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Safety Assessment Framework for Nuclear Power Plant Decommissioning Workers (January 2019)

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ABSTRACT Considering that nuclear power plants have a licensed lifetime, the need for research on decommissioning is increasing along with the number of aging plants globally. Unlike the dismantling of other buildings, the decommissioning of a nuclear power plant involves radiation risk, which necessitates a new systematic safety assessment to reduce this risk. This study proposes a framework for the safety assessment of workers in nuclear power plant decommissioning. The first step of the process is *Accident Identification*, in which initiating events caused by mechanical failures or human errors are identified and categorized in accordance with their causes. The second step is *Frequency Analysis*, in which worker exposure in normal conditions is evaluated to derive the work time for each required task, and possible events that may happen during each task are derived through both a hazard and operability study and a failure mode and effect analysis. The third step, *Consequence Analysis*, models accident scenarios using the dose assessment program VISIPLAN, and evaluates worker exposure in those accident scenarios. The last step is *Risk Analysis*, where radiological risk is calculated quantitatively by the frequencies and exposure results of potential accidents. By performing safety evaluations according to the proposed framework, the safety of workers in nuclear power plant decommissioning may be increased.

INDEX TERMS Nuclear Power Plant, Decommissioning Worker, Safety Assessment, Risk Assessment.

I. INTRODUCTION

Recently, research on the decommissioning of nuclear power plants (NPPs) is actively underway as the operating years of NPPs have been gradually increasing along with a general lack of experience with nuclear facility decommissioning worldwide. In one such case, the Kori NPP Unit 1 in Korea has been permanently shut down and is currently planning to be dismantled; while research reactors have been decommissioned, this will be the first experience in Korea with decommissioning a commercial NPP.

Unlike the dismantling of other buildings, NPP decommissioning involves radiation risk. During planning, safety and radiation exposure evaluations for the dismantling process are important considerations in the selection of optimal dismantling procedures. By evaluating the safety of workers in advance, measures against accident situations can be prepared [1], [2].

There have been several studies on risk evaluation in NPP decommissioning. One method for assessing the risk of workers in radioactive areas during decommissioning obtains expert opinions derived from the semantic differential method [3]. In another study, the assessment method utilizes a risk matrix and fuzzy inference logic, with risk also determined by expert opinion [4]. Likewise, most research to date has been qualitative in nature, employing subjective expert judgment. However, to develop a guideline for workers in radioactive areas to minimize risks and prevent accidents, a quantitative method for risk assessment is required.

This study therefore proposes a framework for an objective safety assessment using statistical data and a systematic methodology. Four steps are developed that identify accidents, analyze accident frequency and consequence, and calculate risk. As a case study, one major containment system to be decommissioned called the bioshield is considered. By

applying this safety assessment framework to NPP decommissioning workers, radiological risk can be derived in a systematic way.

II. Radiological Risk of Workers in Nuclear Power Plant Decommissioning

It has been reported that, for research reactors, approximately 40% of the total dismantling costs are waste disposal costs, and 90% of the waste is concrete [5]. In order to process this waste, radioactive concrete is dismantled and decontaminated. As shown in Table 1, among the total, 260 tons of concrete is radioactive, and most of this radioactive concrete is contained in a structure called the bioshield. As shown in Figure 1, the bioshield is one of the multi-barrier systems for radiation shielding in NPPs. Made primarily of concrete, the bioshield is used to shield radiation (e.g. gamma rays and neutrons) with a shielding performance proportional to the density and thickness of the concrete [6], [7]. Most nuclear reactors use thick concrete shields to create a bioshield with a thin water-cooled layer of lead on the inside to protect the porous concrete from the reactor coolant.

TABLE I
WASTE MATERIALS FROM A RESEARCH REACTOR [5]

FIGURE 1. Multiple barriers in a typical NPP [6]

In general, risk is represented as the product of accident frequency and consequence. In this study, risk is defined as the potential exposure risk of workers during the bioshield decommissioning process, and it is represented as the product of the frequencies and consequences of accidents that could occur during this decommissioning.

III. Radioactive Safety Assessment Framework

A safety assessment framework should be developed with a systematic approach to derive the potential hazards in the decommissioning of NPPs as well as possible accidents during decommissioning activities [9].

The framework proposed in this study consists of four steps, as shown Figure 2. The first step is called *Accident Identification*, in which possible initiating events during a particular decommissioning process are determined. Due to a current lack of decommissioning data, such initiating events were identified here using accident data from the construction industry. Exposure paths are analyzed and possible accidents during NPP decommissioning are derived. The second step is called *Frequency Analysis*, where the decommissioning procedure is analyzed in a systematic manner using a hazard and operability study (HAZOP) [11] and failure mode and effect analysis (FMEA) [12]. Various work times for required tasks are derived by evaluating worker exposure in normal conditions. A frequency analysis is then performed using the analyzed procedural data and work times. The third step is *Consequence Analysis*; in this study, consequence refers to

worker radiation exposure in an accident, and in order to obtain this exposure nuclides are analyzed through the modeling tool MCNP [13] with accident scenarios evaluated through the VIPLAN program [14] and event tree analyses (ETAs) [18]. The last step is *Risk Analysis*, in which risk is calculated from frequency and exposure followed by a sensitivity analysis. This framework can be used to derive the radiological risks for workers in various decommissioning activities. Each step is considered in detail in the following sections.

FIGURE 2. Safety assessment framework process

A. Accident Identification – Step 1

In the *Accident Identification* step, accidents are identified that may occur when the worker dismantles the concrete in the bioshield. To identify the possible accidents, initiating events are analyzed in the decommissioning of NPPs, as shown in Table 2. In general, internal and external events are considered in order to identify potential initiating events; external events indicate accidents from plane crashes or by natural conditions such as earthquakes, while internal events include mechanical failures and human errors. In this work, only internal events were considered [1].

TABLE II
INITIATING EVENTS IN DECOMMISSIONING [1]

The radiation exposure path is also considered, which is a characteristic of NPP decommissioning. Safety evaluation for the decommissioning of radioactive bioshield concrete includes four exposure paths:

- Direct gamma emission from nuclides in the radioactive concrete;
- Contamination (i.e. external exposure to the radioactive concrete);
- Internal exposure to dust from the radioactive concrete;
- Combination of radiological contamination and personal injury (fall, collision, etc.).

Considering the initiating events and exposure pathways, possible accidents are identified during the decommissioning process. As shown in Figure 3, there are three types of accidents: external exposure, internal exposure, and human error. External exposure involves direct radiation or submersion, and internal exposure involves inhalation or ingestion. Submersion refers to the exposure of persons immersed in a dust of radioactive material [10]. Both external and internal exposures are determined by mechanical failure. In the case of human error, which is defined here as falling, getting trapped under concrete, getting cut, and fainting, the sequence may be changed by some mechanical failure. As the purpose of this study is to derive radiological risk, physical wounds were not considered. These accidents change the radiation shielding, time, and distance from the radioactive concrete.

FIGURE 3. Possible accidents involved in decommissioning

B. Frequency Analysis – Step 2

In order to obtain frequencies of the accidents derived in the previous step, as shown in Figure 4, annual working time and working procedure analyses are required in the *Frequency Analysis* step. Worker exposure during normal conditions is evaluated to calculate the annual working time. The human errors that can occur at each step are derived through HAZOP, and possible accidents caused by the mechanical failures of each piece of equipment are identified through FMEA. For accidents caused by human errors, frequency was derived using statistical data from a Korea Occupational Safety and Health Agency (KOSHA) [16] report and the results of HAZOP. For accidents due to mechanical failures, failure rates derived from probabilistic safety assessments (PSAs) of NPPs were used in the frequency analysis. For equipment without reported data, failure rates were assumed.

1) DECOMMISSIONING PROCEDURE ANALYSIS

Since there is no standardized method for bioshield decommissioning in a commercial NPP, the procedure in this study was developed by referring to the decommissioning procedure for the radioactive concrete of a research reactor. Radioactive concrete dismantling consists of five tasks, as shown in Figure 4 [2], [15]. The bioshield is disassembled by first cutting it into concrete blocks of 1 m width, 1 m length, and 1 m height.

FIGURE 4. Bioshield decommissioning procedure

A detailed activity analysis was carried out for the bioshield decommissioning process. In the case of the transportation task, shown in Table 3, the drilling and lifting work were divided, with detailed activities of each step clarified.

TABLE III
EXAMPLE OF DETAILED ACTIVITY ANALYSIS

2) ASSESSING WORKER EXPOSURE IN NORMAL CONDITIONS

Before assessing an accident scenario, exposure in normal states should be calculated. Figure 5 shows the dose rate from the bioshield, where the white sections represent the bioshield surrounding the core. The dose rate is the highest in the red circle, and thus the safety assessment performed here considers this section.

FIGURE 5. Dose rate from the bioshield

Table 4 lists possible working times based on the dose rates from Figure 5. Following International Commission on Radiological Protection (ICRP) data, the effective dose limit was set to 20 mSv per year [17]. Based on the highest dose rate

of 0.024 mSv/h, 832 hours of work time per year was derived using the effective dose limit. To obtain the work time for each task from Figure 4, the ratio of each work time was derived through a detailed analysis of the procedure of each task, as in Table 3. Table 5 shows the derived work times.

TABLE IV
POSSIBLE WORK TIMES BASED ON DOSE RATE

TABLE V
TIME FOR EACH TASK

3) ACCIDENT ANALYSIS OF EACH STEP – HUMAN ERROR

A systematic analysis is needed to derive human error. HAZOP is therefore a good tool as it considers all possible human errors in a systematic way by deriving human errors in a given process using guide words and human action factors. The guide words are shown in Table 6.

TABLE VI
GUIDE WORDS USED IN HAZOP [11]

The guide words “No”, “Not”, and “None” indicate a situation where no action occurs, and the guide words “More”, “High”, “Large”, and “Fast” indicate a situation in which many actions occur. “Less”, “Low”, “Small”, and “Slow” indicate a situation with less activity or a rare occurrence. “Part of” refers to a partial action, “As well as” a situation that adds behavior, and “Reverse” a situation that reverses the behavior. Finally, “Other” indicates a situation with different actions outside the procedure. These guide words are used in combination with human action factors to derive human errors.

TABLE VII
HAZOP HUMAN ACTION FACTORS [11]

According to the actions that are involved in the nuclear decommissioning process, a total of 45 human action factors are identified: 27 hand motions, 3 foot motions, and 15 body motions. Human error is derived by combining the guide words of Table 6 with the human action factors of Table 7. For example, a combination of “Catch” and “Not” gives “Unable to catch”, which can lead to an accident such as “Cannot catch a safety railing” [11].

Table 8 shows detailed accident analysis data for one example task in the application of HAZOP to the concrete decommissioning process. As seen in this table, Step 5.1.3 is “Insert the wire into the perforated hole”, and if a worker does not completely insert the wire into the perforated hole but rather does so partially, the possible accidents falling, getting trapped under concrete, external exposure, and internal exposure appear.

TABLE VIII
HAZOP EXAMPLE

The accidents in each decommissioning task are derived through HAZOP. Figure 6 illustrates the number of human error accidents per task; in the decommissioning process, falling is the most frequent accident in all steps.

FIGURE 6. Result of HAZOP

To obtain accident frequency, this study used statistical construction data from KOSHA [16] due to a lack of decommissioning data. As shown in Table 9, statistical analyses of various accidents have been reported, such as falling, getting trapped under concrete, fire, electric shock, etc. The report also included an analysis of the causes for each incident.

TABLE IX
2015 INDUSTRIAL ACCIDENT ANALYSIS DATA [16]

The accidents are derived for each task, and to obtain frequency, the probability of each accident is calculated by using the number of industrial accident victims from the construction industry considering 5,941,068,434 total annual working hours [16]. Accident frequency is calculated using Eq. (1). Table 10 shows the frequency values obtained from Eq. (1).

$$Frequency = \frac{Number\ of\ Steps\ related\ to\ Each\ Accident\ Type}{Total\ Number\ of\ Steps} * Working\ Time\left(\frac{h}{y}\right) * Probability\ of\ Accident\left(\frac{1}{h}\right) \quad (1)$$

TABLE X
ACCIDENT PROBABILITY AND FREQUENCY

4) ACCIDENT ANALYSIS OF EACH STEP – MECHANICAL FAILURE

It is necessary to analyze accidents by mechanical failure as well as accidents by human error. FMEA is a method of deriving fault for a system or device. When a failure occurs in a device or a component, the effect of the failure on the system is analyzed to derive the particular device or components that have the greatest influence. Measures can be taken for the equipment or components for which high risk has been detected, thereby improving the availability, reliability, or quality of the system. The purpose of FMEA is to derive the mode, cause, and effect of the potential failures of equipment, and to provide solutions to reduce or eliminate the occurrence of accidents, hazards, and potential failures during the decommissioning process [12]. The analysis process is shown in Figure 7.

FIGURE 7. Failure mode & effect analysis process

Table 11 shows the relevant equipment in the application of FMEA during the concrete decommissioning process. For

example, if masks or protective equipment are defective, the potential failure effect is internal exposure.

TABLE XI
FMEA EXAMPLE

Now, failure rates for the above equipment are needed, which can be derived from the reliability data used in the PSA of NPPs [18]. The failure rates of ventilation, protective clothing, and dust collectors were assumed. Table 12 shows the failure rate values used in this study.

TABLE XII
FAILURE RATE

C. Consequence Analysis – Step 3

The purpose of the *Consequence Analysis* step is to evaluate decommissioning worker exposure during accident scenarios. In this study, nuclide analyses are performed using MCNP, and worker exposure is evaluated with VISIPLAN. VISIPLAN 3D ALARA planning is a new calculation tool developed to facilitate planning based on 3D-geometrical, material, and radiological information. Dose calculations are based on a point-kernel method with build-up correction [14]. For the nuclide analyses, only ⁶⁰Co was considered because it is relatively more dominant than the other nuclides in the bioshield, as shown in in Table 13 [19].

TABLE XIII
SPECIFIC ACTIVITIES AT VARIOUS DEPTHS IN THE TROJAN REACTOR BIOSHIELD [19]

This study develops a quantitative model of accident scenarios using VISIPLAN and ETAs as follows: accident sequences are illustrated through event trees (ETs), and the consequence of each end state is calculated by VISIPLAN.

The ETA is a method mainly used in PSA, which is often employed in plant safety evaluation. ETs assess risk by determining the consequence and probability of an event. As shown Figure 8, each branch considers only component success or failure, or that an accident occurs or does not occur. The sum of the risk values of each tree is the risk of the accident; here, the total risk of decommissioning is the sum of the risks of all accidents [18].

FIGURE 8. Basic event tree schematic

1) ACCIDENT SCENARIO MODELING

Accident sequences are modeled via ETA. Figures 9 and 10 depict ETs of an accident caused by mechanical failure. The ET heads of external exposure (Fig. 9) are protective clothing, ventilation system, and dust collector failures. The ET heads of internal exposure (Fig. 10) are mask, ventilation system, and dust collector failures. Each branch probability uses the equipment failure rates from the previous step.

FIGURE 9. ET for the risk of external exposure from mechanical failure

FIGURE 10. ET for the risk of internal exposure from mechanical failure

Figure 11 shows an ET for an accident caused by human error. The accident assumes that the protective clothing or mask is damaged in the accident, so the ET heads of the accident are ventilation and dust collector failures.

FIGURE 11. ET for a human error accident

For a feasibility study on a human error accident, four scenarios were considered: falling, getting trapped under concrete, getting cut, and fainting. It is assumed that the mask or protective clothing is damaged when the upper incidents occur. In case of falling, it is assumed that it is not an accident if the fall is below 1 m. Depending on the required height of the task, the dose rates differ, and thus the analysis is carried out according to height. Rescue time is assumed to be 20 min, with a sensitivity analysis of the rescue time also performed.

Since the dose is dominant under 6 m, the safety assessment was applied at less than 6 m. The accidents of falling, getting trapped under concrete, and getting cut and fainting are shown in Figures 12, 13, and 14, respectively, which plot rescue trajectories when an accident occurs. Position 1 is the point where the worker dismantles the concrete, and position 2 is the point where the accident occurs and the worker receives emergency treatment. Positions 3 and 4 are the paths that are cleared for the rescue of the worker.

FIGURE 12. Falling trajectories

FIGURE 13. Getting trapped under concrete trajectories

FIGURE 14. Getting cut and fainting trajectories

2) EXPOSURE EQUATION

This section evaluates worker exposure using equations to include inhalation, ingestion, and submersion that are not derived from VISIPLAN, where D_{inh} is exposure from inhalation and D_{ing} is exposure from ingestion.

$$D_{inh} = INH * t_{inh} * \frac{1}{APF} * K * (1 - MD) * \sum (DCF_{inh} * C) \quad (2)$$

$$D_{ing} = INH * t_{inh} * \frac{1}{APF} * (1 - K) * (1 - MD) * \sum (DCF_{ing} * C) \quad (3)$$

Here, INH is worker breathing rate (m³/h), t_{inh} is time during which the worker breathes in a radioactive cloud (h), APF is the assigned protection factor of the respirator type, K is the portion of inhaled activity, DCF is the effective dose coefficient for the i -th radionuclide (Sv/Bq), MD is a mask damage factor, and C is the air concentration of the i -th radionuclide for getting cut (Bq/m³). Among these, a standard breathing rate of 1.2 m³/h and a K of 0.9 were used [20], and APF was 10 due to workers use half mask or dust mask [21].

Lastly, DCF_{inh} of ⁶⁰Co is 9.6E-09 Sv/Bq, and DCF_{inh} of ⁶⁰Co is 3.4E-09 Sv/Bq [22].

$$D_{sub} = t_{sub} * \frac{TIL}{100} * \sum (DCF_{sub} * C) \quad (4)$$

In Eq. (4), D_{sub} is exposure from submersion, DCF_{sub} is the effective dose coefficient for the i -th radionuclide for submersion (Sv/(Bq*s*m⁻³)), and TIL is total inward leakage. DCF_{sub} is 1.45E-13 Sv/(Bq*s*m⁻³) [23], and TIL is 1% [24]. C can be found by $C = Z * l * A * f * t^{-1} * Q^{-1} * (1 - DCR)$, where Z is the width of type-x cutting technology (cm), l is length (cm), A is surface activity of the radionuclide, f is released respirable mass fraction of removed material, Q is air flow from the room to the outside (m³/h), and DCR is the dust collection ratio. Here, f of the employed diamond wire saw is 5E-05 [25], and Q is 2500 m³/h [26].

The radionuclide concentration C was derived from the MCNP, and the other values came from previously reported work. For each accident scenario, considering the mask damage factor, dust collection ratio, total inward leakage related to protective clothing, and air flow, worker exposure was evaluated.

3) EXPOSURE EQUATION

Worker exposure resulting from human error accidents was evaluated by considering mechanical failure. Dose exposure results were found using VISIPLAN and exposure equations. As previously mentioned, in case of the falling accident, it is assumed that there is no injury when falling from 1 m or less. The worst case comes from ventilation system and dust collector failure with human error, as shown in Table 14. Here, the largest exposure is from getting trapped under concrete, because there is radioactive concrete physically on the worker.

TABLE XIV

DOSE EXPOSURE FROM A HUMAN ERROR ACCIDENT PLUS VENTILATION SYSTEM AND DUST COLLECTOR FAILURE

The following Tables 15 and 16 show evaluations of internal and external exposures, respectively, due to various mechanical failures. Such data is useful to see the influence of each equipment. For example, if the ventilation system fails, it will have a relatively large impact on worker exposure.

TABLE XV

INTERNAL EXPOSURE FROM AN INGESTION AND INHALATION ACCIDENT PER MECHANICAL FAILURE

TABLE XVI

EXTERNAL EXPOSURE FROM A SUBMERSION ACCIDENT PER MECHANICAL FAILURE

D. Risk Analysis – Step 4

The final step, *Risk Analysis*, is conducted through an ETA using the frequencies, failure rates, and exposure results obtained previously. Risk is evaluated from the ETs developed in step 3. In Table 17, the first S or F in the risk column refers

to mask and protective clothing operation or malfunction, the second to the ventilation system, and the third to dust collection. The ventilation system has the greatest impact on risk.

TABLE XVII
EXTERNAL EXPOSURE FROM A SUBMERSION ACCIDENT PER MECHANICAL FAILURE

Table 18 lists the risk of human error accidents from ETs with ventilation system and dust collector failure plus falling, getting trapped under concrete, getting cut, and fainting. Falling exhibits the largest proportion in the case of human error accidents.

TABLE XVIII
RISK OF HUMAN ERROR ACCIDENT FF CASE

As shown in Figure 15, the risk of mechanical failure accidents is significantly larger than human error accidents. This is because equipment failure rates are larger than the probability of human error accidents.

FIGURE 15. The distribution of risk when working at a height of 3 meters

Since the rescue time was assumed in accident scenarios, sensitivity analyses were needed. Figure 16 shows that if the rescue time exceeds two hours, human error accidents take up more than 30% of the total risk.

FIGURE 16. Sensitivity analysis

IV. Conclusion

Safety assessments for the decommissioning of NPPs are important for the safety of workers. Unlike in other industries, the dismantling of NPPs involves radiation risk, and therefore, this study aimed to derive the radiological risk of decommissioning workers.

The safety assessment framework presented in this study is systematic and objective. The four steps detail possible accidents and the according frequencies and worker exposure of these accidents in order to assess the radiological risk of workers quantitatively.

Further studies are needed to improve the completeness of this framework, after which more reliable risk data can be obtained. The limitations of the current work are as follows. First, only ^{60}Co among the nuclides was considered, for the reason that a nuclide analysis from the decommissioning of other NPPs found ^{60}Co to be dominant. If other nuclides are considered, the internal and external exposures could change. Further studies will consider additional nuclides. Second, due to a lack of reliability data for the equipment used in decommissioning, the failure rates of some components were assumed. More accurate failure rates are needed for more reliable data.

Third, the decommissioning procedure of the Kori Unit 1 is still under development. Therefore, this study was carried out with reference to the decommissioning procedure of a research reactor. Analysis of the detailed decommissioning procedure for a commercial plant is necessary. Fourth, conservative assumptions were made in this study to consider the maximum amount of concrete, and therefore nuclides, for analysis; in other words, the assumptions did not take into account the continuous removal of concrete blocks over the course of decommissioning. For a more accurate evaluation, it is necessary to describe the intervals of concrete block removal in terms of remaining concrete and nuclides.

Through this study, the main risk factors involved in the decommissioning of an NPP bioshield were identified by sensitivity analyses. In order to minimize the risk quantitatively assessed here, in terms of accident prevention, risk results can be applied as a regulatory guide to decommissioning NPPs, after correcting for the assumptions and limitations of the current work.

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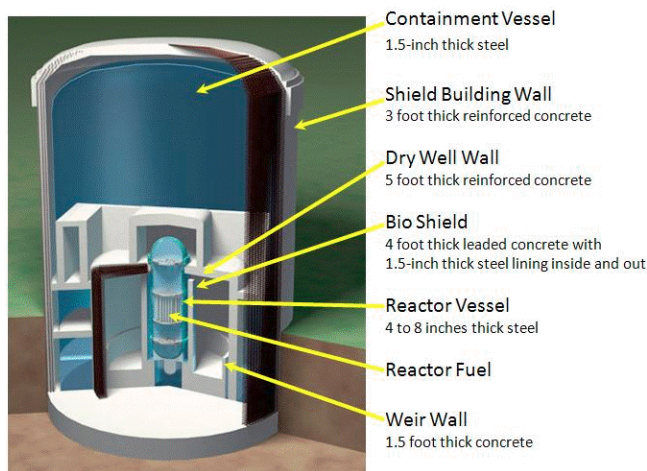


FIGURE 1. Multiple barriers in a typical NPP [6]

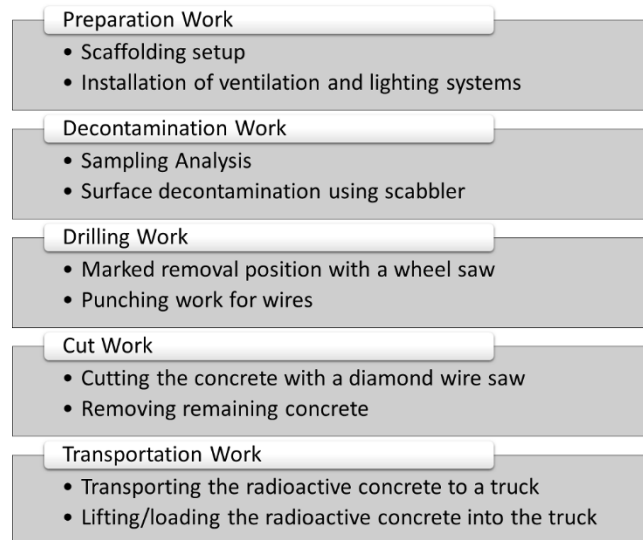


FIGURE 4. Bioshield decommissioning procedure

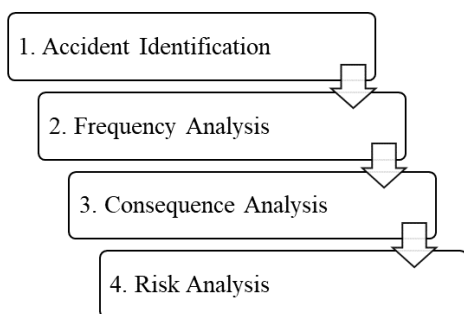


FIGURE 2. Safety assessment framework process

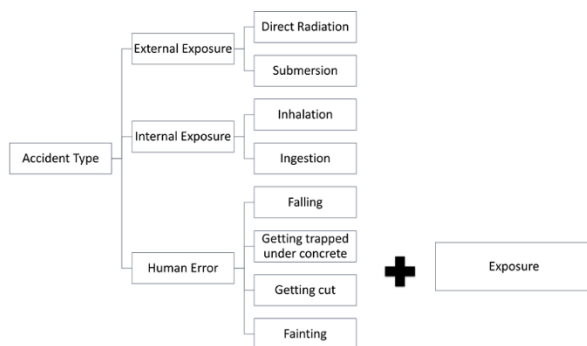


FIGURE 3. Possible accidents involved in decommissioning

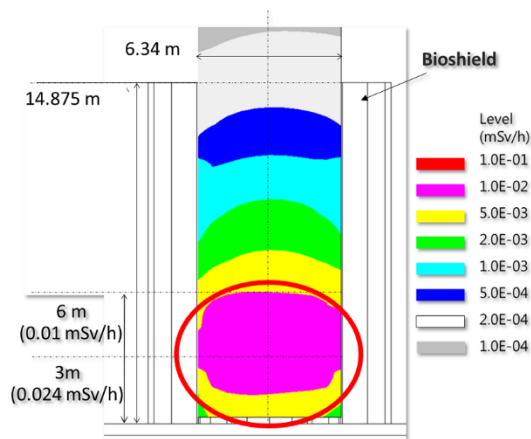


FIGURE 5. Dose rate from the bioshield

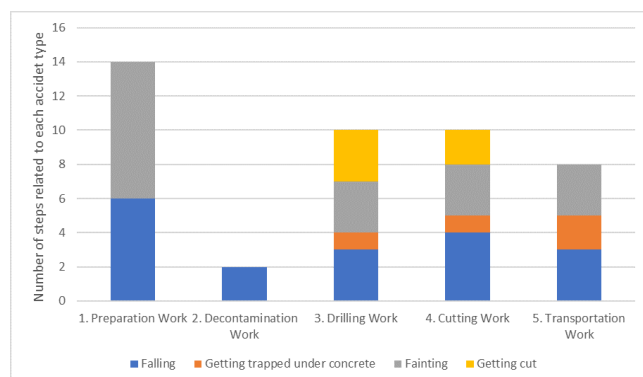


FIGURE 6. Result of HAZOP

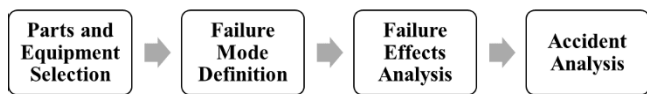


FIGURE 7. Failure mode & effect analysis process

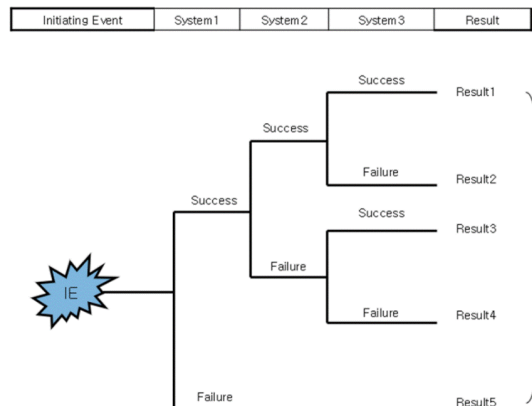


FIGURE 8. Basic event tree schematic

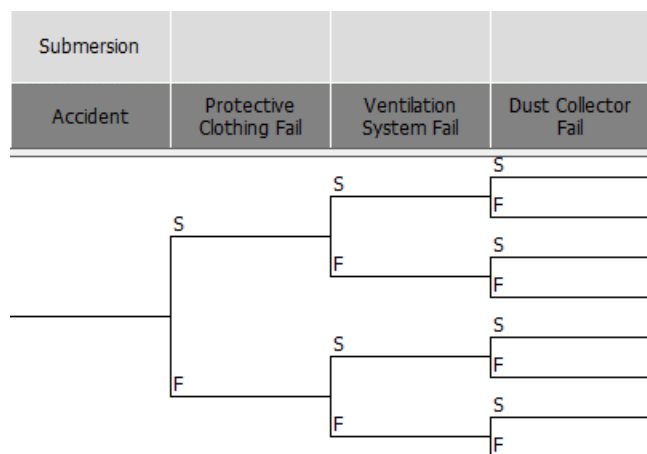


FIGURE 9. ET for the risk of external exposure from mechanical failure

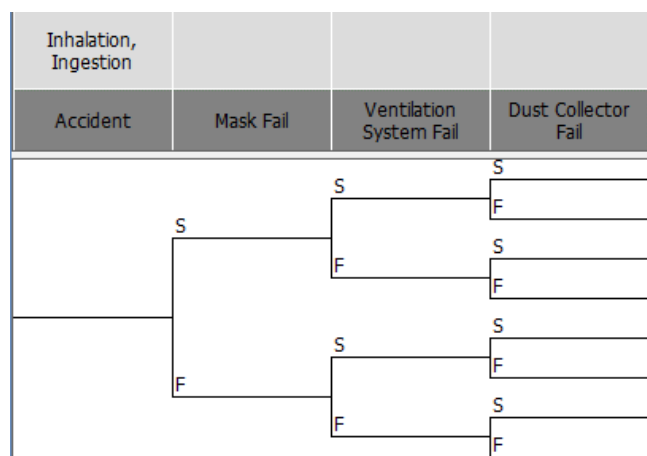


FIGURE 10. ET for the risk of internal exposure from mechanical failure

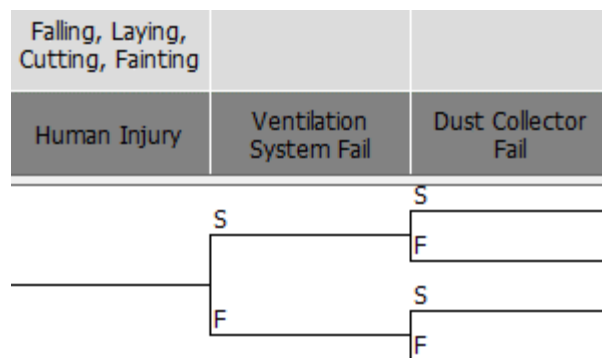


FIGURE 11. ET for a human error accident

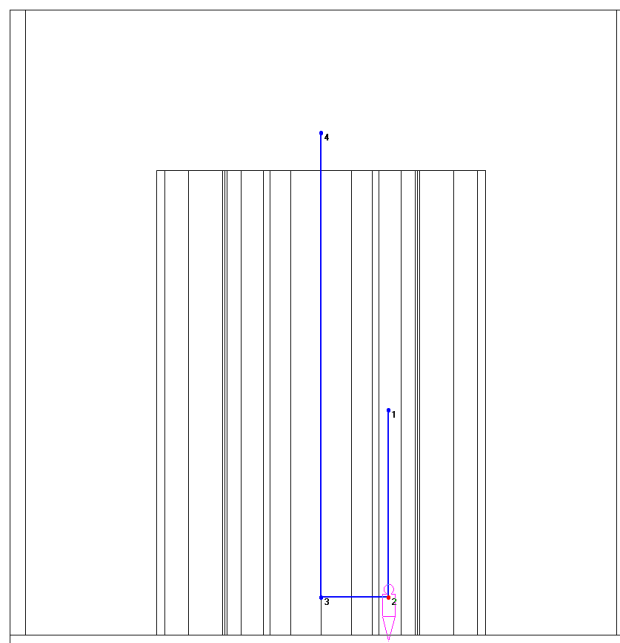


FIGURE 12. Falling trajectories

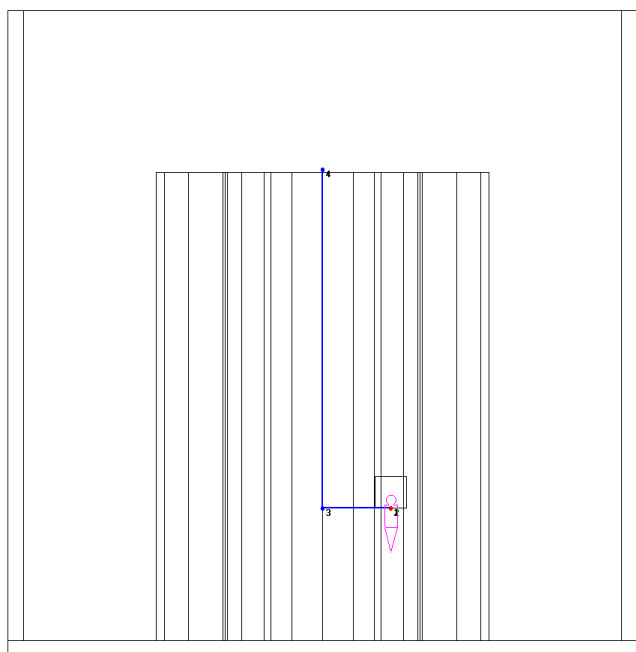


FIGURE 13. Getting trapped under concrete trajectories

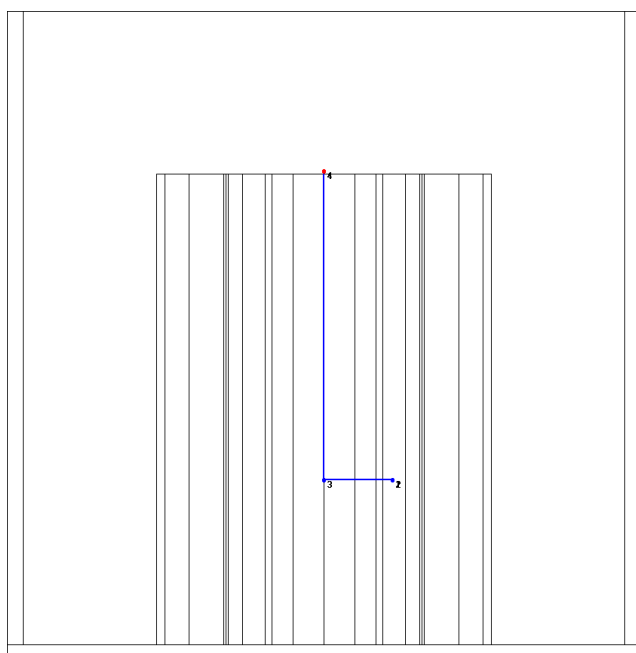


FIGURE 14. Getting cut and fainting trajectories

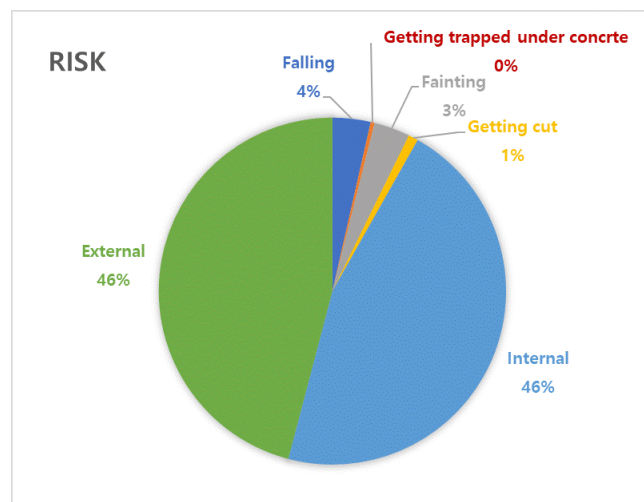


FIGURE 15. The distribution of risk when working at a height of 3 meters

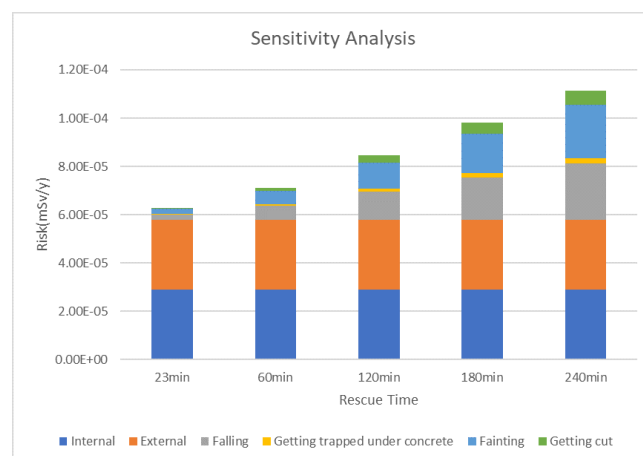


FIGURE 16. Sensitivity analysis

TABLE I
WASTE MATERIALS FROM A RESEARCH REACTOR [5]

	Radioactive	For release	Total
Metal	18 ton	163 ton	181 ton
Concrete	260 ton	1,746 ton	2,006 ton
Other	17 ton	35 ton	52 ton
Total	295 ton	1,944 ton	2,239 ton

TABLE II
INITIATING EVENTS IN DECOMMISSIONING [1]

External initiating event	<ul style="list-style-type: none"> Natural conditions (e.g. earthquake) Airplane crash
Internal initiating events by mechanical failures	<ul style="list-style-type: none"> Fire, explosion, structural collapse due to instrument defect Lighting system failure, ventilation system failure Failure of mask or other protective equipment
Internal initiating event by human errors	<ul style="list-style-type: none"> Errors in the operation of a machine Access to dangerous places Personal injury during work (e.g. falling)

TABLE III
EXAMPLE OF DETAILED ACTIVITY ANALYSIS

Task	Step	Detailed Activities
5. Transportation Work	5.1 Radioactive concrete drilling prior to lifting	5.1.1 Setting the puncturing positions according to field judgment
		5.1.2 Perforating the markings
		5.1.3 Inserting wires into perforated holes
	5.2 Lifting of radioactive concrete	5.2.1 Checking the fixed wires
		5.2.2 Lifting with a crane and loading into a truck
		5.2.3 Transporting by truck after loading

TABLE IV
POSSIBLE WORK TIMES BASED ON DOSE RATE

Dose rate (mSv/h)	2.40E-02
Effective dose limit per year (mSv/y)	20
Yearly possible working time (h/y)	832.38
Daily possible working time (h/d)	2.77

TABLE V
TIME FOR EACH TASK

Work	Working time (h)
1. Preparation	118
2. Decontamination	118
3. Drilling	238
4. Cutting	238
5. Transportation	118

TABLE VI
GUIDE WORDS USED IN HAZOP [11]

Guide words
No, Not, Node
More, High, Large, Fast
Less, Low, Small, Slow
Part of
As well as
Reverse
Other than

TABLE VII
HAZOP HUMAN ACTION FACTORS [11]

Human Action Factors	Human Action Factors
Catch / Grasp / Support	Slip / Fall
Pull	Foot Motion Step
Push	Kick
Press down	Stand
Stretch	Sit
Touch / Contact	Bend
Stroke	Spread out
Wipe	Turn around
Lift	Lay down
Set / Lower	Kneel down
Turn	Body Motion Cover
Shake	Wear / Put on
Throw	Take off
Stab	Walk
Wield	Run
Hit	Lean
Insert	Jump
Remove	Tremble / Shake
Combine / Assemble	
Separate / Disassemble / Release	
Tilt	
Reverse	
Tumble	
Scratch	
Bet	
Turn on	
Turn off	

TABLE VIII
 HAZOP EXAMPLE

Task	Step	Detailed Activities	Deviation	Predictable Accident	Accident Type
5. Transportation	5.1 Radioactive concrete drilling prior to lifting	5.1.1 Setting the puncturing positions according to field judgment	N/A	N/A	N/A
		5.1.2 Perforating the markings	Cannot catch	Pulling a perforator weakly may cause personal injury	Cutting, External exposure
		5.1.3 Inserting wires into perforated holes	Only partly.	Failure to catch the railing after tipping during wire insertion.	Falling, Internal exposure, External exposure
	5.2 Lifting of radioactive concrete	5.2.1 Checking the fixed wires	Cannot hang	Partially hung wire falls out of concrete during lifting	Getting trapped under concrete, Falling, Internal exposure, External exposure
		5.2.2 Lifting with a crane and loading into a truck	Hanging partly	During the lifting, concrete is only partially secured and falls back down	Getting trapped under concrete, Internal exposure, External exposure
			Press another	Crane operator error, dropping radioactive concrete and damaging protective equipment	Fainting, Falling, Internal exposure, External exposure
		5.2.3 Transporting with truck after loading	Press another	Concrete falls out of the truck onto workers	Fainting, Getting trapped under concrete

TABLE IX
 2015 INDUSTRIAL ACCIDENT ANALYSIS DATA [16]

Disaster	Falling	Collapse	Collision	Electric shock	Getting cut	Getting trapped under concrete
Annual disaster	8259	327	3168	138	2625	766

TABLE X
 ACCIDENT PROBABILITY AND FREQUENCY

Accident	Falling	Fainting	Getting cut	Getting trapped under concrete
Industrial Accident Victims	8586	5264	2625	766
Probability of Accident (/h)	1.445E-06	8.860E-07	4.418E-07	1.289E-07
Frequency (/h)	5.727E-04	1.457E-05	2.921E-04	8.012E-05

TABLE XI
 FMEA EXAMPLE

Equipment	Potential Failure Mode	Predictable Accident	Potential Failure Effects
Mask	Defective mask	Defective mask failure to block harmful air	Internal exposure
Crane	Crane operating equipment damage	Crash of malfunctioning crane, damage to protective equipment	Fainting, External exposure, Internal exposure
Ventilation System	Ventilation system failure	Air is not ventilated during decommissioning	External exposure, Internal exposure
Dust Collection	Dust collection failure	Dust is not absorbed during decommissioning	External exposure, Internal exposure

TABLE XII
FAILURE RATE

	Protective Clothing Failure Rate	Mask Failure Rate	Ventilation Failure Rate	Dust Collector Failure Rate
Failure Rate (/y)	0.002	0.002	0.003	0.001
Failure rate considering work time (/y)	1.900E-04	1.900E-04	2.849E-04	9.498E-05

TABLE XIII
SPECIFIC ACTIVITIES AT VARIOUS DEPTHS IN THE TROJAN REACTOR BIOSHIELD [19]

Sample location (cm from inner shield surface)	⁶⁰ Co	¹⁵⁰ Eu	¹⁵⁴ Eu	¹³⁴ Cs
7.6	1.11E+4	1.07E+4	9.99E+2	3.52E+2
41.9	9.25E+2	1.07E+3	1.04E+1	1.85E+0
71.6	2.18E+1	2.55E+1	2.04E+0	2.78E-1

TABLE XIV
DOSE EXPOSURE FROM A HUMAN ERROR ACCIDENT PLUS VENTILATION SYSTEM AND DUST COLLECTOR FAILURE

Height	Falling (mSv)	Getting trapped under concrete (mSv)	Fainting (mSv)	Getting cut (mSv)
6 m	3.70E-03	3.50E-03	1.90E-03	1.90E-03
5 m	3.75E-03	5.20E-03	3.25E-03	3.25E-03
4 m	8.03E-03	9.93E-03	9.03E-03	9.03E-03
3 m	8.13E-03	2.02E-02	1.14E-02	1.14E-02
2 m	6.06E-03	6.96E-03	5.26E-03	5.26E-03
1 m	0	4.28E-03	4.18E-03	4.18E-03
0 m	0	3.11E-03	3.01E-03	3.01E-03

TABLE XV
INTERNAL EXPOSURE FROM AN INGESTION AND INHALATION ACCIDENT PER MECHANICAL FAILURE

Height/Scenario	No failure (mSv)	Dust collector failure (mSv)	Ventilation system failure (mSv)	Mask failure (mSv)
6 m	8.29E-15	8.29E-13	2.07E-11	8.29E-12
5 m	3.19E-13	3.19E-11	7.98E-10	3.19E-10
4 m	2.70E-11	2.70E-09	6.76E-08	2.70E-08
3 m	2.70E-11	2.70E-09	6.76E-08	2.70E-08
2 m	1.45E-11	1.45E-09	3.62E-08	1.45E-08
1 m	4.36E-12	4.36E-10	1.09E-08	4.36E-09
0 m	4.36E-12	4.36E-10	1.09E-08	4.36E-09

TABLE XVI
EXTERNAL EXPOSURE FROM A SUBMERSION ACCIDENT PER MECHANICAL FAILURE

Height/Scenario	No failure (mSv)	Dust collector failure (mSv)	Ventilation system failure (mSv)	Mask failure (mSv)
6 m	5.36E-15	5.36E-13	1.34E-11	5.36E-13
5 m	2.06E-13	2.06E-11	5.16E-10	2.06E-11
4 m	1.75E-11	1.75E-09	4.37E-08	1.75E-09
3 m	1.75E-11	1.75E-09	4.37E-08	1.75E-09
2 m	9.37E-12	9.37E-10	2.34E-08	9.37E-10
1 m	2.82E-12	2.82E-10	7.05E-09	2.82E-10
0 m	2.82E-12	2.82E-10	7.05E-09	2.82E-10

TABLE XVII
EXTERNAL EXPOSURE FROM A SUBMERSION ACCIDENT PER MECHANICAL FAILURE

Risk (mSv/y)	External	Internal
SSS	OK	OK
SSF	6.84E-07	6.84E-07
SFS	2.05E-06	2.05E-06
SFF	1.95E-10	1.95E-10
FSS	1.37E-06	1.37E-06
FSF	1.30E-10	1.30E-10
FFS	3.91E-10	3.90E-10
FFF	4.77E-14	3.72E-14
Sum	4.10E-06	4.10E-06

TABLE XVIII
RISK OF HUMAN ERROR ACCIDENT FF CASE

Height/Risk (mSv/y)	Falling	Getting trapped under concrete	Fainting	Getting cut
6 m	2.12E-06	5.10E-08	5.55E-07	1.52E-07
5 m	2.12E-06	6.85E-09	9.35E-07	2.56E-07
4 m	2.18E-06	8.30E-08	1.40E-06	3.85E-07
3 m	2.23E-06	2.33E-07	2.10E-06	5.77E-07
2 m	2.18E-06	6.85E-08	1.75E-06	4.81E-07
1 m	0.00E+00	5.25E-08	1.69E-06	4.65E-07
0 m	0.00E+00	3.54E-08	1.11E-06	3.04E-07