HEPA filter is 99.97% and the maximum weight of dust accumulated at the filter is 2,000 g [17].
- When the accumulated weight of the HEPA filter reaches at the maximum, the filter will be exchanged to new one.
- Fire events were assumed to cause the 100% release from mobile inventory accumulated in filter attached at a contamination control enclosure, because the filters are flame-retardant which does not mean non-flammable.

The time required for the dismantling was calculated under the conditions as follows.

- The time required for each dismantling activity is calculated by the DecAssess-R program according to the number and size of devices to be dismantled, and a dismantling process schedule is output.
- To simplify the evaluation, cutting speed of plasma arc cutting was set to be 1 cm/s, regardless of the thickness of the target device, and the cutting time is determined by evaluating the length of the cutting line according to the internal dimensions of the storage container.
- The time for storing the segmented pieces in a container is evaluated based on the number of cut pieces and considering the size and weight of the cut pieces. For the generated containers, the transfer time to temporary storage or waste storage is also evaluated based on the number of containers and the transfer distance. In this case, the work crew consisted of seven workers, one supervisor, and one radiation control staff member.

3.1.4. Place of mobile inventory for each initiating event

Table 5 shows the mobile inventory corresponding to the initiating event. The local filter is located at the contamination control enclosure and the building filter at the air conditioning system. Suspended and attached particles are in the contamination control enclosure during dismantling work.

Table 5. Mobile inventory corresponding to the initiating event

Initiating event	Mobile inventory
Fire	Particles accumulated at a local filter, suspended particles, particles attached at a contamination control enclosure
Explosion	Suspended particles, particles attached at a contamination control enclosure
Drop	Suspended particles, particles attached at a contamination control enclosure
Cease of active equipment	Suspended particles
Failure of equipment	Particles accumulated at a building filter
Loss of power	Suspended particles
Landslide	Suspended particles
Volcanic eruption	Particles accumulated at a building filter, suspended particles

3.2. Results and Discussion

3.2.1 BWR

Figure 2 shows the calculation result for dismantling schedule for components at reactor building of BWR without working in parallel. Approximately 29 years are necessary for components except reactor internals and the reactor pressure vessel, because the equipment was dismantled sequentially without setting up parallel operations. Figure 3 shows the temporal change of mobile inventory. Because dismantling began with non-radioactive equipment, mobile inventories of local filters accumulated in the latter half of the work period in both Areas A and B. The largest mobile inventory for the BWR will be in 12 years, and the dismantling of contaminated equipment in the reactor building is underway. Because reactor internals and the reactor pressure vessel are segmented underwater, the mobile inventory at local filter, where radioactive particles leaked from water with bubbles during cutting are accumulated, is smaller than those at dismantling in-air cutting. Figure 4 shows the exposure risk for eight initiating events. The fire event has the largest value because the probability of occurrence is higher than the other cases and the local filter is set with a high value for the mobility inventory. In the decommissioning period of 12-20 years, the exposure risk is not indicated in most cases because the equipment without radioactive contamination is dismantled due to the lack of mobile inventory of the green house, but in the cases of equipment damage and volcanic eruption, the building filter is set as a mobile inventory, so the exposure risk is plotted continuously. It is confirmed that exposure risk depends on the change of mobile inventory.

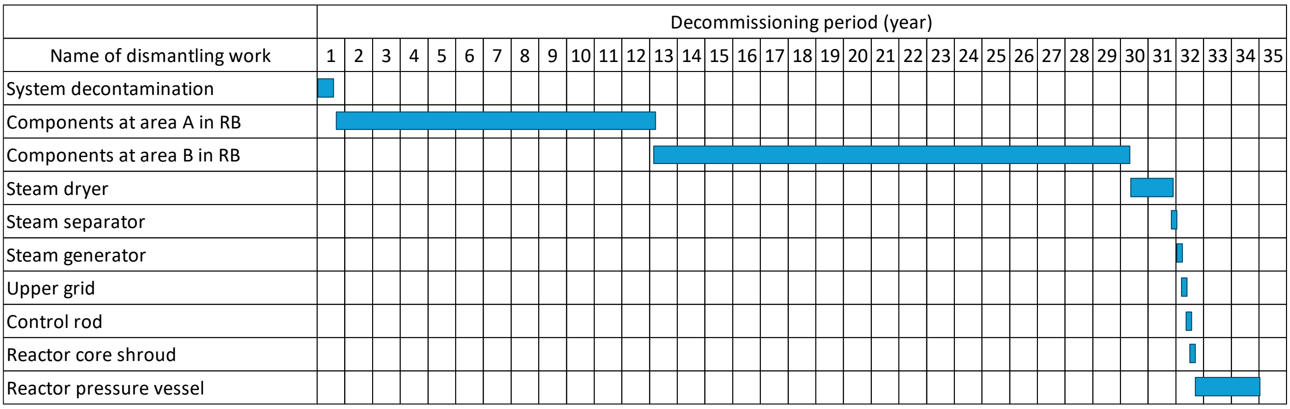


Figure 2. Dismantling schedule for components in reactor building of BWR without working in parallel

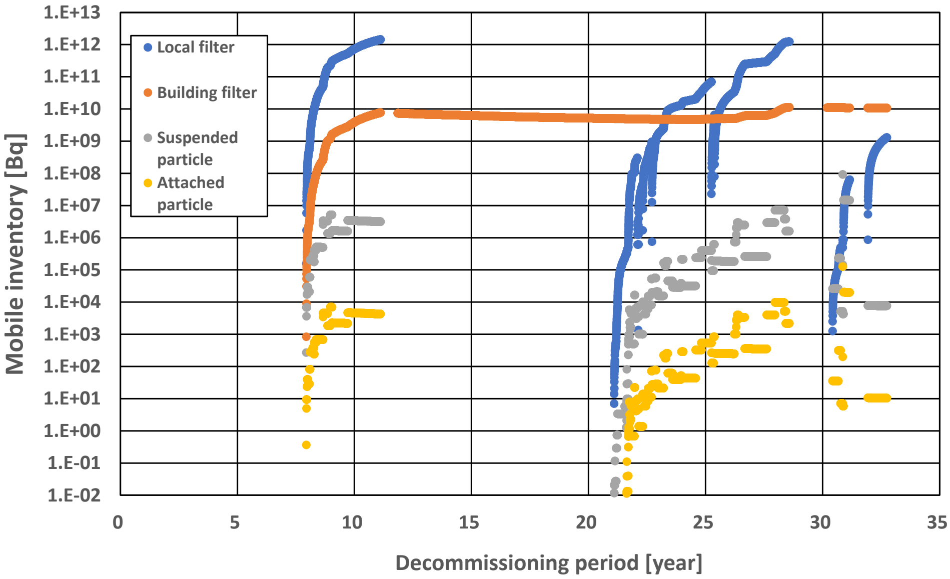


Figure 3. Calculated result of mobile inventory for dismantling of components in reactor building of BWR

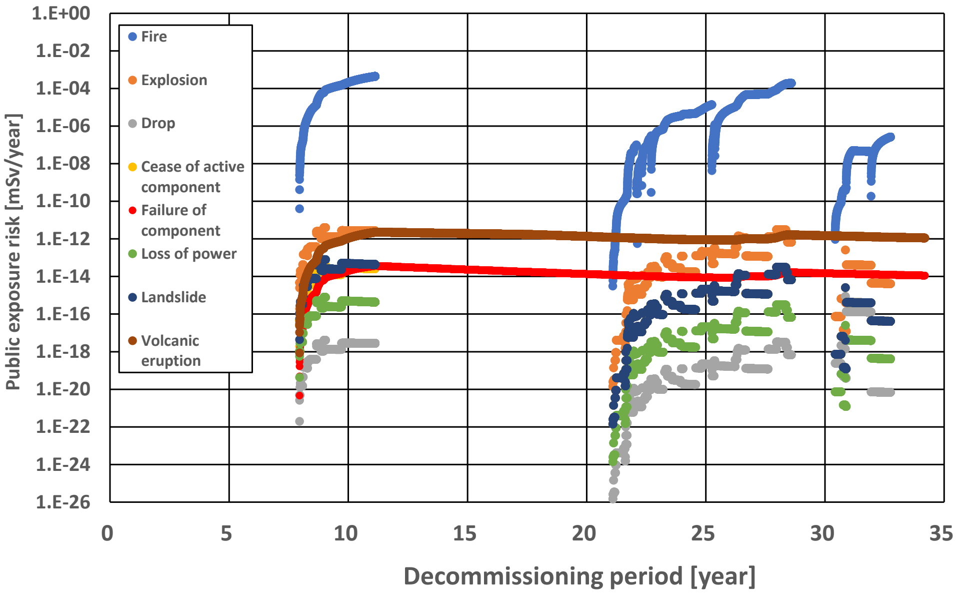


Figure 4. Calculated result of exposure risk for dismantling of components in reactor building of BWR

3.2.2. PWR

Figure 5 shows the dismantling schedule for PWR with working in parallel. Approximately 11 years are necessary for components except reactor internals and the reactor pressure vessel, because the components surrounding the reactor were dismantled sequentially with setting up parallel operations. Figure 6 shows the temporal change of mobile inventory. Due to the large amount of dust generated in the dismantling of the steam generator, the mobile inventory of the local filter is limited to 10^{11} Bq or less, but the mobile inventory of the building filter increased significantly due to the large surface contamination density. As in the case of BWR, the mobile inventory at local filter, where radioactive particles leaked from water with bubbles during cutting are accumulated, is smaller than those at dismantling in-air cutting. Figure 7 shows the exposure risk for eight initiating events. Maximum exposure risk value in PWR was larger by the same order of magnitude than that in BWR. The exposure risk was significantly greater for PWRs for attributable events involving mobile inventories of building filters. The information on time variation of exposure risk calculated in this way could be used for the selection of dismantling processes and target equipment and allocation of resources in nuclear regulatory inspections.

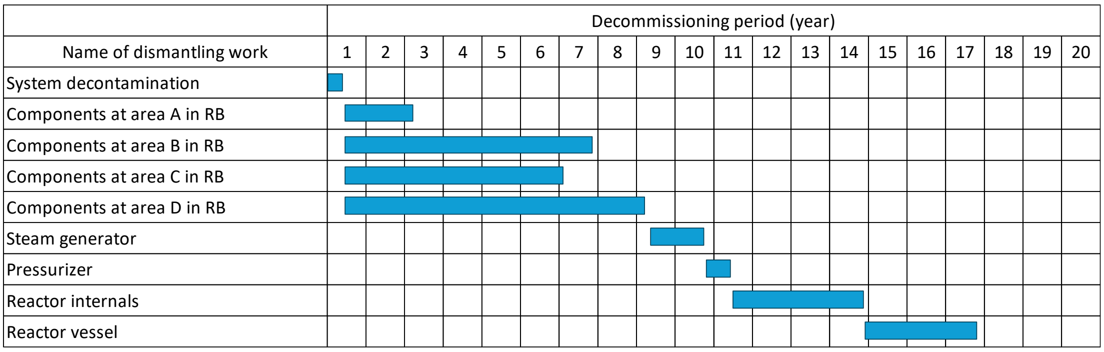


Figure 5. Dismantling schedule for components in reactor building of PWR with working in parallel

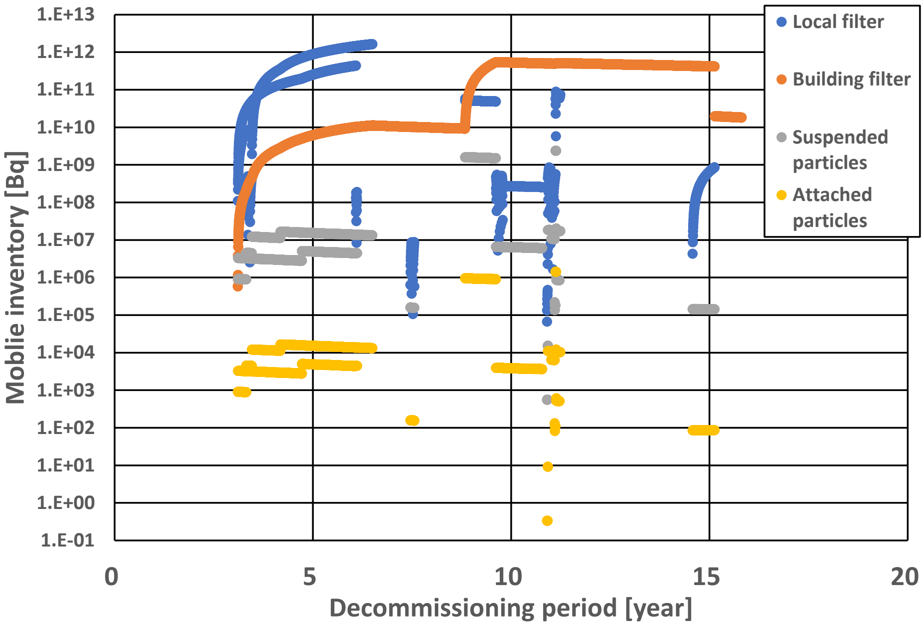


Figure 6. Calculated result of mobile inventory for dismantling of components in reactor building of PWR

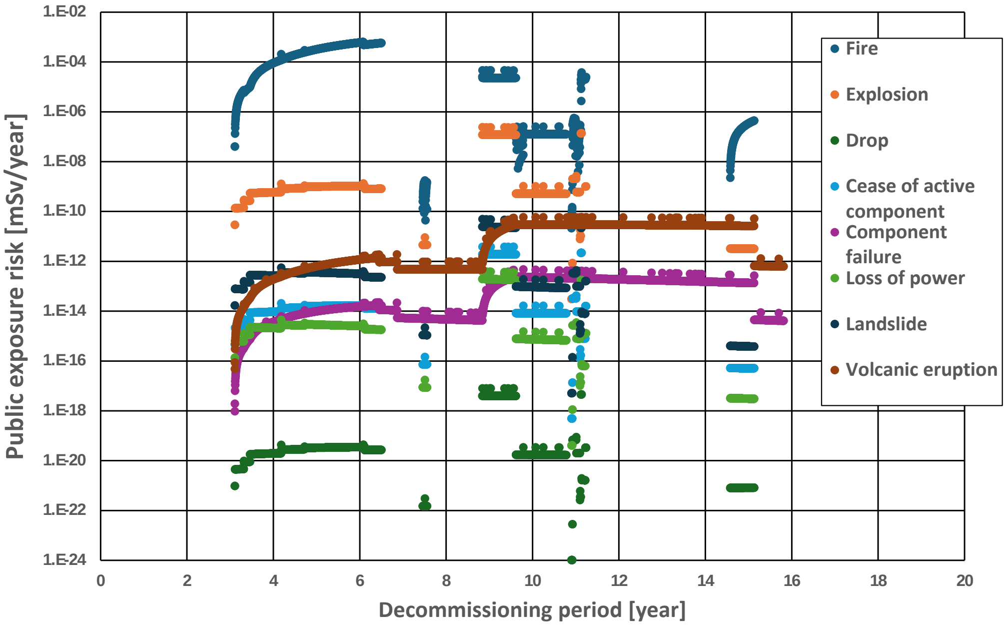


Figure 7. Calculated result of exposure risk for dismantling of components in reactor building of PWR

4. CONCLUSION

A radiation exposure risk assessment method and code, DecAssess-R for the decommissioning phase was applied to components in the reactor building both BWR and PWR in Japan for eight initiating events. Fire events indicated the greatest exposure risk for both BWR and PWR. Because of the high surface contamination density in PWRs and the accumulation of a large amount of mobile inventory in the building filters due to the airborne dismantling of steam generators with large surface areas, the exposure risk was about two orders of magnitude greater than in BWRs for events involving building filter failure. It is possible to indicate points to focus on in the dismantling of non-radioactive equipment. Not only the reactor buildings, but also all buildings, including waste storage areas to which mobile inventories are transported, need to be evaluated for changes in spatial exposure risk.

Acknowledgements

This study was funded by the Secretariat of Nuclear Regulation Authority, Nuclear Regulation Authority, Japan.

References

[1] Nuclear Regulation Authority in Japan, The Challenge of Inspection Program Reform, 2017. https://www.nra.go.jp/ data/000240878.pdf

[2] Nuclear Regulation Authority in Japan, Memo for discussion about safety goal and new regulatory criteria, 2017. (in Japanese)

[3] D. Mercurio, V. M. Andersen and K. C. Wagner, Integrated Level 1–Level 2 decommissioning probabilistic risk assessment for boiling water reactors, Nuclear Engineering and Technology, 50(5), 627-638, 2018.

[4] Y. Iguchi and M. Kato, Risk-Informed Approach for the Regulation of Decommissioning of Nuclear Facilities, J. Eng. Gas Turbines Power, 132(10), 102910, 2010.

[5] International Atomic Energy Agency, Management of Project Risks in Decommissioning, Safety Report Series No.97, IAEA, Vienna, 2019.

[6] T. Sasagawa., T. Shimada and S. Takeda., Development of the evaluation method for the mobile radioactive contaminants for assessing public exposure risk in accidental events during decommissioning of nuclear power station, Proceedings of the 31st International Conference Nuclear Energy for New Europe (NENE2022), September 12–16, Portorož, Slovenia, 2022.

[7] T. Shimada et al., Development of risk assessment code for dismantling of radioactive components in decommissioning stage of nuclear reactor facilities, Proceedings of International Conference on Environmental Remediation and Radioactive Waste Management (ICEM2023), October 3-6, 2023, Stuttgart, Germany 2023.

[8] T. Shimada and T. Sukegawa, “Improvement and testing of radiation source models in DecDose for public dose assessments during decommissioning of nuclear facilities”, Journal of Nuclear Science and Technology, 52(3), 396-415, 2015.

[9] T. Shimada, S. Ohshima and T. Sukegawa, Development of safety assessment code for decommissioning of nuclear facilities (DecDose). J Power Energy Syst. 2010;4:40–53, 2010.

[10] Nuclear Information Archives of Japan (NUCIA), http://www.nucia.jp/index.html. (in Japanese)

[11] Japan Nuclear Safety Institute, “BWR Internal Structures Inspection and Evaluation Guideline [Top fuel guide] (2nd edition)”, JANSI-VIP-11, 2015. (in Japanese)

[12] T. Yoshida et al., Estimation of the generic component reliability parameters for probabilistic risk assessment of the Japanese nuclear power plants, Central Research Institute of Electric Power Industry, NR21002, 2021. (in Japanese)

[13] T. Yoshida et al., Component reliability data collection guide for probabilistic risk assessment, Central Research Institute of Electric Power Industry, NR22006, 2023. (in Japanese)

[14] NRC, “Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station”, NUREG/CR-0672, vol.2, 1980.

[15] NRC, “Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station”, NUREG/CR-0130, vol.2, 1978.

[16] Central Research Institute of Electric Power Industry, Technical Study on Environmental Impact Assessment of Decommissioning of Power Reactor, 2007. (in Japanese)

[17] Nippon muki, Ultra-low pressure loss HEPA filter ATMPK2 Technical Data, GS0117, 2014. (in Japanese)