Optimization of Reactor Pressure Vessel Internals Segmentation in Korea

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1 Introduction

The decommissioning of *Kori unit 1*, which is the first commercial nuclear power plant (NPP) in Korea is planned in the near future. It will be also the first large-scale dismantling experience of a commercial NPP in Korea even though there were experience of the decommissioning of two research reactors and a uranium conversion plant. To perform the successful decommissioning activities of *Kori unit 1*, it is necessary to establish the optimal decommissioning processes and to collect the best practices through the lots of decommissioning experience around the world.

One of the most challenging tasks during plant decommissioning is considered as the removal of highly radioactive internal components of the reactor pressure vessel (RPV) in the *Kori unit 1*. It is also expected to belong to the most difficult activities, because these must be cut underwater due to the severe radiological conditions of the RPV internals *[1][2]*. In order to support this activity, the systems with cleaning of the water in the reactor cavity need to remain operational in *Kori unit 1*. It is therefore recommended that the reactor internals are removed as early as possible in the plant dismantling sequence, so that these water systems and their associated support systems can be released for decommissioning. This minimizes the costs of maintaining these systems in operation after permanent plant shutdown *[2]*.

After removal of spent fuels, reactor internals constitute the next significant contributor to the radiological inventory of the decommissioned NPP. Therefore, the early removals of the reactor internals significantly reduce the total site radiological hazard. Depending on the regulatory requirements applicable at this decommissioning stage, this may allow a reduction in the nuclear safety measures that must be maintained and that eventually leads to additional cost saving. So, it is recommended that the reactor internals segmentation is the first major dismantling activity to be carried out inside the reactor building. The internals segmentation should be performed after the chemical decontamination of the primary system in order to minimize doses to the personnel during the activity.

A cut way of the RPV with the primary internal components of *Kori unit 1* is shown in **Figure 1**. The internal structures adjacent to the core barrel active region are the most highly activated and in the most cases involves intermediate level waste components which may require removal prior to disposal of the remainder of the RPV and reactor internal components *[1]*.

In this paper an optimal segmentation method is described that RPV internals be cut and packaged to meet established national disposal criteria in *Kori unit 1*.

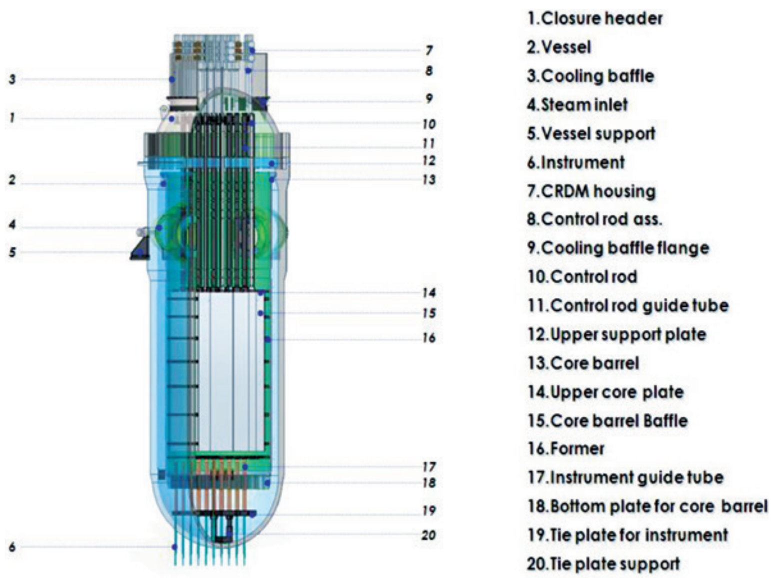


Fig. 1.
A Cut Way of the RPV with the Primary Internal Components of Kori unit 1.

2 Radiological assessment

The radiological effect must be assessed for the decommissioning of its NPP after permanently shutdown, because it is different values among the commercial NPPs due to the different operating conditions and material conditions. To design the decommissioning scenario under the ALARA principle and calculate exposure dose rate for worker, the assessment of the external radiation level is important in the NPP. And also to perform the waste classification and packaging, the detail radiological information can be obtained from results of the radioactivity inventory assessment. In this study, the radiological assessment of *Kori unit 1* was performed for the reasonable design of decommissioning scenario and waste management.

Since the core baffle assembly closes proximately to the active region of the fuel during operation, it is the most highly activated component of the RPV internals. The use of boric acid in *Kori unit 1* coolant requires the use of stainless steel construction for the reactor internals and cladding on the inside of a carbon steel reactor vessel *[1, 3]*. Impurities such as cobalt and other metal such as nickel in the stainless steel are ultimately activated and contribute to the high curie inventories in reactor and reactor internals.

For the radiological assessment, *Kori unit 1* operated for 40 years at the capacity of 90 % leading to 36 EFPY (effective full power year) years of operation. The assessment results 10 year after shutdown are summarized in **Table 1** *[3]*. (About 80 % of the total radioactivity is contained in the core baffle which will be cut and stored on-site as intermediate level waste material.). For the proper packaging

Component name	Weight (kg)	Volume (m^3)	Total specific activity (Bq/g)	Co-60 specific activity (Bq/g)	Ni-63 specific activity (Bq/g)
Vessel Internal					
Baffle plate	9,523	76.40	3.24E+09	2.18E+09	5.56E+08
Barrel	30,472	244.48	1.70E+09	9.57E+08	2.92E+08
Baffle former	2,612	20.96	2.24E+08	1.59E+08	3.48E+07
Thermal shield	23,697	190.13	3.13E+08	2.21E+08	4.85E+07
Upper support assembly	6,153	49.37	5.79E+01	1.17E-01	2.92E+01
Upper core plate	1,534	12.31	3.72E+06	7.51E+03	1.88E+06
Guide tube	8,419	67.55	3.14E+03	6.27E+00	1.61E+03
Upper support column	20,713	166.18	3.80E+03	7.58E+00	1.95E+03
Lower core plate	1,682	13.50	7.02E+05	1.42E+03	3.54E+05
Core support plate	4,192	33.63	2.99E+03	5.97E+00	1.54E+03
Reactor vessel (without reactor head)	185,397	1,465.00	9.07E+06	5.80E+06	1.81E+05

Tab. 1.
Radiological Assessment Results 10 Years after Shutdown of Kori Unit 1.

of the activated components, knowing the cobalt-60 (Co-60) inventory of the various cut pieces was essential.

3 Segmentation and packaging plan

It is necessary to define the sequential steps required to segment, separate, and package each individual component of RPV in the segmentation and packaging plan, based on an radiological assessment. Therefore, the dismantling strategy is established in the most cost effective manner, in consideration of many factors such as waste container selection, disposal costs, transportation requirements, etc. *[2]*. The plan is prepared early in the planning phase before the dismantling activity considering the following sequences and processes *[4]*,

- Collection of various types of design and operating data, if needed, by the interview with current and former employees of the NPP.
- Development of a 3D model of the reactor based on the collected data for the comprehensive understanding of the RPV and for the development of the segmentation strategy.
- Activation analysis of the reactor vessel and internals to define waste characterization and classification of the reactor components.
- Evaluation of disposal options depending on waste characterization and the waste acceptance criteria.
- Conceptual tooling development based on waste characterization and disposal option, which are developed using collected data and information. Note that final tooling design will be developed after completions of the segmentation and packaging plan.
- Segmentation and packaging plan contains optimization packaging efficiency while considering segmentation schedule. And the plan defines type and quantity of waste containers and defines location and number of cuts per waste container.

Based on the dismantling experience of the RPV internals, however, actual developing process of the segmentation and packaging plan is usually made at first by consideration of waste acceptance criteria, available type and size of containers for the disposal options *[2]*. And then begin to select a cutting technology and finally the cut geometry required. With optimized planning with 3D models, these complicated tasks can be performed while maintaining occupational exposure and controlling project costs *[1]*. All cutting processes typically generate various types of secondary waste, which must be properly controlled, collected and packaged for disposal.

3.1 Disposal requirements and waste packages

In 2013, radioactive waste classification system in Korea was revised reflecting the international standard recommended by *International Atomic Energy Agency (IAEA) [5]* as shown in **Table 2**, and specifies Low and Intermediate Level Waste (LILW) further into the Intermediate Level Waste (ILW), Low Level Waste (LLW) and Very Low Level Waste (VLLW) depending on its specific radioactivity *[6]*. Being contaminated less than self-disposal allowable concentration (as the same concept of clearance level), these waste can be self-disposed by a customer.

The disposal option currently available in Korea is the Gyeongju Centralized LILW Disposal Facility of cavern type repository, which has been operated from 2015. This repository is designed to accept Very Low Level Waste (VLLW), Low Level Waste (LLW) and Allowable Intermediate Level Waste (AILW)*, in accordance with the corresponding Waste Acceptance Criteria (WAC), issued by KORAD as owner and operator of the facility.

The WAC provides the detailed acceptance criteria in *Gyeongju* for each required technical items *[7]*. Per the WAC for Gyeongju, the radioactive waste may be classified as VLLW, LLW or AILW. These classifications are

Waste Level	Guideline
High Level Waste (HLW)	For the isotope with $T_{1/2}$ >20y, Specific activity for alpha > 4000 Bq/g or Heat generation > 2 kW/m^3
Intermediate Level Waste (ILW)	$\sum_{i=1}^{n} \frac{A_i}{LD_i} > 1$
Low Level Waste (LLW)	$\sum_{i=1}^{n} \frac{A_i}{CW_i} > 100$, and $\sum_{i=1}^{n} \frac{A_i}{LD_i} \leq 1$
Very Low Level Waste (VLLW)	$1 < \sum_{i=1}^{n} \frac{A_i}{CW_i} \leq 100$
Clearance Waste (CW)	$\sum_{i=1}^{n} \frac{A_i}{CW_i} \leq 1$

Tab. 2.
Classification standard of radioactive waste in Korea.

(*) Based on the Korean national regulation, the radioactive wastes have to be classified as VLLW, LLW, ILW, and HLW. AILW means that some ILW is permitted to be disposed in Gyeongju considering its local site conditions. The other ILW has to be disposed in the separate ILW or HLW disposal Facility.

A_i: Specific activity of isotope i (Bq/g)
LD_i: The radioactivity limit of LLW disposal (Bq/g)
CW_i: The radioactivity limit of clearance waste (Bq/g)

based on the content of both long- and short-lived radionuclides in accordance with National Notice *[6]*. According to the WAC, the VLLW, LLW and AILW require immobilization and encapsulation inside the packages.

To diversify disposal options of the decommissioning wastes and to utilize the existing cavern type repository in the most cost effective manner, KORAD have constructed a near-surface land facility for the LLW disposal and have a plan to construct a VLLW disposal facility. Since some wastes that exceed AILW limits (called as Non-AILW) are not acceptable to the existing repository, they must be managed concurrently with the spent nuclear fuel or high level waste.

Waste containers are classified with steel drums, concrete containers, HIC, and polyethylene containers in *Gyeongju*. The steel drums are classified with 200 L and 320 L drums, and the concrete containers are classified with circular concrete containers and rectangular concrete containers *[7]*. LILWs packed in 200 L drums are disposed of in a 16-pack concrete disposal container. The extra compressed 200 L drums are packed again in 320 L drums. The nine 320 L drums are disposed of in a 9-pack concrete disposal container. The other concrete containers are disposed as itself in the repository.

Non-AILW is stored in the specially designed canisters (SDCs), which are then placed into a temporary storage building or in an ISFSI *[6]*.

3.2 Selection of a cutting technology

Segmentation of the RPV internals can be performed using thermal and mechanical cutting technology and the best technique chosen will depend on the application and item to be cut *[1]*. Thermal segmentation of metals refers to the technique of cutting without making direct contact and using a high energy process. In direct contrast to mechanical cutting, thermal cutting uses a medium other than a cutting edge to sever the metal by making use of a heat source to melt, sublimate, combust or weaken a material to enable the separation of large structures to manageable formats. The thermal cutting technologies can be further subdivided according to the type of energy source (chemical means, electric current and laser beams) they make use of for generating the heat. Mechanical cutting technologies include: grinders, saw blades, drilling machines and cold cutting technologies (nibblers, shears, and cutters for bolts, pipes, and tubing) as well as diamond wire, arc saw, and Mechanical Disintegration Machining (MDM). Hydraulic techniques include abrasive water jet cutting (AWJC) with injection and suspension modes.

According to the decommissioning experience in the world, the mechanical cutting technology has been preferred due to lower generation of secondary waste and lower radiation exposure to worker than the thermal cutting technology *[8, 9, 10]*.

Selection of the proper cutting technology in *Kori unit 1*, however, will be made considering the following factors in detail based on the past experience,

- Occupational safety and optimization for radiation protection,
- Secondary waste minimization,
- Process safety and simple operation,
- Reliability and maintainability,
- Cutting capacity.

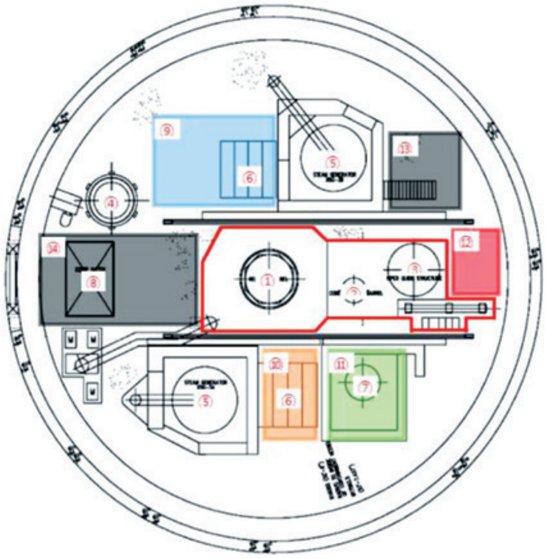
4 Optimization of dismantling process

Before starting any cutting activities in *Kori unit 1*, it is important to demonstrate that the proposed dismantling process is safe and approved by the optimization process. Based on the optimization process, the licensing documents have to be prepared in accordance with the national regulation.

4.1 Preparation activities

For making the segmentation work easier and safer, the preparation activity has to be performed including some plant system and civil structure modifications *[2, 10]*. To define the scope of the preparation activity, required space requirements at first are defined according to the applied cutting technology, associated remote handling equipment such as manipulator and waste handling tools and container. And then the environmental conditions of the reactor building especially around of the reactor cavity are carefully reviewed in view of the required space requirements for the cutting activity. Depending on its environmental conditions, it will be determined a number of preparation activity, which have to be performed before the actual cutting activities can start.

The levels and dimensions of the cut positions are based on the expected activity levels and the dimensions of the waste containers. For example the preparation activities will include cutting of some wall around the reactor cavity, securing the pool integrity, characterizing the internals, retrieval of existing components, installing a new working bridge and cleaning of the pool floor and water, etc. based on the reactor building layout in *Kori unit 1* as shown in **Figure 2**.



1. Reactor Cavity (Reactor Vessel),
2. Core Barrel & Baffle Assembly,
3. Upper Guide Structure
4. Replaced RX Vessel Head,
5. Steam Generator,
6. Reactor Coolant Pump,
7. Pressurizer

Fig. 2.
Reactor Building Layout in Kori unit 1.

Cutting of the wall may be necessary to provide access to a deeper pool and led to better water shielding for the operators. That constituted a substantial design change and detailed structural analyses had to be performed to demonstrate that this demolition is safe. The sealing of the pool walls was a challenging task as the initial leakage was substantial and coming from all over the pool area.

Other significant civil work modifications occurred for allowing the installation of a hot cell for the future drying and characterization of the cut internals and final container loading. To achieve that, a previous steam generator pit has been sealed with a concrete slab to create the necessary space for installing the hot cell. Another steam generator pit has been also sealed for installing the future dry cutting workshop. Other significant works had to be performed for bringing new electrical cabinets and installing new ventilation ducts.

A new working bridge crane may have to be installed in the cavity with higher capacity, and placed at a height compatible with the maximum water level. This new arrangement has the additional benefit of placing the access to the bridge at the floor level, simplifying the access of personal and equipment to it.

4.2 Cutting process

All items inside the RPV are removed with available lifting tools and equipment. The lower internals are positioned on an inside flange in the RPV and the upper internals are positioned onto the upper flange of the lower internals. The RPV internals cutting sequence starts with the segmentation of the upper internals, follows by the lower internals, removes from the RPV and transfers to the assigned area, where transferred part are segmented as a small parts *[2, 10]*.

The potential complete RPV internal segmentation sequence can be summarized as follows, even though total cutting steps consist of about 45 steps:

1. Cutting the upper internals (which is done from the top and proceeds down).
2. Cutting the core barrel upper section.
3. Cutting the thermal shield (which is separated from the core barrel belt line area)
4. Cutting the core barrel belt line area, including core baffle and formers.
5. Cutting the lower core plate.
6. Cutting the core lower section.
7. Cutting the core support column.

4.3 Risk mitigation and prevention

One key issue is to prevent and mitigate an anticipated radiological risk during the segmentation and packaging activities. Many of pieces that will cut and packaged need to be rigged to get them into their respective disposal container. During the movement many of these pieces could potentially cause a radiation exposure to workers if they were inadvertently raised out of the water. Safety measures must be in place to prevent any possibility of this occurring. Another risk is if one of the cut pieces are dropped, damage to the reactor cavity liner or other critical equipment could result. Detailed procedures and specialized rigging equipment have been developed to prevent these risks. To mitigate these possible risks due to uncontrolled drop of heavy pieces and resulting damages to the stainless steel liner of the pool floor *[1]*.

Different types and amounts of wastes may be generated during cutting process. The specific amount and character of this waste material and the handling requirements to control exposure depends on the type and scale of the cutting performed and the detailed characterization information on the radionuclide concentrations and surface contamination levels for the materials being cut. The radiological risk related with the secondary waste management should be considered as one of safety measures during the cutting process *[12, 13]*.

Based on the related risk mitigation and prevention, the safety analysis report has to be prepared which identifies both nuclear and conventional risks associated with the performance of the segmentation of the RPV internals,

4.4 Secondary waste and debris management

The expected volume and total and specific activity of radioactive waste are expected to be generated as result of the segmentation activity, as well as the corresponding packaging strategy.

Different types and amounts of secondary wastes, mainly in the form of dust, sludge, metal debris, filters and some liquids, etc., are generated during cutting process. In general, mechanical cutting processes produce large sized debris and very few aerosols. Filtering or collecting the debris is typically possible using catch trays, baskets, ordinary HEPA filters and vacuum cleaning. Mechanical cutting technology also provides benefits in terms of lower secondary waste volume and water clarity during underwater cutting. Thermal processes, on the contrary, produce fine debris and large amounts of hot particles, dust and aerosols that require extensive filtering, conditioning and containment. *[14]*. Debris collection and ventilation systems employed must be designed to pick up the debris close to the source. The environment must also be protected from the spread of contamination by employment of a suitable containment and ventilation system. *[15]*

All secondary wastes are segregated and collected in specially designed drainable containers. Debris produced during the segmentation of the LLW and AILW part of the RVI are introduced inside LLW waste containers, while those coming from the segmentation of the non-ILW portion are packaged into the specially designed containers. These wastes have to be managed according to the waste acceptance criteria in *Gyeongju*.

4.5 Qualification

The qualification of cutting and handling equipment has to be done under as realistic conditions as possible in the way they are supposed to and in the expected environment. The qualification process includes all expected operations (clamping, handling, cutting, packaging and water cleaning), and is done under water, in accordance to the established test procedures, which describe the workflow for the qualification through the mockups. The qualification test also serves a part of the training of personnel before their deployment. The mockup testing is an important step in order to verify the function of the equipment and minimize risk during segmentation work on site *[2]*.

The mock up tests are performed in a large pool used for training personnel before the actual segmentation activity in *Kori unit 1*. This pool has to be equipped with a working bridge similar to the one used at *Kori unit 1*, and the conditions and equipment for handling are the same as those expected at the actual work location. With full sized mock-up of representative components to be cut, in general, tools have to be tested in a worst case scenario, e.g., the thickest most complicated cuts in all regions.

For the water cleanup the complete filtration skid should be fully tested prior to bringing it on site. The filtration skid should be designed for underwater operation and the design of all the active components should allow replacement or repair from the surface, without removing the skid from the cavity pool.

4.6 ALARA analysis

The RPV internal segmentation is the major area of primary focus to reduce a radiation exposure in the radiological engineering group during decommissioning because the task has the greatest potential for high personnel radiation exposures *[12]*. Because the RPV internals segmentation is performed entirely underwater, engineering effects on the ALARA focus on controlling cutting debris and maintaining shielding (water) between workers and segmented components. Underwater tooling and rigging are engineered or marked as appropriate to maintain water shield over segmented components.

ALARA reviews are developed to address various areas of the work scope as follows:

- Segment and package RPV internals.
- Dose profile RPV internals components.
- Segmented parts loading and cask handling.
- Lower internals handling.
- Secondary waste removal and shipment preparation.

The detailed ALARA review continues the process begun by the radiological engineering group during design development. The ALARA review establishes controls for work activities and provides guidance for activity sequencing. In conjunction with the development of the ALARA reviews, ALARA personnel are continuously involved in the planning and scheduling process. Every attempt is made to eliminate, simplify or increase the efficiency of work activities without compromising personnel safety.

5 Conclusion

It is important to well prepare the dismantling plan of a RPV internals in advance. A detailed study of the optimum dismantling scenario must be done in the upstream of the decommissioning phase, considering the available plant systems and infrastructure. Especially for *Kori unit 1*, significant plant modifications need sometimes to be considered for completing the reactor dismantling, including civil work modifications, new water filtration system, new power supply, new HVAC system, etc. specific waste management constraints may also require installation of dedicated characterization and handling equipment before final container loading.

Extensive predeployment planning, simulation, and testing should be done prior to any onsite segmentation work. Experience has clearly shown the benefits of comprehensive testing involving a full mockup of the cutting arrangement, materials, tooling, and waste capture and processing system. Computer simulations, such as 3D models, can help to identify and mitigate high risk factors in advance.

One of the most difficult challenges in the entire segmentation process is maintaining water clarity through the removal of debris created in the cutting process. Colloidal suspension from the fragmentation of garnet can also present a major challenge. In order to maintain water clarity, it is important to segment the pool cutting area and focus waste collection on this zone. In addition, the processing capacity and the reliability and maintenance of the filtration system are essential to project success.

The amount of cutting should be optimized with respect to the number of cuts and the size of the final waste packages. The cutting plan should minimize the number of cuts, produce waste pieces that can be easily packaged, and minimize the final waste volume. Segmentation should begin with the least irradiated components in order to gain experience with the tooling before applying it to highly radioactive components, where tooling failure could significantly increase personnel exposure.

In accordance with the previous decommissioning experience since a major risk of the decommissioning project is the lack of its stakeholders acceptance, it is necessary to apply various complementary policies with regard to education, supporting the local economy and especially, communication.

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