Evaluation Methodology of Remote Dismantling Equipment for Reactor Pressure Vessel in Decommissioning Project

D. J. Hyun, B. S. Choi*, K. S. Jeong, J. H. Lee, G. H. Kim, and J. K. Moon

Korea Atomic Energy Research Institute

Abstract : *A novel methodology to evaluate remote dismantling equipment for a reactor pressure vessel (RPV) in a decommissioning project is presented in this paper. The remote dismantling equipment, mainly composed of cutting tools and positioning equipment, is absolutely required to cut and handle highly radioactive and large components in nuclear power plants (NPPs); this equipment has a great effect on the overall success of the decommissioning project. Conventional evaluation methods have only focused on cutting technologies or positioning equipment, although remote dismantling equipment cannot achieve its goal without organic interaction between the cutting tools and the positioning equipment. In this paper, the cutting tools and the positioning equipment are evaluated by performance parameters according to their original characteristics, the relationship between the two systems, and common factors. Finally, the remote dismantling equipment used in recent decommissioning projects has been evaluated based on the proposed methodology. The results of this paper are expected to be useful for future decommissioning projects.*

Keywords : *Evaluation methodology, Remote dismantling system, Cutting tool, Positioning equipment and Reactor pressure vessel*

1. INTRODUCTION

RPVs in NPPs are one of the most difficult components to dismantle because they are highly radioactive and made with very thick walls or complex structures. Generally, an RPV is composed of a reactor vessel (RV) that has a comparatively simple structure but very large thickness and RV internals (RVI) that have very complex structures but comparatively thin walls. In this study, for simplification, RPVs are considered to be RVs, because the area of discussion will become too large in a case in which both RVs and RVIs are covered. RVIs can be discussed in another article.

The thickness of the RPV, that is the RV, is generally greater than 150 mm and greater than 300 mm in some areas. There are not many tools that can cut steel plates of

which the thickness is greater than 200 mm. Candidate tools to for evaluation are only contact arc metal cutting (CAMC) tools, high pressure abrasive water jets (HPAWJ), mechanical saws, and diamond wire saws. Candidate examples of positioning equipment are the manipulator, which is mainly composed of rotational joints, and the carrier system, which is mainly composed of simple linear motions and has a stiff structure.

Conventional evaluation methods [1], [4], and [5] have only focused on cutting technologies or positioning equipment, even though remote dismantling equipment cannot achieve its goal without organic interaction between the cutting tools and the positioning equipment.

The objective of this work is to establish a proper evaluation method that can find the best remote dismantling equipment for an RPV with a consideration of the relationship between the cutting tools and the positioning equipment. In this paper, as a case-study, the evaluating factors for cutting tools and positioning equipment are defined and the remote dismantling equipment used in the Rancho Seco decommissioning project and the Würgassen decommissioning project are analyzed and evaluated using the established method.

Received : July 31, 2013 · Revised : September 03, 2013 · Approved : September 03, 22, 2013

*Corresponding Author : B. S. Choi

Korea Atomic Energy Research Institute

Tel : +82-42-868-8947 E-mail : bschoi@kaeri.re.kr

Daedeuk-daero 989-111, Yuseong-gu, Daejeon 305-353, Republic of Korea

Fig. 1. Relationship between cutting tools and positioning equipment.

2. EVALUATION METHODOLOGY OF REMOTE DISMANTLING EQUIPMENT

In this paper, the evaluating factors are mainly classified into three categories, as shown in Fig. 1. As the first category, the original characteristics of the cutting tools or positioning equipment are defined as the performance parameters. Therefore, the two components have evaluating factors that are different from each other, such as cutting capability and range of motion. As the second category, the requirements and the response show a correlation between the cutting tools and the positioning equipment. Cutting tools require suspending stiffness, payload, positioning accuracy, and force-control to positioning equipment. The positioning equipment must respond to these requirements well. Otherwise, the cutting system cannot achieve its goal. For example, a mechanical saw with a large reaction force should not be equipped with a manipulator composed of rotational joints and long arms, because a combination of rotational joints and long arms is not suitable for the large stiffness required of such a saw. The suspending stiffness and the payload seem to be similar to each other. However, the suspending stiffness is determined by the structure and the payload is determined by the actuator. Generally, the suspending stiffness is proportional to the payload. As the last category, the reliability shows common factors between cutting tools and positioning equipment. Fig. 1 shows the relationship between cutting tools and positioning equipment.

2.1 Evaluating Factors of Cutting Tools

The evaluation factors of the cutting tool can be largely

divided into three categories ; these are the performance parameters, requirements for the positioning equipment in remote operations, and reliability, which is commonly needed in any decommissioning project. In the following we provide a detailed list of factors included in these categories and describe their definitions.

2.1.1 Performance parameters

- Cutting capability : This factor is defined by the thickness that the cutting tool can cut: the larger the thickness, the better the performance. Generally, to complete the RPV cutting process, a cutting capability greater than 300 mm is needed. The CAMC, the HPAWJ, the mechanical saw, and the diamond wire saw have demonstrated their cutting capability in other decommissioning projects. However, the CAMC seems not to have been used recently because it excessively spoils the visibility of water in underwater operations.
- Cutting speed : A faster cutting speed is preferred because cutting speed is the most important factor that directly influences the work schedule. In terms of auxiliary issues, a prolonged schedule due to slow cutting speed could bring problems in maintaining air conditioning equipment or inventory of compatible supplies. According to the cutting tool, the cutting speed can decrease directly in proportion to the thickness or exponentially in proportion to the thickness.
- Versatility : This factor is defined by the ability to change the cutting path to a direction perpendicular

to the cutting plane. Greater versatility is preferred. For example, with mechanical sawing it is difficult to change the cutting direction because the stiff blades stick deeply into the kerfs. Thus, mechanical sawing leads to difficulty in cutting the head and the bottom of the RPV with hemispheric surfaces. Contrarily, the HPAWJ can freely change the cutting direction.

- Secondary waste : This factor is defined by the volume of particles or swarfs produced during the cut; these materials are produced in a manner that is directly proportional to the thickness of the kerfs. In the case of the HPAWJ, abrasive garnet and injected water make secondary waste increase considerably.

2.1.2 Requirements for the positioning equipment

- Suspending stiffness : This factor is determined by the reacting force during the cut; lower stiffness is preferred for the cutting tool. A cutting tool requiring low stiffness leads to a wide range of selection for the positioning equipment.
- Payload : A lighter weight for the portable part of the cutting tool or system is preferred. Similar to the case of the suspending stiffness, a smaller weight for the system can make various selections possible for the positioning equipment. For example, a water jet nozzle is the only moving part of the HPAWJ and is much lighter than a mechanical saw. A cutting tool with a light moving part can be equipped with slender positioning equipment so that it can be inserted into narrow spaces and can be applied for precise cutting operations.
- Positioning accuracy : Lower positioning accuracy as required by the cutting tool is preferred because a cutting tool of good productivity despite bad position accuracy can allow for robust positioning equipment of simple structure. Generally, positioning equipment of high precision has a complex structure, many sensors, and complicated control algorithms, so that failure probability increases steeply.
- Force-control : Identical to the case of positioning accuracy, a cutting tool requiring small force-control capability can be adopted for use with simple and robust positioning equipment. Basically, force-control requires more complexity of the positioning equipment.

2.1.3 Reliability

- Maintenance : This factor of the cutting tool is defined by the existence of expendable supplies and how easy it is to supply them. Expendable supplies

mean wearing parts during the cut, like electrodes in the electrical discharge machining (EDM). In the case of the HPAWJ, abrasive garnet could be defined as an expendable supply. However, abrasive garnet is supplied continuously with pipelines so that the HPAWJ might not be degraded due to the maintenance factor. A highly radioactive environment makes manual supply very severe and complicated.

- Durability : Durability is a very important factor because repair work takes time and has considerable cost. Repair work requires the direct intervention of experienced technicians and delicate decontaminating work. Additionally, broken parts become radioactive waste.
- Decontamination : Decontamination means how easy it is to clean the surface of the cutting tool. If the cutting tool cannot be decontaminated easily, maintenance and reuse of such tools becomes difficult.
- Resistance to the environment : This factor is defined by the functional insensitivity to the radioactive environment and the characteristics of easy decontamination; in a good situation, a cutting tool with smooth and sleek surfaces can be easily cleaned using a shower.

2.2 Evaluating Factors of Remote Positioning Tools

As was shown in the previous section, the evaluation of the factors of remote positioning tools can be divided into three categories, which are the performance parameters of the remote positioning tool, the factors responding to the requirements of the cutting tool, and common reliability. The following is a detailed list of these factors and their definitions.

2.2.1 Performance parameters of the remote positioning tool

- Range of motion : A larger range of motion is better, although a range of motion excessively larger than the work piece is not required. Range of motion is dependent on the mechanism, so that it would be difficult to use a manipulator with rotational joints to expand the range of motion. Load paying to a joint that increases steeply with the range of motion is enlarged. Therefore, a manipulator with rotational joints has a disadvantage in terms of range of motion.
- Speed of motion : Faster movement is better in order to shorten the elapsed time of the work, which is determined by the speed of the positioning equipment and the cutting speed of the cutting tool.
- Dexterity : This factor is defined as the ability to handle

the cutting tool freely not only in terms of position but also in terms of orientation. That is, to allow the user to have six degrees-of-freedom in the work space of the positioning tool. In order to cut arbitrary surfaces freely, greater dexterity is preferred.

- Occupied volume : A smaller volume is better because a positioning tool occupying a small volume can be inserted into narrow spaces or into spaces in which there are many obstacles. Almost all RPVs are equipped with small pipes on their heads and bottoms.

2.2.2 Factors responding to cutting tool

The following four factors were already defined in the previous section. However, in terms of the positioning equipment, evaluation standards for these factors are contrary to those for the cutting tool. For example, a lighter payload is better in terms of the cutting tool. A heavier payload is better in terms of the positioning equipment. Generally, the following factors must be designed according to the requirements of the cutting tool.

- Suspending stiffness
- Payload
- Positioning accuracy
- Force-control capability

2.2.3 Reliability

- Maintenance : This factor from the aspect of the positioning equipment is defined by the existence of

parts requiring periodic check or replacement and how frequently it is necessary to manage them. Underwater equipment and hydraulic-powered equipment require more maintenance.

- Durability : This factor is almost the same as those described in the previous chapter. In the case of the positioning equipment, durability of the control line, the electrical power line, and the hydraulic power line is needed. Especially, if the hydraulic power line is broken, then the work space will be severely contaminated.
- Decontamination : This factor is almost the same as those described in the previous chapter. If the positioning equipment cannot be decontaminated easily, maintenance and reuse of the equipment becomes difficult.
- Resistance to the environment : This factor is almost same as those described in the previous chapter. Since the size and cost of the positioning equipment are much larger than those of the cutting tool, inability to reuse the positioning equipment can have a bad influence on the decommissioning project.

2.3 Evaluation of Remote Dismantling Equipment for RPV

Four candidates for RPV cutting are selected to implement the evaluation method described in the previous section. The HPAWJ, the mechanical saw, the diamond

Fig. 2. Evaluation of cutting tools - performance parameters.

Fig. 3. Evaluation of cutting tools - requirement for positioning equipment.

Fig. 4. Evaluation of cutting tools - reliability.

wire saw, and the CAMC are the candidates that have been used in practical experience to cut steel plates of more than 200 mm thickness in completed or ongoing decommissioning projects. Fig. 2-4 show the evaluation results for the performance parameters, and the requirements for positioning equipment and reliability, respectively. In all the figures, the axis of the graph indicates 0 to 5, better performance wins a higher point, and the points are determined by a relative comparison among candidates from the references. For example, in the secondary waste factor shown in Fig. 2, the mechanical saw wins the best score because it produces the smallest quantity of secondary waste among all the candidates. In terms of performance parameters, the HPAWJ and the mechanical saw show complementary characteristics. The HPAWJ shows the best versatility; the mechanical saw shows the worst versatility. In terms of the secondary waste factor, these two show opposite results. In the RPV, the cylindrical part is suitable for the mechanical saw and the head and the bottom are not suitable for it. In terms of the requirements for the positioning equipment, the HPAWJ shows the best evaluation results, as can be seen in Fig. 3. This means that the HPAWJ is the most suitable for the remote handling technology. In terms of reliability, the HPAWJ and the mechanical saw show good evaluation results, as can be seen in Fig. 4.

Candidates for positioning equipment are the 6-DOF manipulator, the gantry manipulator, and the linear motion. Fig. 5-7 present the evaluation results for the performance parameters, the response for the cutting tools, and the reliability. In terms of the performance parameters, the 6-DOF manipulator shows the best results, as can be seen in Fig.

5. However, the linear motion shows the best results in terms of response for cutting tools and reliability, as can be seen in Fig. 6. From these evaluations, the 6-DOF manipulator can be seen as suitable for the HPAWJ and the mechanical saw can be seen as suitable for the linear motion. From lessons drawn from previous decommissioning projects [1], it can be stated that the reliability is the most important requirement. Therefore, a combination of

Fig. 5. Evaluation of positioning equipment - performance parameters.

Fig. 6. Evaluation of positioning equipment - response for cutting tools.

Fig. 7. Evaluation of positioning equipment - reliability.

the mechanical saw and the linear motion is recommended as possible. In real dismantling missions, a combination of the mechanical saw and the linear motion cannot handle very complex structures. Therefore, a combination of the HPAWJ and the 6-DOF manipulator is preferable.

2.4 Case Studies

Rancho Seco [2] and Würgassen [3] were chosen as recent decommissioning projects in which RPVs were segmented by remote dismantling equipment. Rancho Seco completed segmentation of the RPV using the HPAWJ and a diamond wire saw between 2006 and 2007. Würgassen completed segmentation of the RPV using the HPAWJ and the band saw between 2008 and 2010. All those decommissioning projects can be good references representing recent trends in remote dismantling equipment for RPVs.

2.4.1 RPV segmentation at Rancho Seco site

The reactor of the Rancho Seco Nuclear Generating Station was a 2,772 MWt Babcock and Wilcox pressur-

Fig. 8. Manipulator gantry with HPAWJ nozzle (left), segmented RV (right).

Fig. 9. Diamond wire saw (left), segmented reactor head (right).

ized water reactor; it was operated commercially from April 1975 to June 1989. The decommissioning project began in early 1997 and ended in October 2009.

The cutting tools used in Rancho Seco were the HPAWJ for the RV (Fig. 8) and the diamond wire saw for the reactor head (Fig. 9). The cutting nozzle of the HPAWJ was remotely handled with a manipulator gantry of which the payload was not very large but was suitable to treat the cutting nozzle. The diamond wire saw was not suitable to use with remote technologies. Control of the cutting conditions was too complicated to treat automatically or remotely, so that most of the cutting work was done manually by technicians. In Rancho Seco, the cutting of the reactor head was assumed to be done manually.

Rancho Seco was successful in segmenting, removing, transporting, and disposing of the RV in terms of cost, ALARA (As Low As Reasonably Achievable), and safety perspectives. The schedule did fall behind by approximately two months due to delays experienced during the initial equipment start up and due to garnet collection. The RV was segmented into 21 pieces. The precise operation of the HPAWJ ensured that actual cuts were very close to the specifications in terms of the projected overall size and weight.

The following Fig. 10-13 are shown to present the evaluation results for the Rancho Seco site. The HPAWJ and manipulator gantry seem to make a good combination; however, the positioning accuracy provided by the

Fig. 10. Evaluation of HPAWJ at Rancho Seco - cutting tool.

Fig. 12. Evaluation of relationship between cutting tool and positioning equipment at Rancho Seco.

Fig. 11. Evaluation of gantry manipulator at Rancho Seco - positioning equipment.

Fig. 13. Evaluation of reliability at Rancho Seco.

gantry manipulator was insufficient. At the positioning accuracy axis, the response graph of the gantry manipulator did not envelop the entire requirement graph of the HPAWJ, as can be seen in Fig. 12.

2.4.2 RPV segmentation at Würgassen site

The reactor at Würgassen was a 640MWt boiling water reactor and was shut down in September 1995. The decommissioning project began in 2003 and ended in 2008.

The cutting tools used in Würgassen were the HPAWJ

for the reactor cylinder slice, the reactor head, and the reactor bottom, and the band saw to segment the slices of the reactor cylinder (Fig. 14). When slicing the reactor cylinder, a specially designed linear motion was used to handle the HPAWJ nozzle as the positioning equipment. A 6-DOF manipulator was adopted to cut the reactor head and bottom (Fig. 15). The band saw was used to segment slices of the cylinder into several pieces. Total cut segments were 252 pieces.

The following Fig. 16-19 present the evaluation results of the Würgassen site. The remote dismantling equipment

Fig. 14. HPAWJ (left upper), band saw (left lower), segmented RV (right).

Fig. 15. Cutting with manipulator and HPAWJ (left), segmented reactor head (right).

Fig. 16. Evaluation of HPAWJ and mechanical saw at Würgassen - cutting tool.

Fig. 18. Evaluation of relationship between cutting tool and positioning equipment at Würgassen.

Fig. 17. Evaluation of linear motion at Würgassen - positioning equipment.

Fig. 19. Evaluation of reliability at Würgassen.

at the Würgassen site shows a good correlation, as can be seen in Fig. 18. The response graph of the linear motion envelops the entire requirement graphs of the HPAWJ and the mechanical saw. However, it is hard to apply the remote dismantling equipment to hemispheric surfaces like the head and bottom of the RPV due to the system's low dexterity.

3. CONCLUSIONS

Evaluation results are examined to conclude that the dismantling operation at Würgassen was much more efficient than that at Rancho Seco. In terms of cutting tools, the HPAWJ and the mechanical saw are excellent and have complementary characteristics to each other at the same time. A combination of the two cutting tools can produce a synergy effect. In terms of positioning equipment, the manipulator and the linear motion are excellent and have complementary characteristics as well. The use of the gantry manipulator was intended to take advantage of two technologies but did not show any distinct improvement. To consider the total time to complete the cutting, Rancho Seco took 2 years to segment the RV

into 21 pieces, whereas Würgassen took 3 years to segment the RV into 252 pieces, which is 12 times faster than the rate at than Rancho Seco.

This paper reports on a method to evaluate remote dismantling equipment for RPVs and demonstrates the reasonability of the proposed methodology based on the case studies. The evaluation factors defined in this work can be helpful for making decisions on preferable remote dismantling equipment out of numerous alternatives.

REFERENCES

- [1] Radioactive Waste Management Committee, "Remote Handling Techniques in Decommissioning" (2011)
- [2] Electric Power Research Institute, "Rancho Seco RV Segmentation Experience Report" (2008)
- [3] Annette Bender and nee Schmitz, "Dismantling of RPV Internals Experience within AREVA NP" (2010)
- [4] Robert W. Henderson, Ludger Eickelpasch, "Cutting Reactor Pressure Vessels and their Internals - Trends on Selected Technologies - 10247" (2010)
- [5] L.E. Boing, D.R. Henley, W.J. Manion and J.W. Gordon, "An Evaluation of Alternative RV Cutting Technologies for the Experimental Boiling Water Reactor at Argonne National Laboratory" (1989)