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Systems Engineering Approach for the Reuse of Metallic Waste From NPP Decommissioning and Dose Evaluation

금속해체 폐기물의 재활용을 위한 시스템엔지니어링 방법론 적용 및 피폭선량 평가

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The oldest commercial reactor in South Korea, Kori-1 Nuclear Power Plant (NPP), will be shut down in 2017. Proper treatment for decommissioning wastes is one of the key factors to decommission a plant successfully. Particularly important is the recycling of clearance level or very low level radioactively contaminated metallic wastes, which contributes to waste minimization and the reduction of disposal volume. The aim of this study is to introduce a conceptual design of a recycle system and to evaluate the doses incurred through defined work flows. The various architecture diagrams were organized to define operational procedures and tasks. Potential exposure scenarios were selected in accordance with the recycle system, and the doses were evaluated with the RESRAD-RECYCLE computer code. By using this tool, the important scenarios and radionuclides as well as impacts of radionuclide characteristics and partitioning factors are analyzed. Moreover, dose analysis can be used to provide information on the necessary decontamination, radiation protection process, and allowable concentration limits for exposure scenarios.

Keywords: Decommissioning, Metallic waste, Systems Engineering, Dose evaluation, RESRAD-RECYCLE

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한국의 가장 오래된 상업 원전인 고리 1호기가 2017년에 해체가 이루어질 예정이다. 원전 해체 폐기물의 적절한 처리는 효율적인 원전해체에 있어 중요한 역할을 할 것이다. 특히, 저준위 또는 오염되지 않은 금속폐기물의 재활용은 폐기물 발생 저감은 물론 처분장의 공간을 절약하는데 기여할 것이다. 본 논문은 재활용 시스템의 개념설계와 정의된 업무 흐름에서 발생하는 피폭 선량을 평가하는데 그 목적이 있다. 작업의 흐름과 운전 개념을 정립하기 위해 다양한 형태의 다이어그램을 설계하였다. 선량평가에 필요한 시나리오는 개념설계를 기반으로 선정되었으며, RESRAD-RECYCLE을 이용하여 선량을 평가하였다. 이를 통하여, 결정적 시나리오 선별, 핵종 특성 및 핵종 분배가 선량에 미치는 영향을 분석하였다. 더 나아가, 선량분석은 피폭 시나리오에 대한 대체 방안 수립, 필요한 제염 및 방사선방어 프로세스 그리고 허용 방사능 검토의 정보를 제공하는데 사용 될 수 있을 것이다.

중심단어: 해체, 금속폐기물, 시스템엔지니어링, 선량평가, RESRAD-RECYCLE

1. INTRODUCTION

Decommissioning is on the horizon for South Korea since it is expecting the oldest Nuclear Power Plant (NPP), Kori-1, to be permanently shut down starting in 2017. Proper treatment for decommissioning wastes is one of the key factors to decommission a plant successfully. Decontamination and waste minimization will contribute to the reduction of disposal volume and costs, which are going to be essential for effective management. Metallic wastes from NPP dismantling will be treated according to radioactivity concentration. Especially, Clearance Waste (CW) could be recycled then reused for customer goods or radioactive waste containers in repository facilities. The estimated amount of metal waste in Kori-1 is about 17% (26,255 m^3) of the total waste volume, which is subjected to treatment for recycling (Fig. 1). In addition, if there are proper decontamination methods that can reduce radioactivity concentration to an appropriate level for Low Level Waste (LLW) and Very Low Level Waste (VLLW), it leaves additional room for more metallic wastes which could be recycled. When metallic waste is recycled instead of being dumped directly to the disposal facility, it contributes to reducing waste generation, and reusing resources in an effective manner.

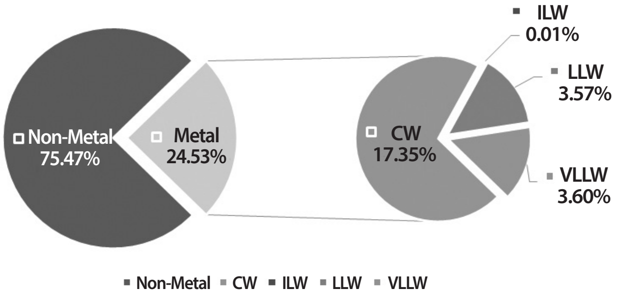

Fig. 1. Composition of metal waste in Kori-1.

However, in Korea, the proper preparation of metallic waste infrastructures for decommissioning still seems insufficient and a more substantial review is required. Therefore, the main purpose of this study is to define the recycling system, and to evaluate the incurring doses from the defined work steps. Systems Engineering (SE) approach was used to identify the system requirements that help to understand relationships, capabilities, functions, etc [1]. It provides a fundamental approach to recognizing system requirements, what is needed to process metal waste, and work scenarios that are expected to contribute to worker and public dose. Then, the radiation work environment was discussed for the assessment of dose with a view of dose criteria. As shown in Fig. 2, the overall flow of this study is largely divided into system configuration using SE, and dose evaluation using RESRAD-RECYCLE.

The problem of assessing the dose associated with the recycling of radioactively contaminated materials is com-

Fig. 2. The overall flow of the study.

plicated by the need to consider the many steps in the recycling process that can lead to the exposure of various receptors. Several computer codes, such as CONDOS, CONDOS-Ⅱ, and IMPACT-BRC have been designed but they do not provide a comprehensive analysis of the recycling process, limited to some radionuclides, and use outdated DCF's (Dose-equivalent Conversion Factor) [2]. The RESRAD-RECYCLE computer code was developed by ANL's (Argonne National Laboratory) EDA (Environmental Assessment Division) under the support of the U.S. DOE (Department of Energy) for the purpose of assessing the radiological consequences of recycling and reuse of clearance level of steel and aluminum. This is a code that evaluates the material exposure doses and risks for the workers using collecting, transporting, processing workers, consumer goods, and public goods in accordance with the recycling process of radioactive metal waste. For the time being, RESRAD-RECYLE is considered the tool available to assess dose in the process for recycling contaminated waste.

In this study, the systematic construction of the recycling system using SE approach will, therefore, be discussed and dose evaluation will be performed in connection with RESRAD-RECYCLE. In addition to the evaluation of each scenario, we will discuss the causes and major factors of high dose working scenarios. We observe a dependence of partitioning factors, such as ingot, baghouse, and slag used for dose assessment suggesting that it may be possible to predict the effect to the scenarios. Moreover, we calculate the derived concentration for each scenario and discuss the appropriateness of the allowable concentration.

2. METHODOLOGY

2.1 Introduction of systems engineering

According to INCOSE (International Council on Systems Engineering) systems engineering handbook, the definition of systems engineering is introduced; systems engineering is a profession, a process and a perspective as illustrated by these three representative definitions. Systems engineering is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect. (Ramo) Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system. (Eisner) Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems (INCOSE) [3].

System engineering perspective is based on system thinking. This system thinking is a unique perspective on reality. System's thinking can be detected through dialogue to discover, learn, diagnose and understand reality better, and is the process of understanding the system through learning and continuous improvement, which brings system closer to reality. The modern origins of systems engineering developed in the 1930's followed by other supporters. Since the introduction of the international standard ISO/IEC 15288 in 2002, the field of system engineering has been formally recognized as a desirable mechanism. Nowadays, the systems engineering discipline emerged as an effective way to manage system that is complicated or complex. By using systems engineering early in the design stage, we have shown that it reduces life cycle cost by controlling uncertainty and errors. A well-defined system with systems engineering efforts can be a positive factor in controlling cost overruns and reducing the uncertainty of project execution.

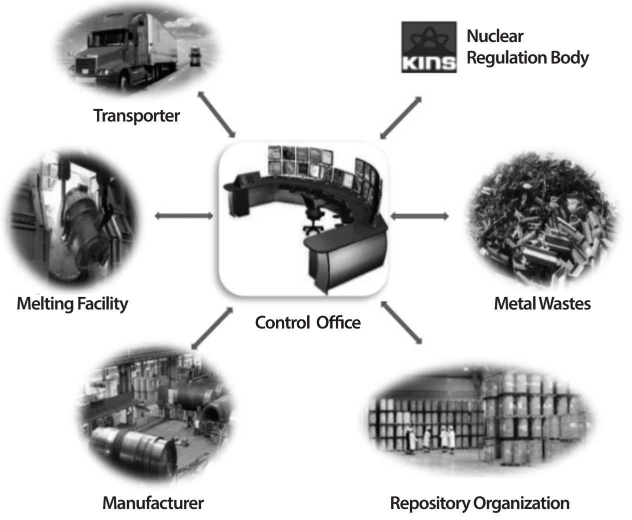

Fig. 3. Personnel and organization of the system.

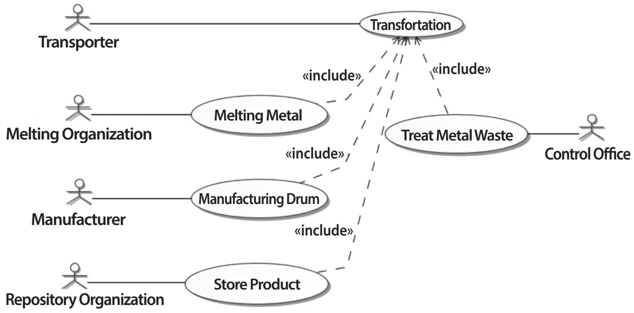

Fig. 4. Use case diagram.

2.2 Description of the recycling system

The recycling system aims to reduce decommissioning metallic wastes by reusing it for radioactive waste containers at the repository. In an operational concept, the performing personnel and organization have been established as shown in Fig. 3. First, when wastes are generated, it will be necessary to have control center, which handles waste classification and the acquisition of waste information. To process metal wastes, it must next be transported to the next step. Once transported, a smelter will be needed to melt the metals, and if the smelter produces products at a pre-stage, the transporter will have to transfer it to the place where the object is made. The object could be a radwaste container or rebars for the building which will be fabricated in manufacturing company. The regulation body that acts as surveillance for handling radioactive contaminated materials should also be included. The mutual interactions of each component for the treatment of metal waste around the control center will be important. To make the recycling system more concrete, this paper introduces several diagrams to better understand; it has been developed in operational views providing use case, class, activity, and sequence diagrams. These different diagrams provide the concept of asking questions about system requirements. This is a conceptual design for facilitating proper work procedures and operation [4]. We have constructed mutual functions and roles through repetitive modifications to make each diagram suitable for the purpose, and the relationship and interactions between system components are made to work consistently.

The use case diagram (Fig. 4) illustrates a use case of how the system actually works. Metallic wastes should be treated by the control office where accessing and classifying metallic wastes and the control center will have to place an order for a transporter to move the wastes to the melting facility. The melting organization receives an order, melts the scrap, and produces ingots that are going to be

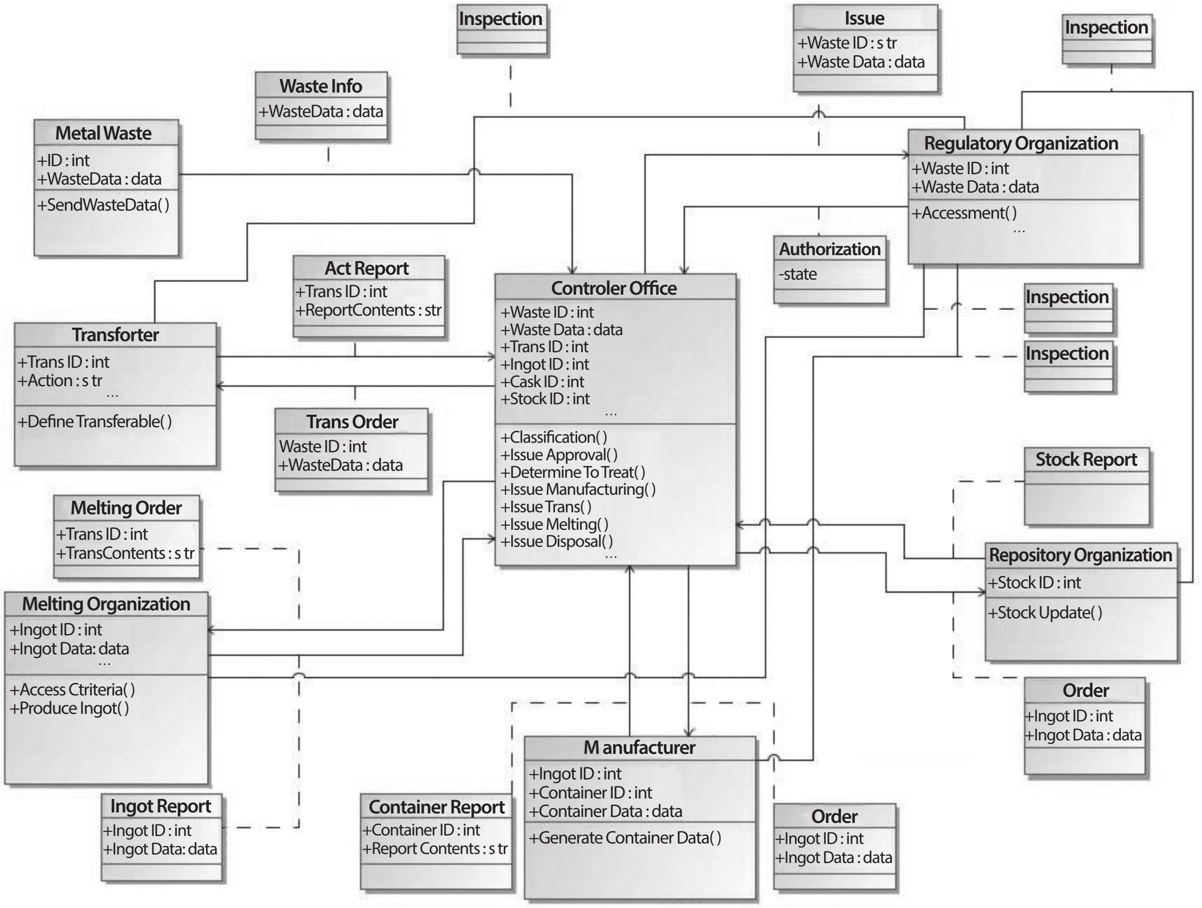

Fig. 5. Class diagram.

transported to the manufacturer. The manufacturer receives ingots and makes radioactive waste containers that are also to be transported to the repository. The repository facility receives products from the transporter and will use it as radioactive waste containers. Waste handling, melting, and manufacturing all relate to transportation in their planning.

The class diagram (Fig. 5) gives an overview of the recycle system by showing its classes, relationships, and interactions. Each class has its own attributes and functions which display static interactions. Once the metallic wastes are generated, the control office has to have several attributes and functions between metallic wastes, smelters, manufacturers, repository facilities, and the regulatory body. Attributes and functions are considered as the means of communication between each other. It is possible to derive functions that each entity should have in the whole system while specifying roles and functions among them. In summary, the control office needs to handle the information such as the radioactivity, weight, and volume of the metallic waste, so they must have the attribute of identification tag and the processing standard accordingly. The regulatory body will be assessing the adequacy of the handling of the waste to be reprocessed, thus the function of assessment, inspection, and judgement will be required. Transporters will receive orders from the control center to transfer the waste, ingots, and products to their destination; thus, the order, destination, and transportation reporting will be the major factor. When the smelter receives metal scraps from

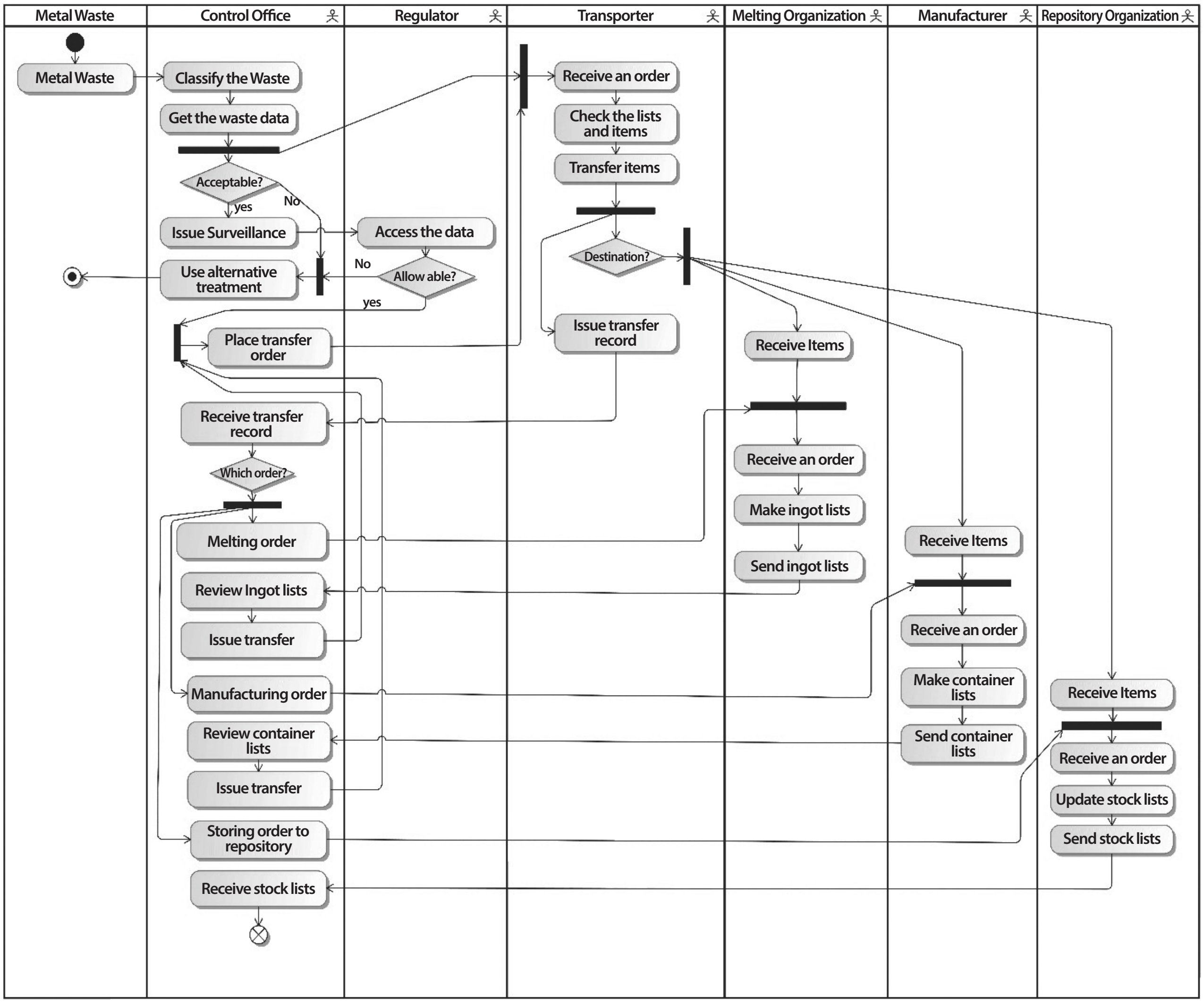

Fig. 6. Activity diagram.

transporters and receives a reprocessing order from the control center, they melt the scrap and create ingots. Identification of the scrap received and identification of the ingot produced are key attributes; the smelting order and ingot reporting will be the function of the smelter. Similar to a smelter, when the manufacturer receives ingots from transporters and receives a production order from the control center, they fabricate products with ingots. Identification of the product, receiving an order, and reporting the product will be the key attribute and function. The repository facility receives the product from the transporter and use it as a radioactive waste container, so the inventory tag and products use and management will be the main interaction.

The activity diagram (Fig. 6) describes an activity of work is required and specifies how it is carried out. This shows the flow from activity to activity. The control office classifies and receives the waste data to determine whether it is suitable for recycling. When it is suitable, the control office places an order of transporting the materials based on what will be transported; otherwise, it will use a method

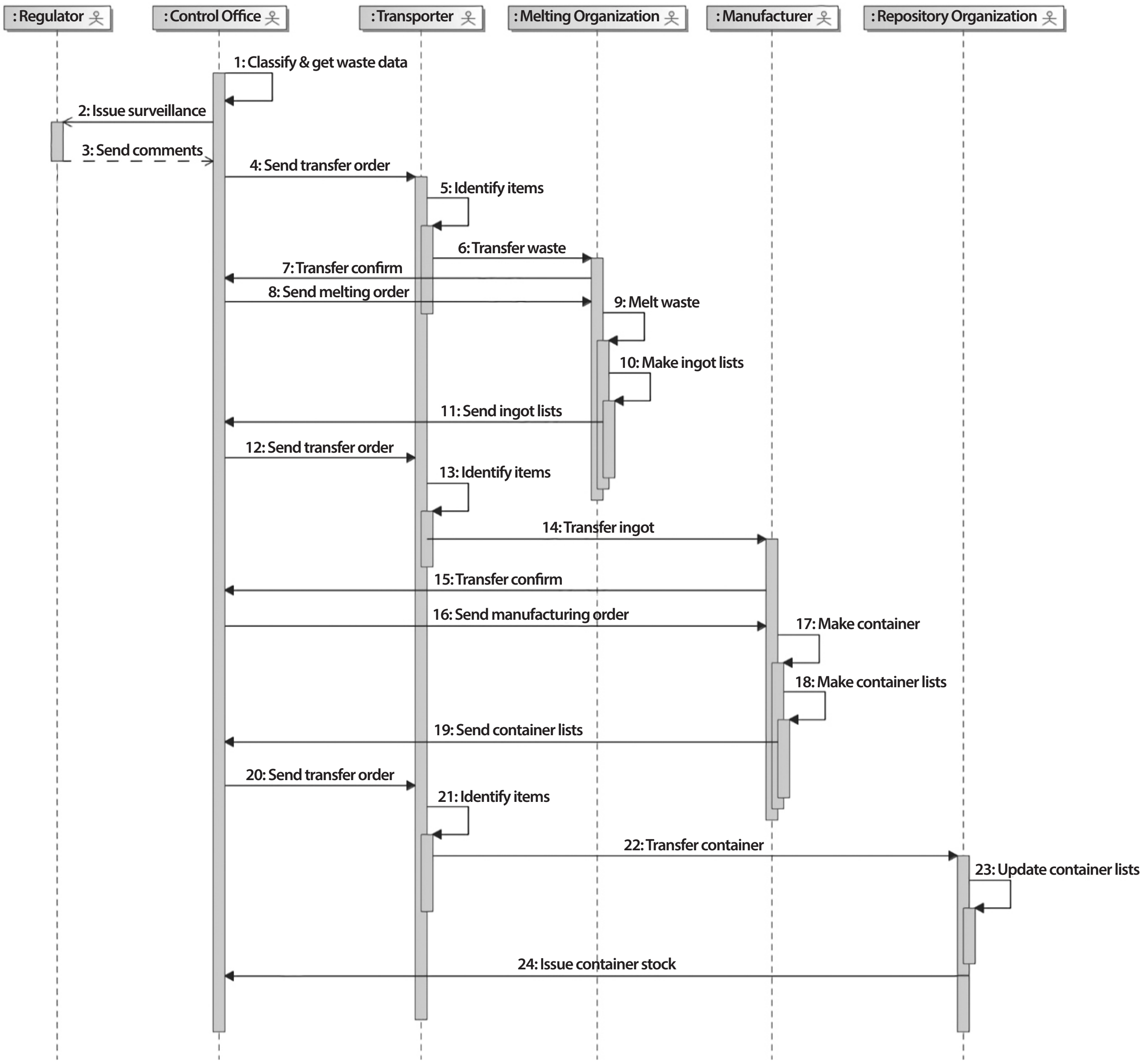

Fig. 7. Sequence diagram.

other than recycling. The transporter receives the list of items, issues transport records, and transfer the items to their destination. The destination will be a smelter, manufacturers, and repository facilities. Once the materials are transported, each facility will perform its own roles such as melting, making ingot, fabricating containers, and managing inventory. After that, the ingot list, product list, and inventory are then returned to the control center. Upon receiving this feedback, the control center will place orders for subsequent processes in the transport, smelter, manufacturer, or repository facility. Through the activities of each these components, we can classify procedures necessary for performing the activities and discover the missing activities.

The sequence diagram (Fig. 7) describes behaviors in terms of a sequence of messages exchanged between parts of systems. The control office classifies the wastes and issues surveillance to the regulatory office; once approved, the control office sends a transport order to the transporter. The transporter identifies the item and transfers it to the melting organization. When the smelter receives the metallic waste, it reports to the control center that it has received the object. The control office sends a message of a melting order to the smelter, the smelter then makes ingots, and returns the ingot list to the control office. The control office again sends a transport order to the transporter, the transporter identifies the item, and transfers the ingot to the manufacturer. The manufacturer sends a confirmation message to the control office and the control office returns production order to the manufacturer. The manufacturer produces goods and sends the product list to the control office. The control office will then send a transport order to the transporter. The transporter identifies the item and transfers it to the repository facility. Through this sequential flow, the sequence diagram shows which step should be done first and what is the next steps for achieving system requirements in the view of work flows.

2.3 Radiation exposure environment

Dose results obtained using RESRAD-RECYCLE focusing on two major sections including workers and the public could indicate whether each work sequence is appropriate in terms of nuclear safety limits. Prior to beginning that, the recycle system design was established based on the conceptual and architectural diagrams. Architectural modeling diagrams provide an understanding of their characteristics by defining the relationships between entities in iterative procedures resulted by identifying the consistencies in between diagrams. From the system design, radiation exposed steps for workers and the public are considered as shown in Table 1. This study adopts twenty eight recycling process steps provided by RESRAD-RECYCLE: scrap delivery (4), scrap smelting (9), ingot delivery (3), initial and final fabrication (5), product distribution (5), and use of product (2). Although this study deals primarily with radioactive containers for recycling metallic waste, building with rebars scenario is included to compare the public use of the product. The worker and the public are classified in terms of who will be the receptor in each scenario. Selecting the proper scenarios steps and recognizing the necessary scenarios were possible by matching SE definitions and RESRAD-RECYCLE scenarios. With the aids of this matching process, it is thought that the public doses from transportations (scrap, ingot, and product delivery) should be considered for each delivery.

2.4 Applicable regulation

As mentioned above, in the definition of recycling system, scrapping, smelting, fabricating, and use of the product will be the main tasks. Scrapping is work that includes shredding, cutting, and bending the scrap metal and mainly occurs in the NPP site where waste is generated. If the radioactive concentration of the waste is high, the work will be done within the radiation control zone. Since the use of the product is a radioactive waste container, it is mainly used in a repository facility, it will also be used in a radiation control zone. However, in the case of smelting and fabricating, if the level of radioactive material is high, a separated radiation control zone would be necessary for these activities at present. This means that it will be necessary additional infrastructures and generate costs. Furthermore, when transporting waste, ingots and products, additional regulation should be applied for transport containers and handling. If the recycling system can handle high radioactive materials, it will lead to big costs but will be able to reprocess more metallic waste. However, if we handle clearance-level waste, the existing infrastructure can be used without additional facilities and costs. According to the Nuclear Safety and Security Commission, radioactive wastes below clearance level can be deregulated by entombment, incineration, or recycling which is also called self-disposal. It describes

Table 1. Matching between system design and RESRAD scenarios

System Engineering Behaviors	Receptor		RESRAD Scenario		Receptor	
	Worker	Public	Step	Scenario	Worker	Public
Metallic Waste Treatment	○		Scrap Delivery	Scrap Cutter	○	
Metallic Waste Transfer	○	○		Scrap Loader	○	
				Scrap Truck Driver	○	
				Public Transportation		○
Melting Metallic Waste	○		Scrap Melting	Scrap Processor	○	
				Smelter Yard Worker	○	
				Smelter Loader	○	
				Furnace Operator	○	
				Baghouse Processor	○	
				Refinery Worker	○	
Making Ingot	○			Ingot Caster	○	
				Small Object Caster	○	
				Slag Worker	○	
Ingot Transfer	○	○	Ingot Delivery	Ingot Loader	○	
				Ingot Truck Driver	○	
				Public Transportation		○
Product Manufacturing	○		Initial Fabrication	Storage Yard Worker	○	
				Sheet Maker	○	
				Coil Maker	○	
			Final Fabrication	Sheet Handler	○	
				Coil Handler	○	
Product Transfer	○	○	Product Distribution	Product Loader	○	
				Product Truck Driver	○	
				Sheet Assembler	○	
				Warehouse Worker	○	
				Public Transportation		○
Use Product	○	○	Public Product	Building with Rebars		○
			Controlled Product	Radwaste Container	○	

Table 2. Dose criteria for the worker and the public

Receptor	Individual ($\mu Sv \cdot yr^{-1}$)	Collective ($man\text{-}Sv \cdot yr^{-1}$)
Worker	10	1
Public	10	1

Table 3. Allowable concentration by radionuclide for clearance

Radionuclide	Concentration ($Bq \cdot g^{-1}$)
^{60}Co	0.1
^{137}Cs	0.1
^{90}Sr	1

the activity concentration limit of key radionuclides; the individual and the collective dose from clearance practice should be 10 μSv or less and 1 man-Sv or less, respectively [5]. Therefore, recycling of clearance-level of radioactively contaminated materials is assumed in this study. It can be seen that self-disposal criteria can be applied to both workers and the general public as shown in Table 2.

In this study, three representative radionuclides (^{60}Co, ^{137}Cs and ^{90}Sr) are chosen because these are the major source of radiation dose in metallic wastes from the NPP. The allowable concentration limits by regulation are shown in Table 3. In case of the radionuclide compound, the sum of each concentration fraction on allowable limit should be less than 1 as shown in Eq. (1). Each radionuclide concentration can be a maximum from the table, but if the concentration of one radionuclide is almost at maximum of the allowable concentration, the other should be zero under a given condition. We applied the maximum value of allowable concentration, even if the sum of the concentration fraction could be more than 1. However, if all the scenarios with this maximum concentration can receive acceptable dose, concentrations below the maximum will meet the dose criteria. Then the concentration fraction should be considered after that according to the concentration composition ratio.

1) This formula will be applied for the radionuclide compound.

$$\sum i \frac{C_i}{C_{L,i}} < 1 \tag{1}$$

where

C_i : Concentration of radionuclide i ($Bq \cdot g^{-1}$)

$C_{L,i}$: Allowable concentration of radionuclide i for clearance given by ($Bq \cdot g^{-1}$)

2) 0.1 $Bq \cdot g^{-1}$ can be applied as an allowable concentration of clearance for radionuclides which are not given by table and not an alpha emitter.

2.5 RESRAD-RECYCLE parameters

This study modifies some parameters to reflect domestic situation and recently available data. The RESRAD-RECYCLE code calculates internal (ingestion and inhalation) doses with the DCF's obtained from EPA FGR (Federal Guidance Report) No. 11 (Eckerman et al. 1988). These DCF's were developed on the basis of ICRP (International Commission on Radiological Protection) Publication 30 (1979~1988) and 48 (1986). Therefore, it is necessary to reflect ICRP Publication 60 (1991), which is the current domestic standard. For workers, DCF's for inhalation and ingestion are applied to the values specified in ICRP Publication 72 (1995). For AMAD (Activity Median Aerodynamic Diameter) of workers in inhalation, a default value of 5 μm AMAD was used based off of ICRP Publication 68 (1994). In terms of clearance types, "M" for Co-60 and "F" for ^{90}Sr are assumed [6].

The critical contributors of the radiation exposure from inhalation are an airborne-dust-loading factor, a respirable-fraction factor, and a respiratory protection factor. The RESRAD-RECYCLE adopts a value of 1.0×10^{-3} $g \cdot m^{-3}$ as upper-bound of dust loading factor, a fraction of upper-bound value for scenarios where dust suspensions are not likely to occur, and a value of 0.1 as a respirable-fraction factor. To eliminate ambiguity of the distinction of dust loading for scenarios, we applied upper bound value of 1.0×10^{-3} $g \cdot m^{-3}$ conservatively for all worker scenarios. For workers, a respiratory protection factor will be largely dependent on the efficiency of the respiratory mask. It ranges from 0 to 1 (i.e., assumption of no respirator). We can assume the actual work site is a general industrial site and that a respiratory protection value of 0.2 is applicable based off of U.S. OSHA (Occupational Safety and Health Administration) [7]. However, considering the fact that it is a general site, we conservatively applied 1 as the default. If the proper management for respiratory protection is possible, 0.2 will be applicable. An ingestion rate value of 0.00625 $g \cdot h^{-1}$ is provided by default in RESRAD-RECYCLE and a uniform distribution of 0 - 0.02 $g \cdot h^{-1}$ is specified by NUREG-1640 [8]. Therefore, a more conservative value of 0.02 $g \cdot h^{-1}$ is used in this study. In the case of scrap, ingot, and product deliveries, the number of drivers is doubled from the default value because it is assumed that the transport manager should accompany the driver when transporting.

For transportation scenarios to the public, by default, five shipments are required to deliver 100 t of radioactive materials and shielding provided by truck body is considered to be 0.2 cm thick. As a reference, we investigated where the clearance of metallic waste is actually being melted and confirmed that there is a case in Dongkuk Steel and Hyundai Steel located in Pohang city. Therefore, this study assumes that the deliveries (waste, ingot, and product) will be carried out in the route of Seosaeng-myeon, Ulsan city, and Pohang city. Kori-1 NPP is located near Ulsan city, facilities (Dongkuk Steel and Hyundai Steel) smelting are located in Pohang city, and the repository facility is located in Gyeongju city. Conservatively, a population density of Ulsan, which has the highest among these cities, is applied: 1099.6 $people \cdot km^{-2}$ (Koran Statistical Information Service, 2016). A distance from Kori-1 site to the smelter is considered the longest route as shown in Fig. 8. A value of 100 km as the distance and a value of 60 $km \cdot h^{-1}$ as the truck velocity rate are applied. Public transportation for scrap can equally be applied to ingots and the product deliveries. Even though the mass and partitioning factors of ingots and products are different from those of the scrap, the radiation dose to the public under the transportation scenario for the ingot and the product can be assumed to be the same as the scrap. Since the mass and partitioning factor of the ingot and product are less than those of scrap, the result of the scrap can be conservatively applied to the ingot and product deliveries.

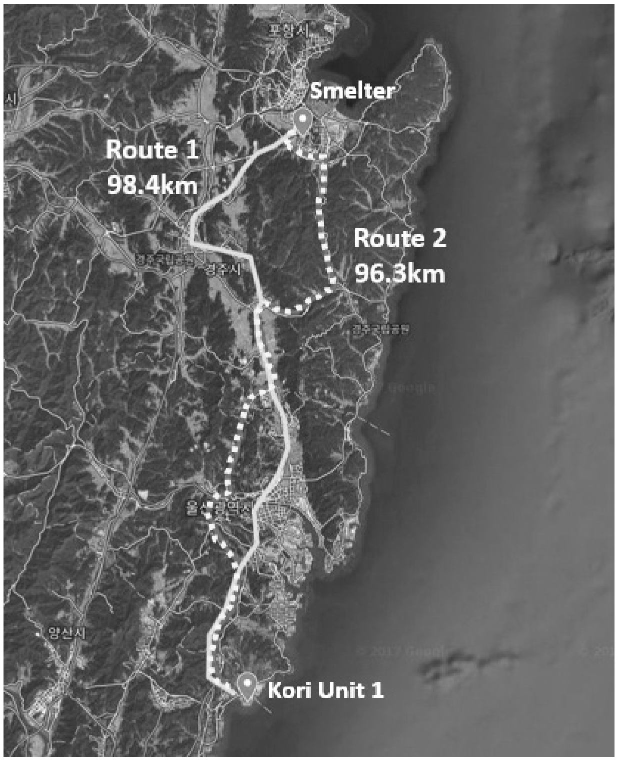

Fig. 8. Estimated distance from Kori Unit 1 to smelter.

3. RESULT

Dose scenarios illustrated in RESRAD-RECYCLE are multiple processes and all procedures are related to handling of radioactive contaminated materials, thus dose results involved in the recycle system would be separated into workers and the public as shown in Table 4. The results

Table 4. Dose evaluation of RESRAD-RECYCLE

Receptor	Scenario	Individual (μSv·yr $^{-1}$)	Collective (man-Sv·yr $^{-1}$)
Worker	Scrap Delivery: Scrap Cutter	1.09×10^{-2}	3.28×10^{-8}
	Scrap Delivery: Scrap Loader	7.53×10^{-3}	1.51×10^{-8}
	Scrap Delivery: Scrap Truck Driver	4.46×10^{-3}	4.46×10^{-8}
	Scrap Smelting: Scrap Processor	1.10×10^{-2}	3.30×10^{-8}
	Scrap Smelting: Smelter Yard Worker	8.20×10^{-2}	8.20×10^{-7}
	Scrap Smelting: Smelter Loader	3.86×10^{-2}	1.93×10^{-7}
	Scrap Smelting: Furnace Operator	6.25×10^{-2}	1.87×10^{-7}
	Scrap Smelting: Baghouse Processor	2.66×10^{-2}	2.66×10^{-8}
	Scrap Smelting: Refinery Worker	5.85×10^{-2}	1.76×10^{-7}
	Scrap Smelting: Ingot Caster	9.17×10^{-3}	1.83×10^{-8}
	Scrap Smelting: Small Objects Caster	4.16×10^{-1}	8.32×10^{-7}
	Scrap Smelting: Slag Worker	1.50×10^{0}	1.50×10^{-6}
	Ingot Delivery: Ingot Loader	4.79×10^{-3}	9.58×10^{-9}
	Ingot Delivery: Ingot Truck Driver	1.06×10^{-2}	1.06×10^{-7}
	Initial Fabrication: Storage Yard Worker	1.74×10^{-2}	1.74×10^{-7}
	Initial Fabrication: Sheet Maker	7.22×10^{-4}	1.08×10^{-8}
	Initial Fabrication: Coil Maker	3.09×10^{-3}	3.09×10^{-9}
	Final Fabrication: Sheet Handler	6.06×10^{-4}	1.21×10^{-8}
	Final Fabrication: Coil Handler	2.39×10^{-1}	1.19×10^{-6}
	Product Distribution: Product Loader	4.79×10^{-2}	9.58×10^{-8}
	Product Distribution: Product Truck Driver	1.69×10^{-2}	1.69×10^{-7}
	Product Distribution: Sheet Assembler	1.22×10^{-2}	2.43×10^{-7}
	Product Distribution: Warehouse Worker	3.20×10^{-1}	1.60×10^{-6}
	Controlled Products: Radwaste Container	5.18×10^{-4}	5.18×10^{-10}
Public	Building with Rebars	1.28×10^{0}	2.10×10^{-4}
	Scrap Transportation	-	1.87×10^{-9}
	Ingot Transportation	-	1.87×10^{-9}
	Product Transportation	-	1.87×10^{-9}

Table 5. Scenario input parameter

Step	Scenario	Time (h)	Internal	External	Geometry	
			Medium Concentration	Medium Concentration	Radius/Thick (cm)	Distance (cm)
Scrap Delivery	Scrap Cutter	12	Scrap	Scrap	30/90	200
	Scrap Loader	4	Scrap	Scrap	127/253	400
	Scrap Truck Driver	4	Scrap	Scrap	60/900	200
Scrap Melting	Scrap Processor	12	Scrap	Scrap	30/60	200
	Smelter Yard Worker	80	Scrap	Scrap	175/351	1,000
	Smelter Loader	4	Baghouse	Scrap	139/279	400
	Furnace Operator	5	Baghouse	Scrap	127/253	300
	Baghouse Processor	1	Baghouse	Baghouse	40/100	200
	Refinery Worker	5	Baghouse	Ingot	127/228	300
	Ingot Caster	2.5	Ingot	Ingot	64/100	150
	Small Object Caster	50	Ingot	Ingot	201/1	100
	Slag Worker	25	Slag	Slag	228/45.5	150
Ingot Delivery	Ingot Loader	2	Ingot	Ingot	201/100	400
	Ingot Truck Driver	5	Ingot	Ingot	64/200	200
Initial Fabrication	Storage Yard Worker	40	Ingot	Ingot	201/100	1,000
	Sheet Maker	1	Ingot	Ingot	138/0.2	100
	Coil Maker	1	Ingot	Ingot	58/122	150
Final Fabrication	Sheet Handler	1	Ingot	Ingot	138/0.2	100
	Coil Handler	80	Ingot	Ingot	58/122	150
Product Distribution	Product Loader	20	Ingot	Ingot	201/100	400
	Product Truck Driver	8	Ingot	Ingot	64/200	200
	Sheet Assembler	20	Ingot	Ingot	138/0.2	100
	Warehouse Worker	2,000	Ingot	Ingot	138/1.2	600
Controlled Product	Radwaste Container	1	None	Ingot	100/0.27	100

show that all doses are within the limits specified in Table 2. There are four high susceptible worker scenarios: small objects caster, slag worker, coil handler, and warehouse worker, the top ranked is the slag worker. We traced the input data to determine the key factors that increase exposure dose, selected from the top four scenarios, and observed that there is a close relationship between exposure time and the distance of source geometry. Table 5 shows that expo-

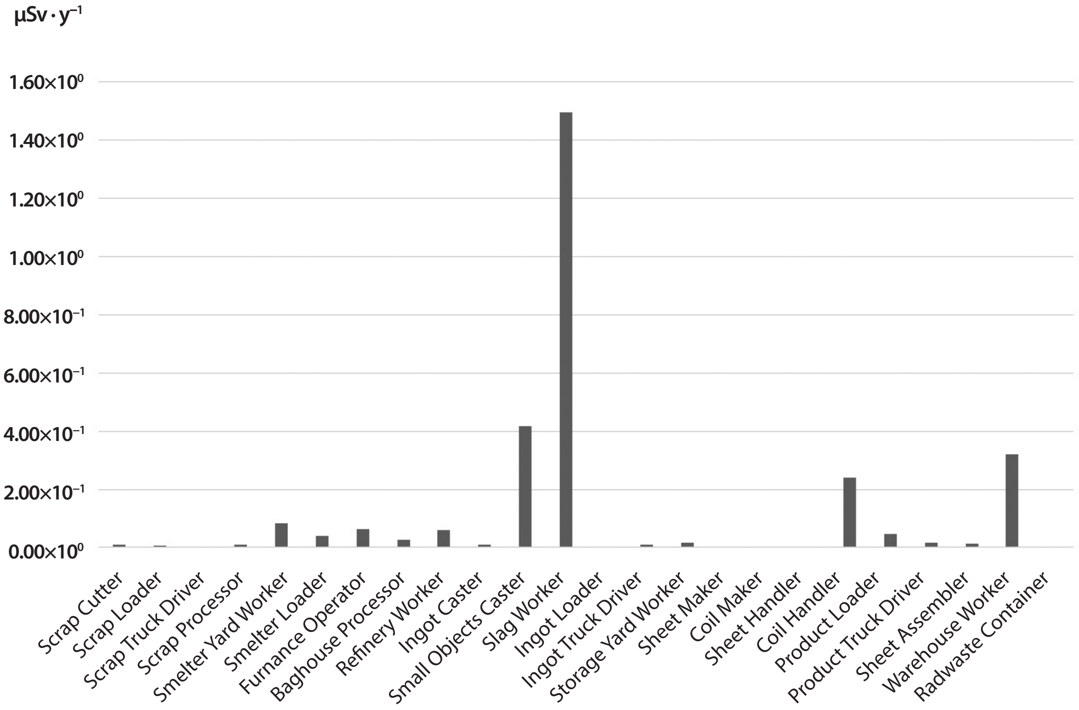

Fig. 9. Worker scenarios ranking.

sure time was relatively long for the top ranked scenarios. Although there are scenarios with long exposure times, it can be seen that the two scenarios, such as smelter yard worker and storage yard worker, that have a relatively long distance between the receptor and the source have a low dose. This indicates that the distance played an important role in reducing exposure dose though exposed for a relatively long time.

There are four scenarios related to the public and the top ranked is the building with rebars. Receptors in building with rebars are exposed to radiation from four sides of wall with distance of 100 cm, 250 cm, 250 cm and 400 cm, respectively, and the exposure time is 2,000 hours based on 50 weeks a year, 5 days a week, and 8 hours a day. From these given parameters, receptors in that scenario are susceptible to radiation. In response to this high dose, the easiest way to react would be to modify the exposure time (as an example). It is possible under the assumption that the building can be used for different specific purpose and people enter there in limited times. This kind of alternative ways would be considered just in case that this scenario dose is above the limits. The dose is the highest among the public, but still remains within the limits.

3.1 The effect of partitioning factors

Radionuclides are present in metallic waste and may exist separately in the source or output of the recycling process such as ingots, baghouses, or slag. This is because the radionuclides are redistributed into three by-products during the furnace melting process. In general, radionuclides with low boiling points are tend to concentrated in the dust, some that are oxidize easily concentrated in slag, and others can be concentrated in ingots. This will differ generally by

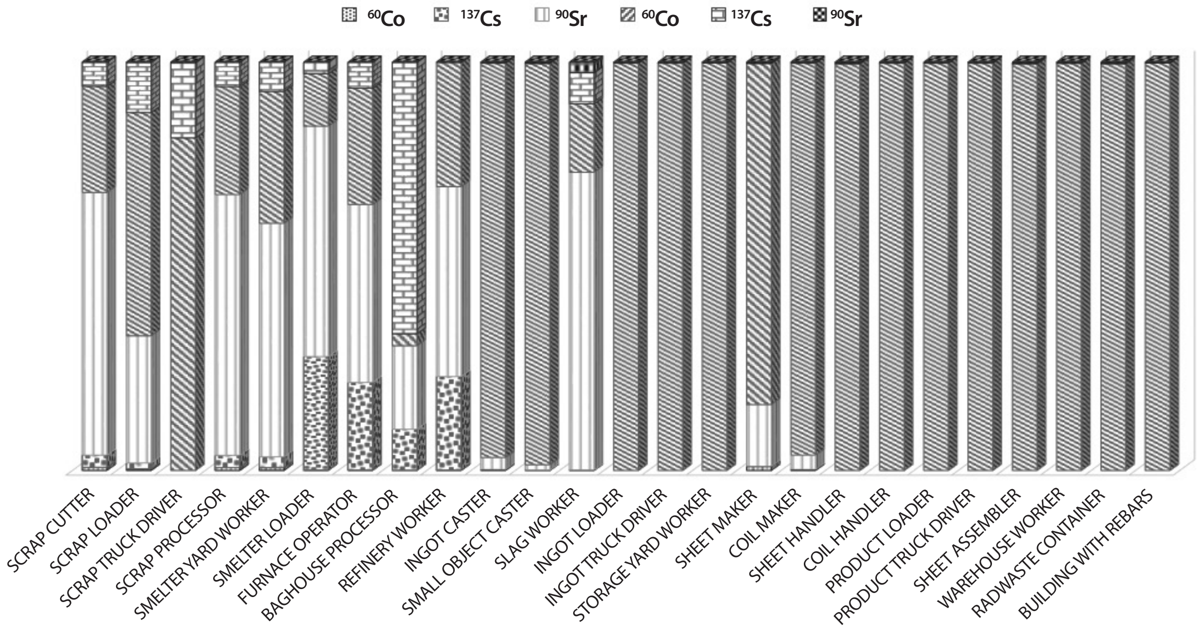

Fig. 10. Dose composition by radionuclides.

Table 6. Radionuclide partitioning factors

Radionuclide	Partitioning Factor (%)		
	Ingot	Baghouse	Slag
^{60}Co	98	1	1
^{137}Cs	1	97	2
^{90}Sr	18.2	9.1	72.7

methods such as melting temperature, furnace conditions, additives, and a method of smelting. In other words, radionuclides could be accumulated in certain types and removed as well. Radionuclides with such a property, called partitioning factors, could be the major source of radiation dose in each scenario. Each radionuclide has own characteristics, such as internal or external contributors, but this property, which is redistributed to a certain type of substances or by-products, will also be a major factor in exposure dose. On the other hand, if the worker handles by-products of small partitioning factors, the exposure dose of the workers may be reduced compared to the handling of original contaminated metallic wastes. This means that the melting process itself behaves like a kinds of decontamination process. In the RESRAD-RECYCLE, the radionuclides concentrations in the various smelting by-products and three radionuclides partitioning factors are as follows [2]:

$$C_{i,\text{by-product}} = C_{i,\text{ scap}} \times RPF_i \times W_{\text{scrap}} / MPF_{\text{by-product}} \qquad (2)$$

where

$C_{i,\text{by-product}}$ = concentration of radionuclide i in the by-product ($Bq \cdot g^{-1}$);

$C_{i,\text{scap}}$ = concentration of radionuclide i in scrap ($Bq \cdot g^{-1}$);

RPF_i = radionuclide i partitioning factor;

W_{scrap} = dilution factor; and

$MPF_{\text{by-product}}$ = mass partitioning factor of the by-product

As can be seen in Fig. 10, the lower three items in the bar chart represent the internal radiation dose of ^{60}Co, ^{137}Cs, and ^{90}Sr. Likewise, the upper three items represent the ex-

Table 7. Individual doses by radionuclides for workers

Scenario	Internal (μSv·yr $^{-1}$)							External (μSv·yr $^{-1}$)			
	By-product	Ingestion			Inhalation			By-product			
		^{60}Co	^{137}Cs	^{90}Sr	^{60}Co	^{137}Cs	^{90}Sr		^{60}Co	^{137}Cs	^{90}Sr
Scrap Cutter	Scrap	8.08×10^{-5}	3.25×10^{-4}	6.98×10^{-3}	9.57×10^{-7}	9.55×10^{-7}	4.27×10^{-5}	Scrap	2.84×10^{-3}	6.41×10^{-4}	6.13×10^{-6}
Scrap Loader	Scrap	2.69×10^{-5}	1.09×10^{-4}	2.33×10^{-3}	3.20×10^{-7}	3.18×10^{-7}	1.42×10^{-5}	Scrap	4.12×10^{-3}	9.25×10^{-4}	6.05×10^{-6}
Scrap Truck Driver	Scrap	-	-	-	-	-	-	Scrap	3.63×10^{-3}	8.19×10^{-4}	7.75×10^{-6}
Scrap Processor	Scrap	8.08×10^{-5}	3.25×10^{-4}	6.98×10^{-3}	9.57×10^{-7}	9.55×10^{-7}	4.27×10^{-5}	Scrap	2.91×10^{-3}	6.52×10^{-4}	6.13×10^{-6}
Smelter Yard Worker	Scrap	5.37×10^{-4}	2.17×10^{-3}	4.66×10^{-2}	6.39×10^{-6}	6.36×10^{-6}	2.85×10^{-4}	Scrap	2.65×10^{-2}	5.88×10^{-3}	1.38×10^{-5}
Smelter Loader	Baghouse	2.69×10^{-5}	1.07×10^{-2}	2.16×10^{-2}	3.20×10^{-7}	3.14×10^{-5}	1.32×10^{-4}	Scrap	4.95×10^{-3}	1.10×10^{-3}	7.11×10^{-6}
Furnace Operator	Baghouse	3.36×10^{-5}	1.34×10^{-2}	2.71×10^{-2}	3.99×10^{-7}	3.94×10^{-5}	1.65×10^{-4}	Scrap	1.78×10^{-2}	3.96×10^{-3}	3.02×10^{-5}
Baghouse Processor	Baghouse	6.73×10^{-6}	2.68×10^{-3}	5.41×10^{-3}	7.99×10^{-8}	7.84×10^{-6}	3.30×10^{-5}	Baghouse	7.85×10^{-4}	1.77×10^{-2}	1.66×10^{-5}
Refinery Worker	Baghouse	3.36×10^{-5}	1.34×10^{-2}	2.71×10^{-2}	3.99×10^{-7}	3.94×10^{-5}	1.65×10^{-4}	Ingot	1.78×10^{-2}	4.04×10^{-5}	5.60×10^{-6}
Ingot Caster	Ingot	1.68×10^{-5}	6.90×10^{-7}	2.71×10^{-4}	1.99×10^{-7}	2.03×10^{-9}	1.65×10^{-6}	Ingot	8.86×10^{-3}	2.03×10^{-5}	3.72×10^{-6}
Small Object Caster	Ingot	3.36×10^{-4}	1.38×10^{-5}	5.41×10^{-3}	3.99×10^{-6}	4.05×10^{-8}	3.30×10^{-5}	Ingot	4.09×10^{-1}	1.10×10^{-3}	3.39×10^{-4}
Slag Worker	Slag	1.68×10^{-4}	1.39×10^{-3}	1.08×10^{0}	1.99×10^{-6}	4.05×10^{-6}	6.60×10^{-3}	Slag	2.51×10^{-1}	1.14×10^{-1}	3.89×10^{-2}
Ingot Loader	Ingot	-	-	-	-	-	-	Ingot	4.78×10^{-3}	1.09×10^{-5}	1.25×10^{-6}
Ingot Truck Driver	Ingot	-	-	-	-	-	-	Ingot	1.06×10^{-2}	2.41×10^{-5}	4.05×10^{-6}
Storage Yard Worker	Ingot	-	-	-	-	-	-	Ingot	1.74×10^{-2}	3.94×10^{-5}	1.67×10^{-6}
Sheet Maker	Ingot	6.73×10^{-6}	2.76×10^{-7}	1.08×10^{-4}	7.99×10^{-8}	8.07×10^{-10}	6.59×10^{-7}	Ingot	6.03×10^{-4}	1.55×10^{-6}	9.75×10^{-7}
Coil Maker	Ingot	6.73×10^{-6}	2.76×10^{-7}	1.08×10^{-4}	7.99×10^{-8}	8.07×10^{-10}	6.59×10^{-7}	Ingot	2.97×10^{-3}	6.80×10^{-6}	1.25×10^{-6}
Sheet Handler	Ingot	-	-	-	-	-	-	Ingot	6.03×10^{-4}	1.55×10^{-6}	9.75×10^{-7}
Coil Handler	Ingot	-	-	-	-	-	-	Ingot	2.38×10^{-1}	5.44×10^{-4}	9.98×10^{-5}
Product Loader	Ingot	-	-	-	-	-	-	Ingot	4.78×10^{-2}	1.09×10^{-4}	1.25×10^{-5}
Product Truck Driver	Ingot	-	-	-	-	-	-	Ingot	1.69×10^{-2}	3.86×10^{-5}	6.48×10^{-6}
Sheet Assembler	Ingot	-	-	-	-	-	-	Ingot	1.21×10^{-2}	3.11×10^{-5}	1.95×10^{-5}
Warehouse Worker	Ingot	-	-	-	-	-	-	Ingot	3.19×10^{-1}	8.59×10^{-4}	1.53×10^{-4}
Radwaste Container	None	-	-	-	-	-	-	Ingot	5.15×10^{-4}	1.34×10^{-6}	8.54×10^{-7}

ternal radiation dose of ^{60}Co, ^{137}Cs, and ^{90}Sr. It shows that the major radiation dose for most of the scenarios comes from the external pathway and the major contributor is the ^{60}Co. In an internal radiation dose, ^{137}Cs affects the smelter loader, the furnace operator, the baghouse processor, and the refinery worker. As an external dose, ^{137}Cs influences the baghouse processor because the medium concentration is the baghouse. ^{90}Sr also shows that the main dose comes from the internal and the medium concentration is scrap and slag, so the scrap delivery and some smelting processes are significantly affected by the ^{90}Sr before ingots are made. In particular, since ^{90}Sr accumulates in the slag after the smelting process, most of the dose in the slag worker is largely dominated by ^{90}Sr. The radionuclide composition indicates that radiation dose has a close relationship with partitioning factors. Based on this same data, we checked relatively big doses on the Table 7, and it showed that they are closely related to the medium concentration in which the partitioning factor was the major source of radiation dose. From this analysis, we can see that which scenario has been largely influenced by the radionuclide using the information of partitioning factors and radionuclide characteristics. For example, it can be seen here that the main source of exposure for the slag worker with the highest dose among scenarios was due to the ingestion of ^{90}Sr. If ^{90}Sr exists in the waste, precautions should be taken at the actual work site and exposure by ingestion of the slag worker can be reduced by using a protective mask.

3.2 Derived concentration

This study used three radionuclides, ^{60}Co, ^{137}Cs and ^{90}Sr, and showed that workers and public doses were below regulatory limits. For these radionuclides compound, the concentration of each radionuclide can be derived for individual and collective dose as shown in Table 8. Each concentration can be calculated based on the dose fraction of each radionuclide. Conversely, each scenario with this derived concentration will receive a maximum dose in terms of dose limit. In order to meet all scenarios in relation to dose limit, we must choose the minimum of the derived concentrations. Therefore, the critical scenario for ^{60}Co, ^{137}Cs, and ^{90}Sr is the slag worker. Table 9 shows that derived concentration is above regulatory limits, which means regulatory limits are more conservative. Although the derived concentration is above the regulatory value, the derived concentration that meets all scenarios will be meaningful if the dose limit associated with decommissioning can be adjusted. Considering the composition fraction, the allowable radioactivity of three radionuclides could be lower than the regulatory limits. At present, however, applicable law is the self-disposal. Nevertheless, even if the derived concentrations exceeds regulatory limits, it seems that the derived concentration can be applied to the recycling of metallic wastes, if only dose results are considered. This suggests that there is room for mitigation of the allowable concentration criteria in recycling of metallic waste from decommissioning.

4. CONCLUSION

The advantage of the SE approach was useful in defining recycling system from a conceptual and operational perspective. The SE has raised questions about what entities and functions are needed to construct appropriate scenarios and to consider the applicable regulations. To make the recycling system more concrete, we introduced several diagrams to better understand. Based on these design concept, it was possible to understand the appropriate scenario composition for dose assessment and applicable regulation.

This study handles the clearance-level radioactively contaminated materials and sees whether the scenarios are just and feasible. The dose results were drawn from the point of view of exposure to workers and the public. Results showed that doses of all scenarios are lower than individual and collective limits. The major pathway of radiation dose was from the external and the contributing ra-

Table 8. Derived radionuclide concentration

Scenario	Individual ($Bq\cdot g^{-1}$)			Collective ($Bq\cdot g^{-1}$)		
	^{60}Co	^{137}Cs	^{90}Sr	^{60}Co	^{137}Cs	^{90}Sr
Scrap Cutter	91.57	91.57	915.66	2.34×10^{6}	2.28×10^{6}	3.45×10^{7}
Scrap Loader	132.74	132.74	1,327.35	6.64×10^{6}	6.64×10^{6}	6.64×10^{7}
Scrap Truck Driver	224.38	224.38	2,243.79	2.24×10^{6}	2.24×10^{6}	2.24×10^{7}
Scrap Processor	90.89	90.89	908.92	3.03×1^{06}	3.03×1^{06}	3.03×10^{7}
Smelter Yard Worker	12.19	12.19	121.89	1.22×10^{5}	1.22×10^{5}	1.22×10^{6}
Smelter Loader	25.93	25.93	259.31	5.19×10^{5}	5.19×10^{5}	5.19×10^{6}
Furnace Operator	16.01	16.01	160.09	5.34×10^{5}	5.34×10^{5}	5.34×10^{6}
Baghouse Processor	37.54	37.54	375.43	3.75×10^{6}	3.75×10^{6}	3.75×10^{7}
Refinery Worker	17.09	17.09	170.88	5.70×10^{5}	5.70×10^{5}	5.70×10^{6}
Ingot Caster	109.01	109.01	1,090.05	5.45×10^{6}	5.45×10^{6}	5.45×10^{7}
Small Object Caster	2.40	2.40	24.02	1.20×10^{5}	1.20×10^{5}	1.20×10^{6}
Slag Worker	0.67	0.67	6.68	6.68×1^{04}	6.68×1^{04}	6.68×10^{5}
Ingot Loader	208.67	208.67	2,086.75	1.04×10^{7}	1.04×10^{7}	1.04×10^{8}
Ingot Truck Driver	94.09	94.09	940.90	9.41×10^{5}	9.41×10^{5}	9.41×10^{6}
Storage Yard Worker	57.34	57.34	573.36	5.73×10^{5}	5.73×10^{5}	5.73×10^{6}
Sheet Maker	1,385.54	1,385.54	13,855.38	9.24×10^{6}	9.24×10^{6}	9.24×10^{7}
Coil Maker	323.18	323.18	3,231.78	3.23×1^{07}	3.23×1^{07}	3.23×10^{8}
Sheet Handler	1,651.46	1,651.46	16,514.59	8.26×10^{6}	8.26×10^{6}	8.26×10^{7}
Coil Handler	4.19	4.19	41.90	8.38×10^{4}	8.38×10^{4}	8.38×10^{5}
Product Loader	20.87	20.87	208.67	1.04×10^{6}	1.04×10^{6}	1.04×10^{7}
Product Truck Driver	59.01	59.01	590.14	5.90×1^{05}	5.90×1^{05}	5.90×10^{6}
Sheet Assembler	82.30	82.30	823.00	4.12×10^{5}	4.12×10^{5}	4.12×10^{6}
Warehouse Worker	3.12	3.12	31.25	6.25×10^{4}	6.25×10^{4}	6.25×10^{5}
Radwaste Container	1,933.59	1,940.30	18,735.36	1.93×1^{08}	1.94×1^{08}	1.87×10^{9}
Building with Rebars	0.78	0.77	7.48	4.75×10^{2}	4.69×10^{2}	4.56×10^{3}
Public Transportation	N/A	N/A	N/A	5.36×1^{07}	5.36×1^{07}	N/A

dionuclide was ^{60}Co. In the case of internal exposure, the effect by ^{90}Sr was significant. There were top four susceptible work scenarios and one public scenario, all of which had relatively long exposure times and a close distance between the receptor and the source.

In each scenario, radiation doses were largely affected

Table 9. Comparison of derived and regulatory limit

Radionuclide	Derived Concentration ($Bq \cdot g^{-1}$)	Regulatory Limit ($Bq \cdot g^{-1}$)
^{60}Co	0.67	0.1
^{137}Cs	0.67	0.1
^{90}Sr	6.68	1

by the by-products such as ingot, baghouse, and slag. This is because radionuclides are redistributed to by-products when the metallic wastes are melted. This radionuclide partitioning behavior gives the idea that the melting process can act as a decontamination process. We have observed through the dose analysis that the exposure dose tends to be closely related to the partitioning factor, and using the characteristics of the radionuclides and the partitioning factors, we can predict which scenarios are heavily influenced and which pathway is important. Additionally, future studies of classification of radionuclides provided by RESRAD-RECYCLE in accordance with similar effects on doses and scenarios will be useful.

With these results of exposure doses, all the scenarios met regulatory criteria, the critical scenario for ^{60}Co, ^{137}Cs, and ^{90}Sr was the slag worker, and derived concentrations of each radionuclide were determined. The derived concentration is higher than the concentration limit of the current regulatory limits, which confirms that the regulatory limit is more conservative. In addition, we have discussed how to consider the allowable concentrations for the metallic wastes containing various radionuclides; the appropriate concentration limit must take into consideration the constraint of the radionuclide concentration fraction. Given the concentration fractions, the available concentrations could be lower depending on their compositions. This suggests that the allowable concentration criteria in recycling of the metallic wastes from the NPP decommissioning is conservative and there is room for mitigation.

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