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Remotely Operated Decontamination Systems for Use in DFDF

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Abstract

This paper presents the development of the remotely operated decontamination systems for use in a highly radioactive zone of the DUPIC Fuel Development Facility of the Irradiated Material Examination Facility at the Korea Atomic Energy Research Institute. The remotely operated decontamination systems were designed to completely eliminate human interaction with hazardous radioactive contaminants. These decontamination systems are mainly classified into three systems depending on the task environment – a fabrication equipment decontamination system, a hot-cell floor decontamination system, and an isolation room floor decontamination system. A decontamination system for contaminated fabrication equipment utilizes dry ice pellet blasting method to decontaminate contaminated surface of the equipment. The decontamination systems for the hot-cell floor and isolation room floor employ a vacuum cleaning method to decontaminate the contaminated floor and collect loose dry spent nuclear fuel debris and other radioactive waste placed on the floor. The human operator from the out-of-cell performs a series of decontamination tasks remotely by manipulating decontamination systems located in-cell via a handcontroller with the aid of vision feedback information. The environmental, functional and mechanical design considerations, control system and capabilities of the remotely operated decontamination systems at a high radioactive environment are also described.

1. Introduction

The use of robotics and remote technologies in the nuclear industry has been driven by the need to decrease personnel radiation exposure limits. Reducing personnel exposure to ALARA (As Low As Reasonably Achievable) [1] in radiation fields where radiation and contamination levels are high requires human workers to be replaced by robotic devices or other remote devices. Remote equipment or system has been developed and employed at many nuclear material handling sites. In particular, for decontamination operations, tasks of remote systems at high radioactive field are mainly involved with cell floor decontamination, contaminated process room decontamination, hazardous waste storage tank cleanup, and aged equipment cleanup [2].

DUPIC (Direct Use of PWR fuel in CANDU reactors) nuclear fuel [3], which reuses spent PWR (Pressurized Water Reactor) nuclear fuel as raw material, is being developed in the DFDF (DUPIC Fuel Development Facility) at the Korea Atomic Energy Research Institute (KAERI). The DFDF, exclusively occupied for DUPIC nuclear fuel development, is the completely shielded M6 hot-cell of the Irradiated Material Examination Facility (IMEF) of KAERI. As the hot-cell is active, direct human workers' access to the in-cell is not possible because of the nature of the high radiation level of spent PWR fuel. All DUPIC nuclear fuel fabrication processes and equipment operations, therefore, are fully conducted by means of master-slave manipulators or other auxiliary tools in a remote manner.

Undesirable products such as spent nuclear fuel powder debris and contaminated wastes are inevitably created during the DUPIC nuclear fuel development processes. They are placed on the DUPIC fuel fabrication equipment, the inside floor and wall of the DFDF, thereby contaminating the interior of the DFDF. Such radioactive waste is required to be cleaned and disposed of to prevent the contamination from spreading inside the DFDF, and also, it should be collected in order to measure its quantity before it is put into the waste drum and leaves the in-cell for disposal. Therefore, emphasis from a remote system viewpoint is placed on a remote decontamination of the contaminated in-cell floor and wall and the fabrication equipment without human workers being exposed to the radioactive environment.

The objective of this paper was to develop the decontamination systems that could be operated remotely from the out-of-cell to decontaminate the contaminated floor surface and fabrication equipment and collect the high radioactive waste and without endangering the human operators.

2. Overall Design Considerations

The decontamination operations of contaminated floor and equipment surface where, as the hot-cell is active, direct human access, even with protection, to the in-cell is not possible due to high radioactivity must be performed by means of remote equipment or devices in a remote manner. The successful development, in-cell installation and operation of the decontamination systems involve three mutually dependent design elements – the DFDF and DUPIC fuel fabrication equipment's arrangement, and the remote operation and maintenance of the decontamination systems. In the design processes, a compromise should be made between theses elements. The design concept, therefore, must include all the mechanical, electrical, and system integration elements required to produce fully functional decontamination systems for the DFDF applications.

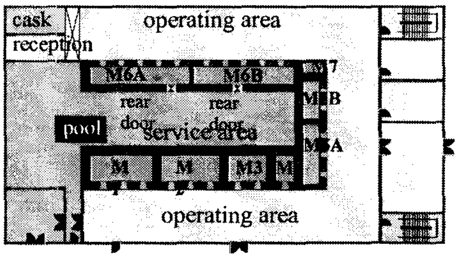


Fig. 1 The layout of the IMEF at KAERI.

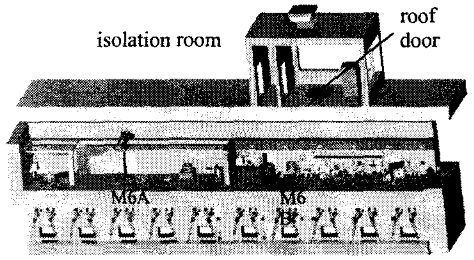
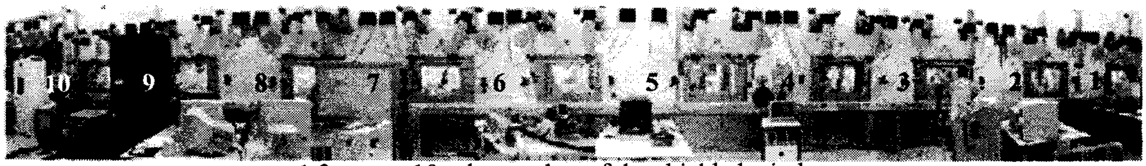


Fig. 2 The graphic model of the M6 hot-cell – DFDF.



1,2, , . . . , 10 : the number of the shielded window

Fig. 3 The M6 hot-cell seen from the operating area (out-of-cell).

2.1 DFDF and In-Cell Fabrication Equipment's Arrangement

The IMEF mainly consists of seven cells – M1 through M7 cells, as shown in Fig. 1. These cell walls were made of a heavy duty concrete with a thickness of 1.1m. The M1 through M5 and M7 cells have been being used for the experimentation of nuclear fuels and reactor materials. The M6 cell, DFDF, has been exclusively occupied for DUPIC nuclear fuel fabrication since 2000. As shown in Fig. 2, this M6 cell is divided into two rooms by a stainless steel wall – the M6A cell for fuel powder and pellet fabrication and M6B cell for fuel rod fabrication. Each cell has a configuration of 10x2x4 (LxWxH) m. The interior of each cell lined with a continuous stainless steel sheet metal liner provides the reliable integrity of the compartment. One overhead crane mounted on the tracks is used to handle the heavy fabrication equipment or devices traversing the length of the two cells. Each cell has five shielding windows, which provide in-cell information or situations, and each window workstation is equipped with two pairs of master-slave manipulators, as shown in Fig. 3. The motions of a human operator via a master manipulator (out-of-cell) are reproduced at the slave manipulator (in-cell). Utilities such as water, gas, compressed air, and electricity are provided from the out-of-cell to the in-cell through penetrations. The DUPIC fuel fabrication equipment or other auxiliary devices [4] can be remotely connected to the outlets of such utilities. The in-cell utility lines of water, gas, air, and electricity for fabrication equipment are installed on the in-cell floor and wall. The size, mobile means, and cleanup and collection tools of the decontamination systems should be determined based on the environmental and spatial limitations of the M6 in-cell facility, geometrical constraints of the fabrication equipment, accessibility to targets to be decontaminated overcoming obstacles, and availability and location of utilities necessary for operation.

2.2 Remote Operation and Maintenance

The design of the decontamination systems for use in the DFDF should take into account remote manipulation strategies, remote repair procedures, and the capabilities and limitations of the remote maintenance handling devices that are available at the DFDF. In addition, all the decontamination operations conducted within the cell should be viewed and monitored by the human operators located at the out-of-cell. Hence, the design of the decontamination systems should include the following considerations [5]:

- Human operator - the operator's experience and needs obtained from the previous decontamination tasks should be reflected in the overall system design and process of the decontamination systems.
- Modular construction - the functional and mechanical structures of the decontamination systems need to be designed in replaceable modules or subassemblies with remote handling features.
- Electric power transmission - the power source and its transmission should be considered to implement efficient, remote control of the desired system.
- Decontamination - the decontamination strategies should be included in the design of the modules or subassemblies.
- Radiation effects - the radiation effects on materials and mechanical and electrical components should be considered in the design.

3. Decontamination Systems

Based on the design considerations described in the previous section, the remotely operated decontamination systems developed are divided into three systems – FEDS (Fabrication Equipment Decontamination System), ROCCS (Remotely Operated Contamination Collection System) -I, and ROCCS-II. FEDS and ROCCS-I were developed for use in the in-cell of the DFDF. ROCCS-II was developed for use in the isolation room of the DFDF.

3.1 FEDS

FEDS was developed to decontaminate contaminated surface of equipment and other devices used for DUPIC fuel fabrication inside the M6 hot-cell - DFDF. FEDS consists of an in-cell chamber and dry ice blasting system, which are operated out-of-cell in a remote manner.

3.1.1 In-Cell Chamber

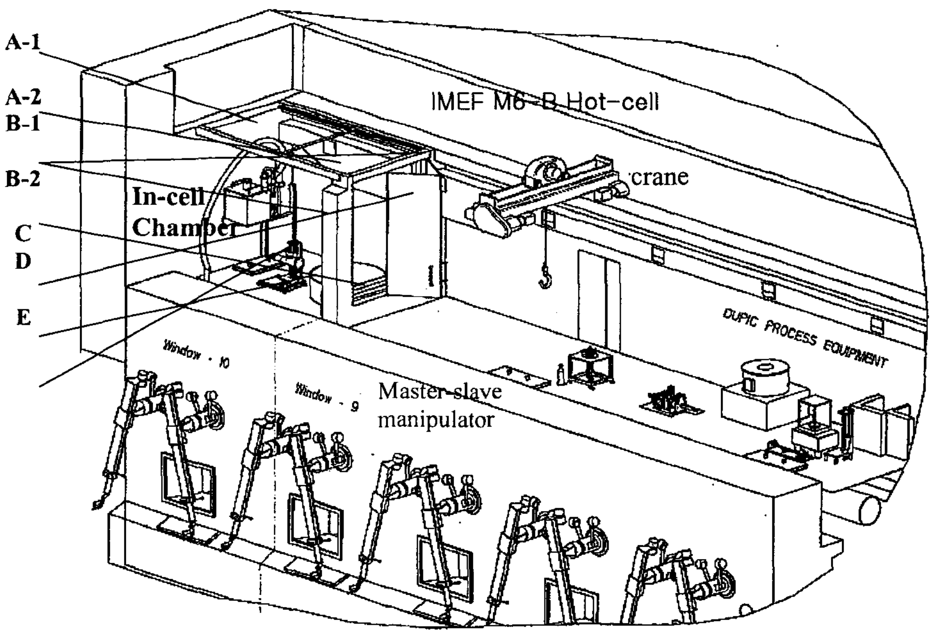
The in-cell chamber [6] is a separate closed room constructed inside the hot-cell. This chamber provides a means of preventing the contamination from spreading inside the hot-cell during decontamination operation. It was designed to allow remote operation to be effected using a master-slave manipulator and other auxiliary tools installed inside the cell.

The in-cell chamber comprises horizontal, vertical, and auxiliary modules for forming into a closed room and rotary and grasping modules for improving decontamination tasks. Fig. 4 shows the schematic of the in-cell chamber including all the modules. All motions of these modules are generated by compressed air in a remote manner, and no electricity was used inside the chamber. As shown in Figs. 4 and 5, the in-cell chamber is located in the most left side of the M6B hot-cell by partitioning the middle of the 9th shielded window and 10th. The horizontal module (A) forms a ceiling of the chamber in a telescopic shape, which was designed not to block the mobility of the crane. The vertical module (B) is a main entrance to import equipment or devices required for decontamination into the chamber and to export them outside the chamber after decontamination. The vertical module has a folding slat mechanism of which several slats are connected in series each other. The vertical module has upward and downward motions to close and open the vertical side of the in-cell chamber. The auxiliary module (C) is a second door to secure a sealing of the chamber when closed. This chamber was also designed to be used as an additional room for other use by keeping both the vertical module and auxiliary module open when it is not in use. The rotary module (D) allows equipment or devices to be decontaminated to rotate in all directions relative to the decontaminating tools, thereby improving the degree of the decontamination. The grasping module (E) can hold the decontaminating tools and allows the decontamination tasks to be semi-autonomous, thereby reducing the operator's mental and physical burdens.

3.1.2 Dry Ice Blasting System

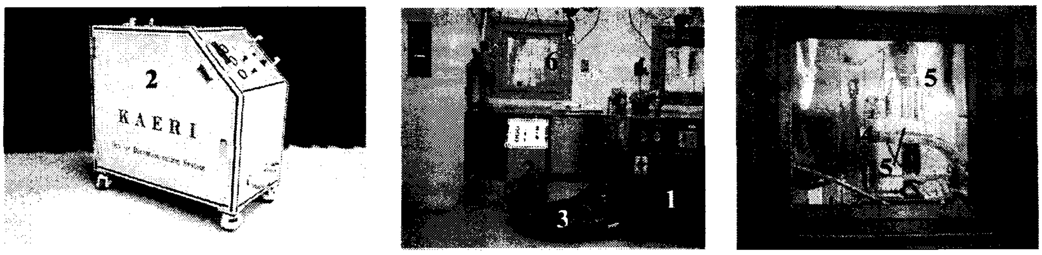
The Dry Ice (solid carbon dioxide) Blasting System [6] that utilizes dry ice pellets as blasting media was developed to remove the contaminants placed or fixed on equipment and other devices used for DUPIC fuel fabrication. Dry ice blasting method was employed in the DFDF because it does not produce second contaminants after decontamination. The Dry Ice Blasting System largely consists of an air cleaner, a blasting body, a dry ice and air feeding lines, a blasting head, and a simultaneous suction device. This system is fully operated by compressed air, and no electricity is needed. The air cleaner and the blasting body are located in the operating area, and the blasting head and the simultaneous suction device installed inside the in-cell chamber. The dry ice and air feeding lines provide a passage between the blasting body and the blasting head.

The air cleaner consists of pre-filter, line filter, and coalescent filter. This cleaner is used to remove such contaminants as water, oil, fine hard particles, etc., which are contained into compressed air supplied from the IMEF. The cleaned compressed air with 8.0 bar produced from the air cleaner is supplied to the blasting body. The blasting body as a core of the Dry Ice Blasting System is two hose system and consists of several mechanical parts of hopper, dry ice hose, compressed air hose, filters, air vibrator, and pneumatic control parts of a number of control valves, ball valves, and regulators. Dry ice pellets are supplied to the blasting body through the hopper. The dry ice and air feeding lines supply, via own line, the dry ice pellets and necessary compressed air from the blasting body to the blasting head. Dry ice pellets and compressed air left from the blasting body are joined at the blasting head. Dry ice pellets are blasted to targets to be decontaminated through a nozzle attached to the blasting head with high- pressurized speed. A purge system is also added to the blasting body in order to prevent the contamination inside the chamber from flowing back to the operating area through the dry ice and air feeding lines. Fig. 6 shows the developed blasting body of the Dry Ice Blasting System and FEDS installed in the DFDF. The operator located in the operating area can control, monitor, and supervise,



A-1: Fixed, A-2: Movable, B-1: U guide, B-2: Folder slats
Fig. 4. The schematic of the in-cell chamber.

Fig. 5 The in-cell chamber constructed inside the DFDF.



a) The developed blasting body b) The Dry Ice Blasting System installed in the DFDF

1: air cleaner, 2: blasting body, 3: dry ice and compressed air feeding lines, 4: blasting head, 5: simultaneous suction device

Fig. 6 FEDS installed in the DFDF.

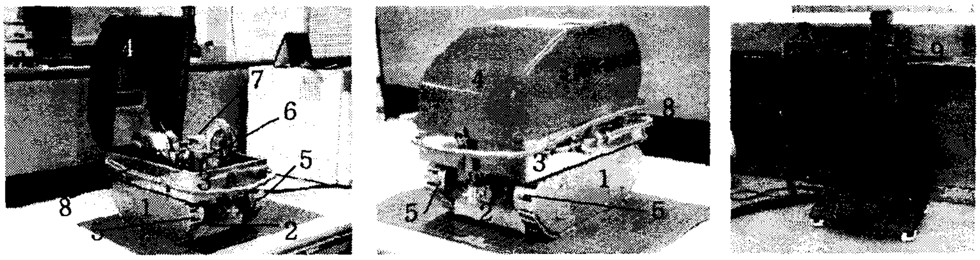
from the front of the 10th shielded window, the decontamination processes performed inside the chamber.

3.2 ROCCS-I

3.2.1 System Overview

ROCCS-I [7] was developed to decontaminate the contaminated in-cell floor of the DFDF, M6 hot-cell of the IMEF, and collect loose spent nuclear fuel debris and other radioactive waste. As shown in Fig. 7, the ROCCS-I was designed and developed to allow remote operation and maintenance to be effected using master-slave manipulators and other auxiliary tools located in the hot-cell. ROCCS-I mainly consists of an electrically driven, tracked mobile platform, a rotary brush tool, and a vacuum unit, which were constructed in modules to facilitate maintenance. They can be separated and assembled easily by remote manipulation. ROCCS-I has a small and compact configuration of 300x400x400 (LxWxH) mm, a maximum speed of 0.2 m/sec, a small turning radius and forward and reserve motions, and an ability to collect contaminated particles of up to 0.3 μm.

The vacuum unit installed above the mobile platform consists of a base frame, an electrical blower, and two filters. All modular components of the vacuum unit can also be remotely exchanged or maintained. A ceramic filer is connected to the brush tool preceding a HEPA (High-Efficiency Particulate Air) filter. A ceramic filter can collect contaminated particles bigger than 1.0 μm mobilized by the brush, and particles as small as 0.3 μm are captured by the HEPA filter. By remote manipulation, the ceramic filter box that is reusable is designed to be able to transfer the collected material to another container using master/slave manipulators, while the entire HEPA filter box is designed to be disposed of.



a) Cover opened b) Cover closed c) Control console

1: mobile platform 2: rotary brush tool 3: vacuum unit 4: protection cover 5: tracks
6: ceramic filter box 7: HEPA filter box 8: vacuum tube 9: hand controller

Fig. 7 The developed ROCCS-I .

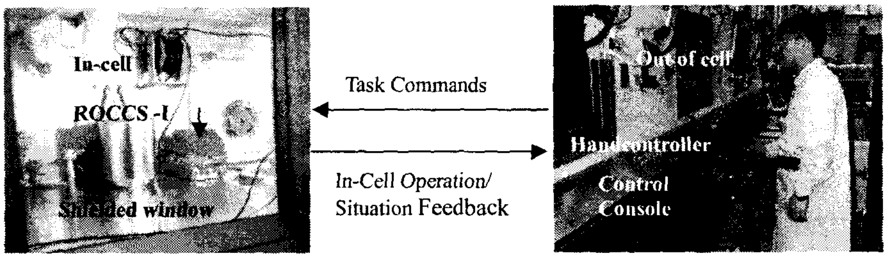


Fig. 8 The human operator, via a handcontroller, manipulating the in-cell ROCCS-I.

3.2.2 Remote Operation

ROCCS-I is powered and controlled via a tether in the manual control mode. This form of power and control was selected because powering ROCCS-I via a tether allows for reliable operations of unlimited duration and eliminates the needs for batteries. Transmission of the control and power signals through a tether ensures reliable control of ROCCS-I, regardless of the remote distance or barrier between the operated ROCCS-I and the operator. The handcontroller is a man-machine interface device that allows interaction between the human operator and the in-cell ROCCS-I. The handcontroller enables the operator to manipulate ROCCS-I throughout the workenvelope simply by moving it.

As shown in Fig. 8, the operator located out-of-cell controls, via a handcontroller, ROCCS-I in order to move it into the desired work location in-cell. The operator then controls the control knobs attached on the console panel to operate both the brush and vacuum unit. In addition, cleanup and collection in an area where ROCCS-I is inaccessible or on surfaces of the in-cell process equipment can be done by a flexible stainless vacuum tube mounted on ROCCS-I. After guiding ROCCS-I to a given target nearby, the operator manipulates the slave manipulator to grasp the vacuum tube via a master manipulator, and then move it to the target to be cleaned. The operator then drives the vacuum for cleaning. The operator out-of-cell supervises all cleanup and collection operations in-cell through shielding windows. The ROCCS-I described in this paper has been installed in the M6 hot-cell of the IMEF at KAERI after tests at the mock-up and is now under hot-cell operation.

3.3 ROCCS-II

3.3.1 System Overview

ROCCS-II [8] was developed to decontaminate the contaminated floor surface of the isolation room of the DFDF and collect loose spent nuclear fuel debris and other radioactive waste. ROCCS-II has more intelligence compared to ROCCS-I in terms of autonomous navigation, omnidirectional cleanup and added vision information. As shown in Fig. 9, ROCCS-II mainly consists of five replaceable submodules - a mobile module for navigation, a cleaning module for dislodging and sucking the contaminated waste, a sensing module for obstacle avoidance, a collection module for storing acquired waste, and a cover module for protecting the collection module. Such modular construction facilitates remote maintenance when necessary. Each submodule can be easily separated and assembled by remote manipulation, using a crane and a master-slave manipulator installed at the isolation room. The used filter box can also be remotely exchanged for new one using a master-slave manipulator in situ. ROCCS-II has a configuration of 465x465 (HxD) mm, a maximum speed of 10 cm/sec, an ability to collect contaminated particles of up to 0.3 μm, as well as an ability to clean up the floor surface in all directions relative to the bottom of the cleaning module of ROCCS-II.

The control console is the interface device between the operator and RCCS-II located at a remote site. All functions for controlling RCCS-II are contained in it. The control console includes a two-axis handcontroller for navigation, control knobs for cleanup and collection, and a graphic simulator for monitoring and path generation. The controller, circuitry, power supplies, and necessary software are also installed within the console.

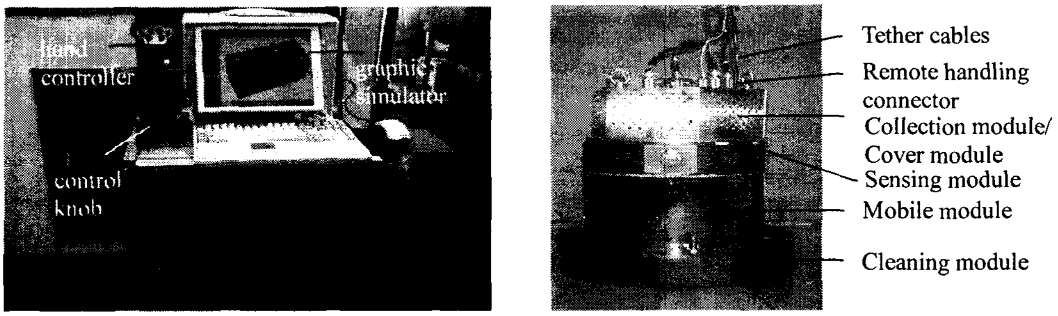


Fig. 9. The developed ROCCS-II.

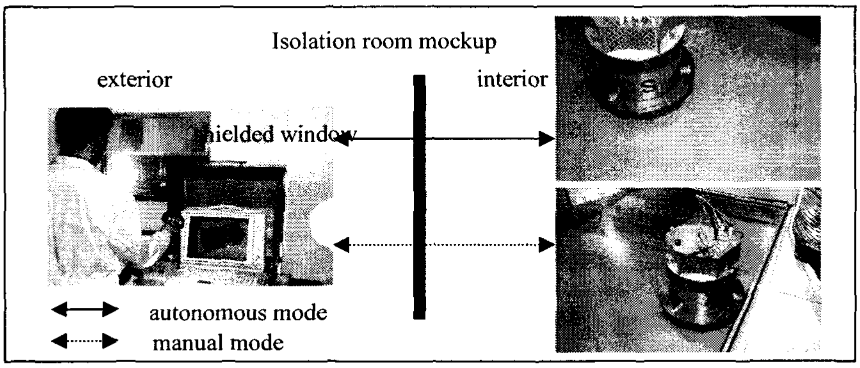
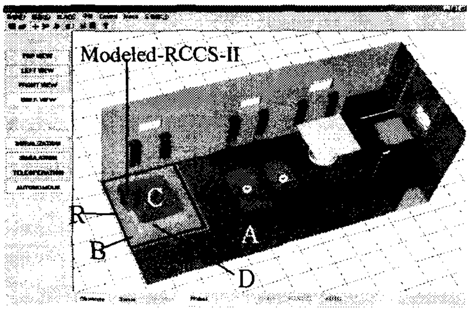


Fig. 10 The mockup test environment of ROCCS-II for decontamination operations.



A: the entire area of the floor surface of the isolation room to be cleaned at the very beginning of the cleanup. **B** : the area that, in the autonomous mode, ROCCS-II cannot reach. **R**: the test area to be cleaned in the shape of a rectangle, which corresponds to the floor of the isolation room's mockup. **C**: the completely cleaned area of the floor surface., the swept area. **D**: unswept area.
As ROCCS-II moves, the trail that ROCCS-II passed on the floor is changed to **C**, thereby differentiating the swept, **C**, and unswept areas, **D**.

Fig. 11 The cleanup status of ROCCS-II displayed on the graphic simulator.

3.3.2 Graphic Simulator

A graphic simulator was developed to provide the operator with added vision information and a more useful means for developing an improved ability to simulate and control ROCCS-II. The graphic simulator largely consists of a graphical model of ROCCS-II and a graphical model of the isolation room (refer to Fig. 11). This simulator allows the operator to simulate any desired decontamination task that ROCCS-II will perform inside the isolation room. In addition the graphic simulator interfaces with the control system of ROCCS-II, thereby providing the operator with the additional vision information during operation. The cleaning paths generated from the graphic simulator are used as a command input to operate ROCCS-II. The decontamination processes of ROCCS-II are displayed in real-time on the graphic simulator. The operator can supervise and intervene the decontamination operations of ROCCS-II through the graphic simulator without seeing the interior of the isolation room through the shielded windows, thereby reducing the operator's physical and mental burdens.

3.3.3 Remote Operation at Mockup

ROCCS-II developed has been tested to verify its performance and capabilities in the mockup of the isolation room at the DUPIC test facility. Fig. 10 shows the mockup test environment of ROCCS-II for a decontamination operation. The human operator and control console are located outside of the mockup of the isolation room, and ROCCS-II located inside it. As the same as in a real application, ROCCS-II is powered and controlled via a tether.

ROCCS-II is operated either by the manual control or by the autonomous control. The graphic simulator is activated both in the manual and autonomous control mode. In the manual control mode the operator manipulates, via the handcontroller, ROCCS-II to move it into the desired locations for decontamination. The operator then controls the control knobs to activate both the cleaning and collection modules. In the autonomous mode ROCCS-II, at the initial stage, identifies its current position and steering direction before it moves. The robot then moves to clean the floor following the path generated from the graphic simulator. In the autonomous mode ROCCS-II, however, has limitations of the cleaning area in terms of mobility because of the nature of the ultrasonic sensors installed on ROCCS-II. Such an inaccessible area around the inside wall in the autonomous mode can be cleaned by switching the control mode to the manual and, via a handcontroller, controlling ROCCS-II to move close to the wall edge. For both the manual and autonomous operations the decontamination status of ROCCS-II is always displayed on the graphic simulator in real-time. Fig. 11 shows the cleanup status of the floor performed by ROCCS-II, which is displayed on the graphic simulator. The swept and unswept area can be clearly identified from the graphical simulator. In both the manual and autonomous modes, the operator can monitor all the cleanup and collection operations of ROCCS-II both through the shielded windows and the graphic simulator.

3.4 Other Research Activities

Currently, our research efforts are putting into the development of mopping systems to be used in the DFDF - TOMS (TeleOperated Mopping System) and TOSS (TeleOperated Swabbing System). TOMS was designed to remotely mop the contaminated floor surface of the M6 hot-cell with specially designed tool after, using ROCCS-I and –II, contaminated dust or dirt placed on the floor was removed. TOMS, employing a bilateral control scheme, has the capability of reflecting a mopping force occurring between the mopping tool of the mobile mopping slave and the floor surface to the human operator through the master, thereby improving the efficiency of remote surface decontamination. The construction of TOMS was completed, and currently, we focus on the performance tests of TOMS in order to acquire its reliability and stability before it is put into service.

TOSS is also being developed to remotely clean the contaminated M6 in-cell wall. A conceptual design of a swabbing system was completed, and its detailed design development has been undertaken.

4. Conclusions

Remotely Operated Decontamination Systems developed in this work demonstrated the remote systems applications for performing decontamination tasks in a high-radiation field where direct human access to the in-cell is strictly limited. The significance of this development is in providing Remotely Operated Decontamination Ssystem that can decontaminate a contaminated in-cell floor and fabrication equipment and auxiliary devices, and collect dry radioactive waste, completely eliminating human interaction with hazardous contaminants. The decontamination operations in a contaminated DFDF using Remotely Operated Decontamination Systems have the benefits of improved worker safety, increased facility soundness and reduced personnel exposure dose rate.

5. Acknowledgements

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