Development of the Maintenance Process Using Virtual Prototyping for the Equipment in the MSM's Unreachable Area of the Hot cell

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Abstract: The process equipment for handling high level radioactive materials like spent fuels is operated in a hot cell, due to high radioactivity. Thus, this equipment should be maintained and repaired optimally by a remotely operated manipulator. The master-slave manipulators(MSM) are widely used as a remote handling device in the hot cell. The equipment in the hot cell should be optimally placed within the workspace of the wall-mounted slave manipulator for the maintenance operation. But, because of the complexity in the hot cell, there would be some parts of the equipment that are not reached by the MSM. In this study, the maintenance process for these parts of the equipment is developed using virtual prototyping technology.

To analyze the workspace of the maintenance device in the hot cell and to develop the maintenance processes for the process equipment, the virtual mock-up of the hot cell for the spent fuel handling process is implemented using IGRIP. For the implementation of the virtual mock-up, the parts of the equipment and maintenance devices such as the MSM and servo manipulator are modeled and assembled in 3-D graphics, and the appropriate kinematics are assigned. Also, the virtual workcell of the spent fuel management process is implemented in the graphical environment, which is the same as the real environment. Using this mock-up, the workspace of the manipulators in the hot cell and the operator's view through the wall-mounted lead glass are analyzed. Also, for the dedicated maintenance operation, the analyses for the detailed area of the end effectors in accordance with the slave manipulator's position and orientation are carried out. The parts of the equipment that are located outside of the MSM's workspace are specified and the maintenance process of the parts using the servo manipulator that is mounted in the hot cell is proposed. To monitor the process in the hot cell remotely, the virtual display system by a virtual camera in the virtual work cell is also proposed. And the graphic simulation using a virtual mock-up is performed to verify the proposed maintenance process.

The maintenance process proposed in this study can be effectively used in the real hot cell operation and the implemented virtual mock-up can be used for analyzing the various hot cell operations and enhancing the reliability and safety of the spent fuel management.

Keywords: Spent fuel Management, Manipulator, Remote Maintenance, Virtual Prototyping, Graphic Simulation

1. INTRODUCTION

The virtual prototyping technology is a realistic, highly visual, 3D graphical representation of an actual device with the real world complexity linked to the production control system and the real facility. It provides the capability of predicting and analyzing the potential problems in the real world as well as in the model world of a virtual environment so that rapid prototyping can be achieved.

The process equipment for handling high level radioactive materials, such as spent nuclear fuel, is operated within a sealed facility, called a hot cell, due to high radioactivity. Thus, this equipment should be maintained and repaired optimally by a remotely operated manipulator to enhance the reliability and operability. The master-slave manipulators(MSM) are widely used as a remote handling device in nuclear facilities such as the hot cell. The equipment installed in the hot cell should be optimally placed within the workspace of the wall-mounted slave manipulator for the maintenance operation. But, due to the complexity in the hot cell, there are some parts of the equipment that are not reached by the MSM.

In this study, the maintenance process for the parts of the equipment that cannot be reached by MSM is developed using virtual prototyping technology. To do this, the virtual mock-up of the hot cell is implemented using a graphic simulation tool, IGRIP. And, the various analyses such as the workspace of the MSM and simulations of the maintenance process proposed in this study are carried out with this virtual mock-up.

2. VIRTUAL MOCK-UP OF THE PROCESS

2.1 Overview of the hot cell process

In this study, as a hot cell process, the Advanced spent fuel Conditioning Process(ACP) is considered. This process is being developed by KAERI to enhance the safety and economic viability for spent fuel management[2]. The objective of ACP is to treat spent fuel in a molten Lithium Chloride (LiCl) bath to remove volatile and high-heat load fission products and to convert the spent fuel into a metallic form more suitable for disposal in a repository. The process consists mainly of two unit operations. One is an air oxidation operation that removes the spent oxide fuel from the cladding and converts UO_2 pellets into a powder form. And, another is the reduction process that exposes the spent fuel powder to lithium in a molten LiCl bath to produce the U-metal. The lithium, which is a very strong reductant, reduces the uranium oxide to a metallic form. Since the spent fuel is very radioactive, all operations, including maintenance and repair, must be performed remotely. The process is conducted in the IMEF hot cell at KAERI.

2.2 Process Equipment

The ACP consists of several unit processes such as decladding, voloxidation, reduction, and smelting. The voloxidizer and the reduction reactor are the main equipment of the process, and the functions of them are described briefly in the following.

The voloxidizer transforms the UO_2 pellet into the U_3O_8 powder by heating and supplying air into the reactor. This equipment consists of a furnace, vibrator and air cylinder for moving up and down the vessel. The reduction reactor converts U_3O_8 powder into the U metal and this equipment consists of a furnace for heating the U_3O_8 powder and the lithium, air agitators for mixing lithium and U_3O_8 powder, and a valve for exhausting the uranium and lithium solution. All the parts of the equipment are graphically modeled and assembled in the graphic environment for the simulation of the maintenance process. Fig. 1 shows the 3D graphic model of the voloxidizer and the reduction reactor.

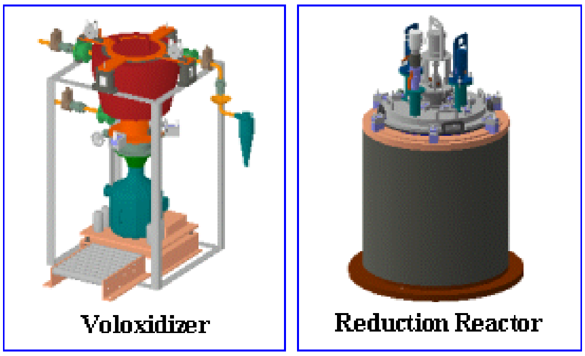


Fig 1. Main equipment of the ACP.

2.3 Maintenance Device : Master-Slave Manipulator

A hot cell is a kind of shielding structure to protect the operators outside the hot cell from the high radiation of the radioactive materials located inside the cell. And, the master-slave manipulators (MSM) are widely used as remote maintenance and handling devices in nuclear facilities, such as the hot cell.

The slave manipulator is attached to the inner wall of the hot cell and is used to maintain and repair the process equipment, and also, to handle and transfer the materials associated with the main process. The master manipulator is attached to the outer wall of the hot cell and is operated by a human operator. Both manipulators are connected by the through-wall tube, which is embedded in the hot cell wall. Table 1 and Fig. 2 show the working range of the MSM [3].

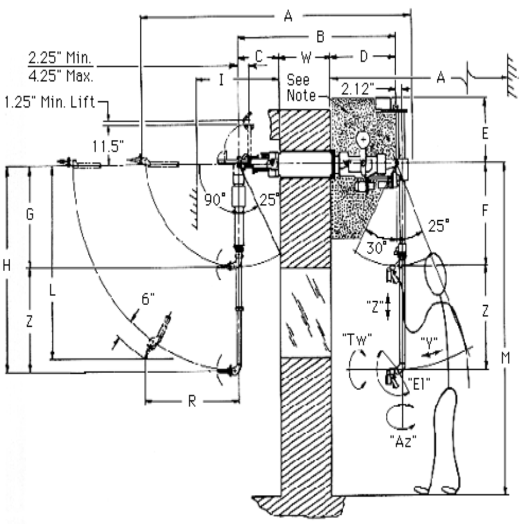


Fig. 2. The schematic diagram of MSM's kinematics.

Table 1. The working range of slave manipulator

Joint	Joint Type	Joint Value
Joint 1	Rotation	± 45°
Joint 2	Rotation	+90° ~ -30°
Joint 3	Translation	1122 mm
Joint 4	Rotation	±164°
Joint 5	Rotation	Up: 40° / Down: 116°
Joint 6	Rotation	±180°

For several analyses in the virtual environment, the MSM is drawn in 3D CAD models using IGRIP. Fig. 3 shows the 3D graphic model of the MSM. The size and shape of the models for all the drawings coincide with the actual ones of the MSM. Also, based on the specification of the real ones, the kinematics of the MSM are assigned.

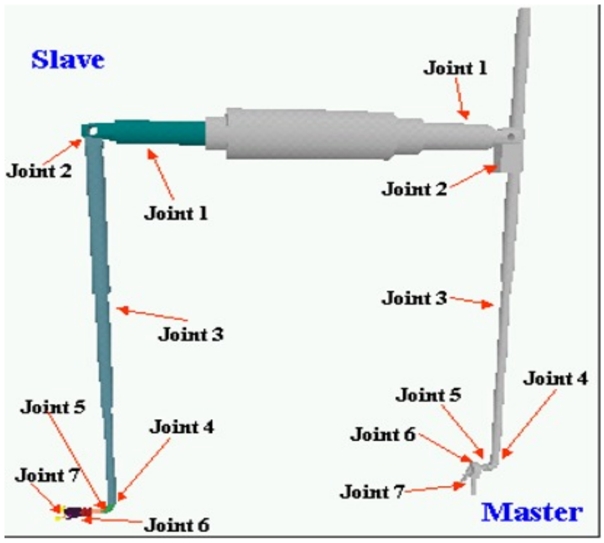


Fig. 3. The graphic model and kinematics of MSM.

2.4. Virtual Mock-up of the ACP

2.4.1 Hot-cell layout

To demonstrate the ACP, the hot test will be conducted in the IMEF hot cell. The process flow of the ACP in the hot cell is shown in Fig. 4. As shown in Fig. 4, the hot cell is divided into two areas, the ACP cell(process cell) and maintenance cell. The processes for decladding, voloxidation and reduction will be carried out in the ACP cell. In the maintenance cell, the repairs of the process equipment will be conducted.

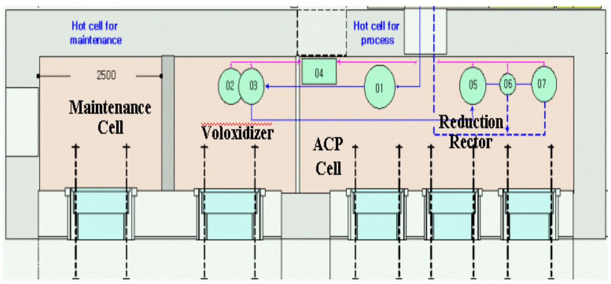


Fig. 4. The process flow of ACP.

In the hot-cell, the MSM is mounted on the wall and the servo manipulator with a telescoping tube set is mounted under the bridge type transportation system. Also, several equipment such as a crane, a slitting device, a voloxidizer, a reduction reactor, smelting furnace, non-destructive assay (NDA) system, etc., are installed in the hot cell. For the hot cell arrangement of the process equipment, the workspace of the remote handling and maintenance system is analyzed based on the process flow.

2.4.2 Virtual mock-up of the ACP

The virtual mock-up of the hot cell process for handling the spent fuel is implemented using IGRIP, the graphic engineering simulation tool, to analyze and define the maintenance processes of the process equipment instead of real mock-up which is very expensive and time consuming[4]. For the implementation of the virtual mock-up, the process equipment and maintenance devices such as MSM and servo manipulator are modeled in 3-D graphics, and the appropriate kinematics are assigned. Also, the virtual workcell of the spent fuel management process is implemented in the graphical environment, which is the same as the real environment. Fig. 5 shows the virtual mock-up of the ACP and this mock-up has several functions for verification such as the analyses for the manipulator's workspace, collision detection, the path planning, and graphic simulation of the processes etc.

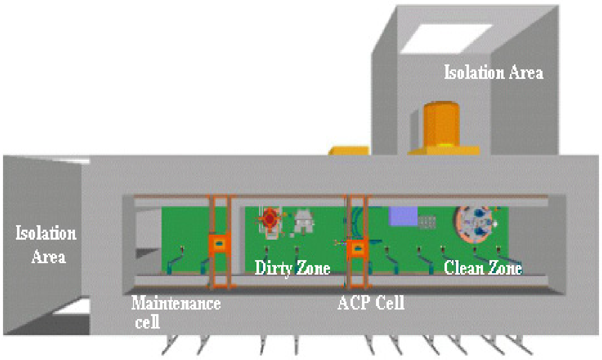


Fig. 5. The virtual mock- up of the ACP.

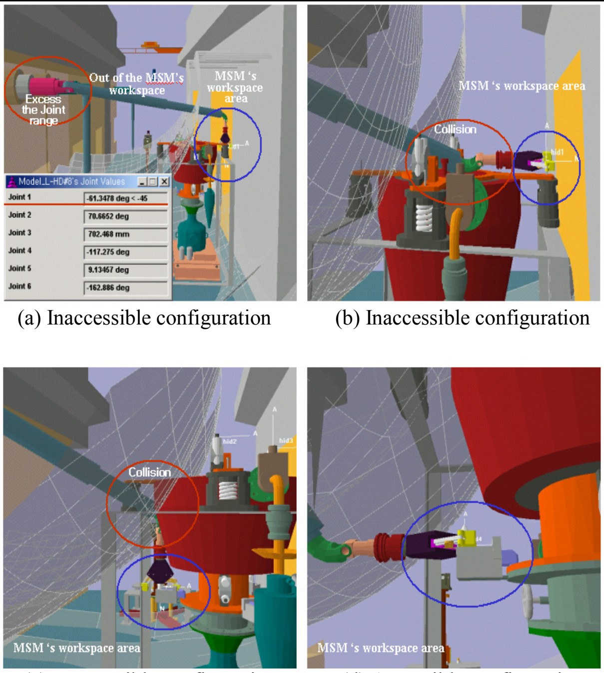
3. ANALYSES USING VIRTUAL MOCK UP

3.1 Analyses of the MSM's workspace

Using this virtual mock-up, the workspace of the MSM in the hot cell is analyzed. Also, for the dedicated maintenance operation, the analyses for the detailed area of the end effectors of the MSM in accordance with the slave manipulator's position and orientation are carried out. And the parts of the equipment that are located outside of the MSM's workspace are specified.

Even though parts of the equipment are located in the workspace of the MSM, there may be the case that these parts cannot be reached by MSM because some joint limits of the MSM are exceeded, or the hot cell is too complex. These cases are shown in the Fig. 6 (a) and (b). Also, even though parts are located in the workspace of the MSM, according to the posture of the MSM and the orientation of the end effectors, some parts cannot or can be reached by the MSM as shown in the Fig. 6 (c) and (d).

In these cases, to operate the main process safely, the maintenance methods for the parts should be provided by another maintenance device, such as a servo manipulator.



(a) Inaccessible configuration (b) Inaccessible configuration

(c) Inaccessible configuration (d) Accessible configuration

Fig. 6. The analyses of the MSM's workspace.

3.2 The analysis of the operator's view

To carry out the remote operation safely, the operator's view should be clear. In this study, the operator's view through the wall-mounted lead glass is analyzed. Fig. 7 shows the view range through the shielding windows based on the normal view of the lead glass in the virtual mock-up. As shown in the figure, there are some areas out of the view range in the hot cell. So, to monitor the process in these areas, additional viewing devices, such as cameras in the hot cell, are needed.

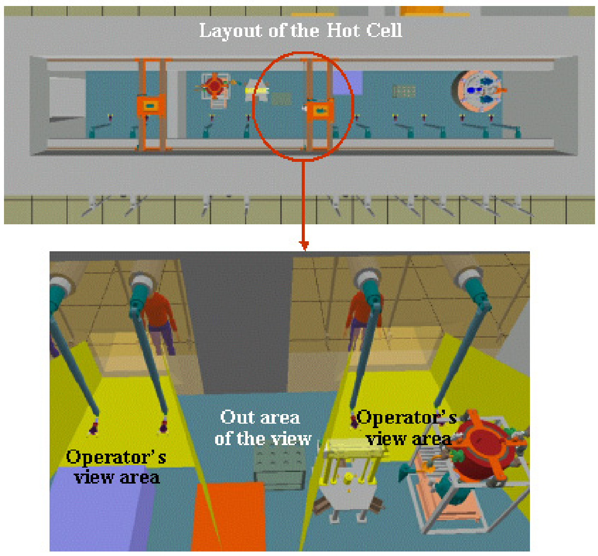


Fig. 7. The operator's view through the shielding windows.

4. DEVELOPMENT OF THE MAINTENANCE PROCESS

4.1 Parts to be maintained

In this study, to develop the maintenance process, the vibrators that are parts of the Voloxidizer are considered. Fig. 8 shows the MSM's accessibility to the vibrators and the operator's view through the shielding windows. As shown in the figure, the MSM can't reach the parts and the operator's view is not clear.

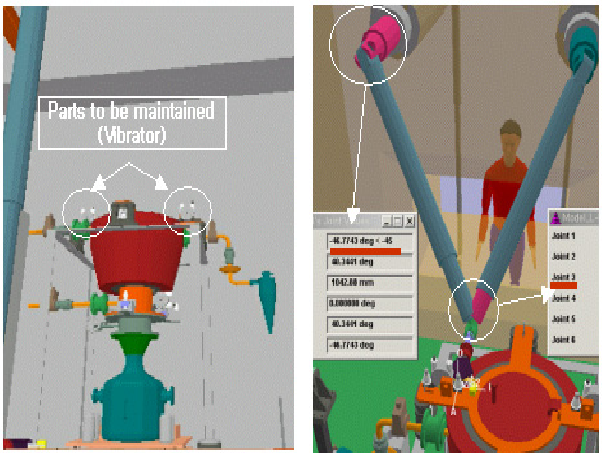


Fig. 8. Parts to be maintained and MSM's accessibilities.

4.2 Maintenance process

4.2.1 Servo manipulator

To maintain the parts that cannot be reached by the MSM, the servo manipulator is proposed. This servo manipulator system consists of three unit assemblies; transportation system, telescoping tube set, and a manipulator. The manipulator is to be transported by an overhead telescoping tubeset, attached by an interface package that includes structural mounting components and viewing cameras. The servo manipulator is also used to transfer the process materials that cannot be handled by the MSM.

For the graphic simulation of the maintenance operations, the graphic model of the system is drawn and the appropriate kinematics are assigned according to the working range of the system in the virtual environment. Table 2 describes the working range of the servo manipulator and Fig. 9 shows the graphic model and assigned kinematics of the system.

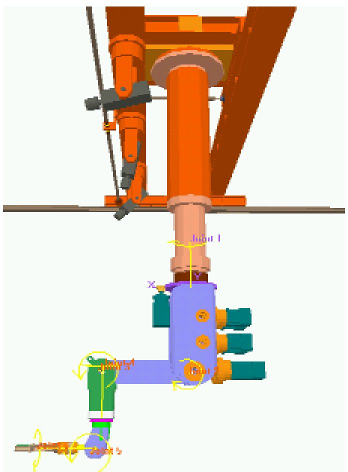


Fig. 9. Graphic model and kinematics of servo manipulator.

Table 2. Working range of servo manipulator and gripper

Joint No.	Joint Motion	Joint Type	Joint Value
Joint 1	Body Twist Motion	Rotation	-180 ~ +180 deg
Joint 2	Shoulder Motion	Rotation	-45 ~ +80 deg
Joint 3	Elbow Motion	Rotation	-45 ~ +80 deg
Joint 4	Forearm Twist Motion	Rotation	-175 ~ +175 deg
Joint 5	Wrist Tilt Motion	Rotation	-50 ~ +140 deg
Joint 6	Wrist Twist Motion	Rotation	-175 ~ +175 deg
Joint 7	Gripper Jaw Motion	Translation	0 ~ 63 mm

4.2.2 Path planning

In this research, to carry out the safe and effective maintenance of the process equipment installed in the hot cell by a servo type manipulator, a collision free path planning method of the servo manipulator using virtual prototyping technology is suggested. The method proposed in this paper is to find the optimal path for the manipulator using the function of collision detection in the virtual mock up. Fig. 10 shows the procedure of path planning to find the optimal path in the hot cell.

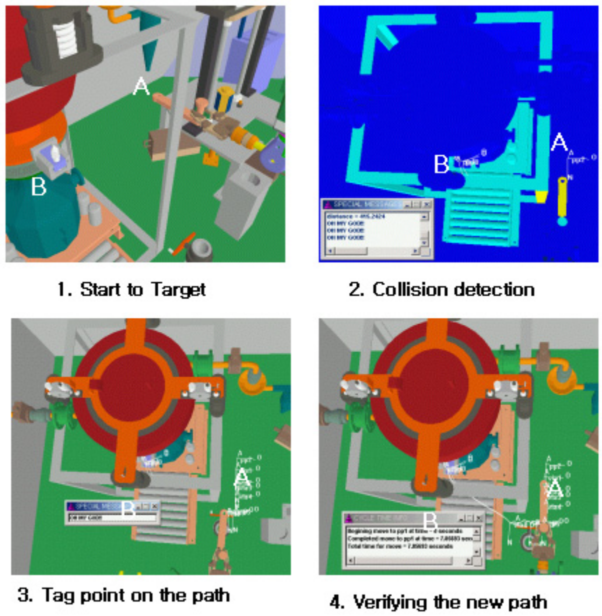


Fig. 10. The procedure of the path planning.

4.2.3 Operator's view

The operator's view in the remote operations is a very important factor to be considered. In this study, to monitor the hot cell process remotely, and to obtain a clear view of the workers, the virtual display system by a virtual camera in the graphic environment is proposed.

To implement the system, Axxess in the IGRIP is used. Axxess is a flexible API (Application Programmer Interface) framework in which the user can easily integrate his own software with the IGRIP.

Fig. 11 shows the virtual display system in the virtual mock up to simulate the maintenance process. Two virtual cameras are installed near the servo manipulator and the camera view windows for these virtual cameras are implemented in the virtual mock up using Axxess. As shown in the figures, the cameras are tracing the parts and the gripper respectively. This system can monitor the hot cell operation remotely.

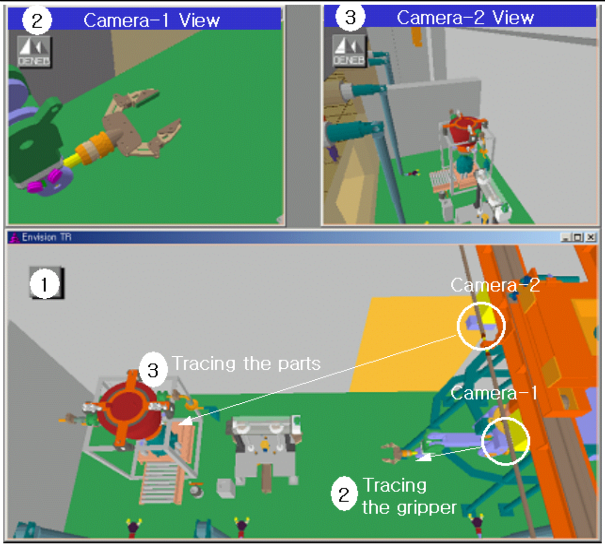


Fig. 11. The virtual display system.

4.3 Graphic simulation of the maintenance process

For the verification of the maintenance process and the virtual display system proposed in this study, graphic simulation using a virtual mock-up is performed. As shown in Fig 12, the proposed maintenance process is well simulated without any collision and any other problems in the virtual workcell during the simulation. The verification of the maintenance process in the real hot cell for spent fuel management should be carried out in the future.

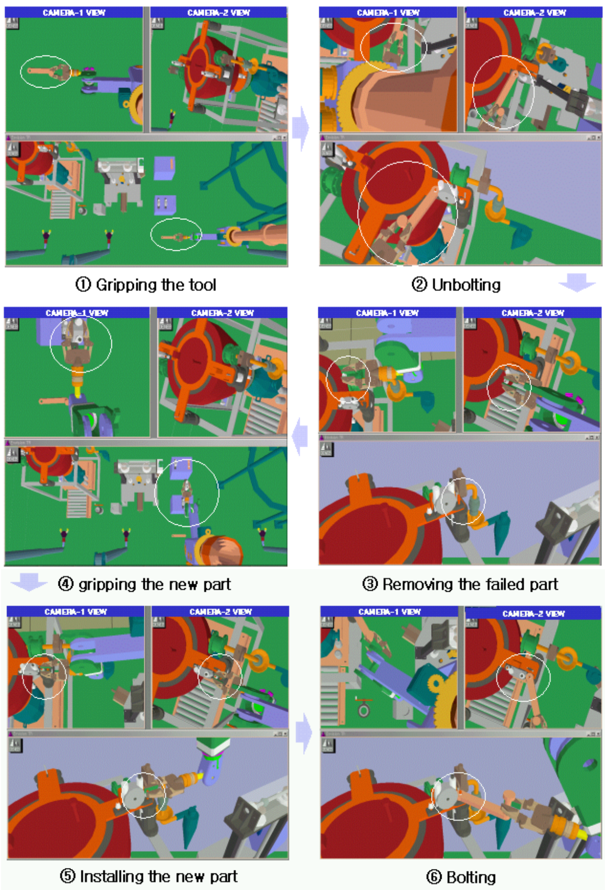


Fig. 12. The graphic simulation of the maintenance process.

5. CONCLUDING REMARKS

The equipment in the hot cell should be optimally placed within the workspace of the MSM for a remote operation. But, due to the complexity in the hot cell, there are some parts of the equipment that cannot be reached by the MSM. In this study, a maintenance process for these parts of the equipment was proposed using virtual prototyping technology.

The virtual mock up of the hot cell process was implemented and the various analyses, such as workspace of the maintenance devices and operator's view through the shielding windows, were carried out in the virtual hot cell. Based on the result of these analyses, a maintenance process using a servo manipulator was proposed. And, for the verification, the graphic simulation of the proposed maintenance process was carried out.

The proposed remote maintenance process of the equipment can be effectively used in the real hot cell operation. Also, the implemented virtual mock-up of the hot cell can be effectively used for analyzing the various hot cell operations and enhancing the reliability and safety of the spent fuel management.

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