

Evaluation of System Automation and Robotics for Decommissioning Applications

2017 TECHNICAL REPORT

Evaluation of System Automation and Robotics for Decommissioning Applications

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Abstract

The approach to nuclear power plant (NPP) decommissioning is currently highly labor intensive. The increased use of system automation and robotics could be beneficial to reduce radiation exposure and project schedule, and thus substantially reduce the cost of decommissioning. The Electric Power Research Institute has systematically evaluated potential applications of system automation and robotics to facilitate more widespread use in decommissioning projects.

Challenges faced in the use of robotics and automation were reviewed. A nonexhaustive review of currently available technologies in both robotics and automation was then conducted, including commercial and government nuclear operations and decommissioning applications within the United States and internationally. This included component removal and segregation, component inspections, conduct of radiological surveys, monitoring and sampling, mechanical and chemical decontamination, application of strippable coatings/fixatives, and work control.

The major tasks of decommissioning a commercial NPP were assessed using a matrix developed to identify those that would benefit from the use of robotics or automation. Examples of available solutions that have been and could be applied in nuclear decommissioning projects were matched against the decommissioning tasks that had been identified to benefit from use of robotics or automation. This included consideration of technologies that have already been applied in nuclear decommissioning or related applications, applied in other industries, or are still in development.

This document provides information and guidance on system automation and robotics applications in NPP decommissioning and will be useful for anyone approaching such work.

Keywords

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PRIMARY AUDIENCE: Vendors and research organizations developing automated and robotic technologies for nuclear power plant decommissioning activities

SECONDARY AUDIENCE: Utility and contractor staff involved in planning and execution of decontamination and dismantlement associated with nuclear power plant decommissioning projects

KEY RESEARCH QUESTION

Historically, most tasks performed during decontamination and dismantlement of decommissioned nuclear power plants have been performed using standard, primarily manual techniques. This approach, though effective, is labor intensive, requires mitigation of the inherent industrial safety risks, and challenges radiation exposure minimization efforts. Increased use of system automation and robotics in decommissioning offers enhancements in effectiveness and safety. However, use of such alternative approaches to the proven techniques currently employed must be done thoughtfully to realize the potential benefits.

RESEARCH OVERVIEW

In this work, decommissioning tasks were evaluated with respect to the level of potential benefits that might be achieved through automation and/or use of robotics. This resulted in a prioritized list of tasks for which efforts should focus in the development of automation/robotic solutions. Based on these results, existing automation/robotics solutions were reviewed to determine those that may be either applied directly or suitably adapted to perform specific decommissioning tasks. Technologies that have been previously employed during plant operations or in applications outside the nuclear industry were considered, as well as those previously used in decommissioning.

KEY FINDINGS

- Although many decommissioning tasks could benefit from increased use of automation or robotics, the results of this study suggest that of the 54 tasks evaluated, only three would clearly and substantially benefit, although there is minimal perceived benefit for more than half of the tasks. This highlights that before embarking on costly development efforts, an assessment of the need for technology improvements and potential benefits that may be realized must be carefully considered.
- The results indicate that research and development efforts in both automation and robotics may optimally be focused on the following main tasks:
 - Load spent fuel canisters and transfer to independent spent fuel storage installation
 - Segment, package, and dispose of reactor internals
 - (Spent fuel pool) Remove and dispose of legacy Class B and C wasteThese tasks are complex and radiation dose intensive, and are typically on the decommissioning project critical path.
- Although the degree of potential benefit may not be as high, other radiation dose-intensive projects, such as reactor vessel segmentation, should be considered for increased use of robotics. Likewise, labor-intensive projects such as building decontamination and site radiological surveys should be considered for increased automation.

- Based on the nonexhaustive review performed during this study, it is clear that many robotic and automated systems already exist both within the nuclear industry and in other industries that may either be used directly or readily modified to perform specific decommissioning tasks. This information may be used by decommissioning project engineers in development of decommissioning work plans, or by research and development groups to adapt existing solutions to decommissioning tasks. As this was a nonexhaustive review, it should be recognized that other robotics or automation solutions not covered in this report may be available to address needs for certain tasks as well.

WHY THIS MATTERS

As the number of plants entering the decommissioning phase of the plant lifecycle increases, it is becoming increasingly important to identify technologies that can reduce the schedule and cost of decommissioning projects, while continuing to improve worker safety and reduce exposure. Targeted use of automation and robotics for specific decontamination and dismantlement tasks is one way to simultaneously achieve all of these goals.

HOW TO APPLY RESULTS

The global decommissioning community is strongly encouraged to use the results of this work to inform and prioritize efforts to develop automation and robotic solutions for decommissioning tasks that are most likely to provide the most benefit.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- The results of this work are intended to inform the global decommissioning research and development community as well as vendors that provide services for nuclear power plant decontamination and dismantlement. It is important that these groups work together and in collaboration with nuclear utilities to rapidly develop technologies to enhance efficiency in decommissioning.
- As a collaborative research organization, EPRI continually seeks opportunities to engage with other research groups and with service providers to foster development and deployment of advanced technologies for decontamination and dismantlement tasks.

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Section 1: Introduction

Although limited use of remotely operated systems (robotics) and automation has been employed during nuclear power plant decommissioning projects, most tasks are currently performed manually. It is commonly accepted that decommissioning could benefit from increased use of enhanced technologies, including robotics and automation [1].

The use of more efficient technologies and processes could reduce the decommissioning project schedule and therefore reduce the staffing costs incurred throughout the decommissioning project life. Such systems may also offer a substantial benefit with respect to worker safety and exposure reduction. However, tasks for which use of such systems is beneficial must be carefully considered, being robust and generally trouble free to operate in the demanding environment of commercial power plant decommissioning [1].

Two approaches to these kinds of technologies are considered in this report, and are defined as follows:

1. Robotics – robotics are defined as technologies where human intervention and control is required to conduct the task, but the task itself is conducted remote from the individual. Typically such tasks are conducted to enhance worker safety and reduce radiation exposure. The task itself is not usually repeatable or programmable, and requires human navigation.
2. System Automation – an automated task is one that is programmable. Typically this is because the task is predictable, often with repeatable subtasks. In this case, the task is programmed by an operator and then the remote equipment performing the task operates with minimal ongoing intervention. Manual over-ride may remain possible.

General issues associated with the use of robotics and automation are addressed in Section 2, along with an overview of the types of solutions that are currently available. Much of the published research relates to the use of robotics. The Organization for Economic Development (OECD), for example, has published a good report on the use of remote handling techniques in decommissioning [2]. Less information is available in the literature on the use of automation, although some robotic systems incorporate a degree of automation.

A review of the major decommissioning tasks involved in the decommissioning of a nuclear power plant is provided in Section 3, and each of the tasks is assessed for its suitability for the use of robotics and/or automation. Based on this evaluation, a recommend list of tasks that should be examined in more detail has been prepared. Other tasks that have been previously cited in the literature that could benefit from the use of robotics or automation are also identified, resulting in a master list of all tasks for review.

In Sections 4-9, a non-exhaustive review of available solutions that could be applied to each of the identified decommissioning tasks is presented. Solutions that have been used in other industries or are under development are also provided. Finally, some conclusions are offered in Section 10, along with recommendations for further work.



Section 2: Robotics and Automation Solutions

2.1 Development of Robotic and Automated Technologies

Operating plants have existing remotely operated equipment that may be used during the decommissioning phase. This could include equipment such as remotely operated cranes, fuel handling machines, automatic guided vehicles, palletizing robots, cranes, hoists, elevators and conveyors [2]. Likewise, use of robotics solutions developed for decommissioning tasks may also be beneficial during operations/refueling outages. Thus, the investment in robotics or automation of processes may be able to be spread over the costs of multiple operations or decommissioning projects.

One-off customized robotic development and deployment has been more typical in the worldwide nuclear industry as a whole, and these systems can cost millions of dollars and take months, if not years, for research and development, mockups and trial runs, operator training and deployment. This often results in customized solutions for very specific problems, and physical and environmental conditions. Even when effective for the specific application for which they were developed, such solutions are always transferrable to other buildings or other sites with different conditions.

Robotic system failures due to high radiation effects pose an obstacle that may impact further deployment and longevity of these systems. This has been found within the U.S. DOE high-level tanks and other waste cleanup efforts, U.S. commercial nuclear reactor inspections, and in the response to nuclear accidents where such capabilities are required. This may be less of an issue during commercial nuclear power plant decommissioning. However, the equipment must be sufficiently robust to perform in highly hazardous and radioactive environments, considering both performance and the cost for repairs including tool replacement costs, labor, and collective dose expenditures associated with maintenance. For nuclear facility management dealing with tight schedules and high expenses during decommissioning operations, it may be difficult to justify expenditures on these new technologies versus standard techniques if the techniques have not been field-proven. Some decommissioning contractors have experienced problems with complex customized robotic systems and remain skeptical about their use.

Ideally, robotic equipment should be kept simple and be subject to rigorous demonstration testing under field conditions prior to deployment to ensure satisfactory operation in hazardous environments and avoid unexpected costs and exposure resulting from retrieval of a failed piece of remotely operated equipment [2]. Whenever possible, simplified, off-the-shelf technologies should be considered for both robotics and automation, as this presents potential significant time and cost savings in development, even if some adaptation is required. Such systems can also be more reliable, having been proven in other applications, and can be modified for use in a radioactive environment as required.

If systems can be outfitted or readily adapted for numerous functions and standardized, it is anticipated that costs can be reduced and their use can be expanded outside of their original focus. Some robotic systems that have been deployed and tested extensively for other purposes or industries (for example, defense, emergency recovery, underwater inspections, and so on) show reliability and potential cost-effective transfer to nuclear operations and decommissioning. An example is the use of systems developed by iRobots for non-nuclear applications. These systems have been successfully adapted and deployed for reactor building inspections at Fukushima Dai-ichi, and have been used at U.S. nuclear plants for remote inspections and waste operations (see Section 4.3.2.1). Likewise, the transfer of technology from the car and munitions industry to use in decontamination has been demonstrated to be effective in Magnox in the UK.

The use of off-the-shelf automated systems for the conduct of repetitive tasks where it has been deployed (for example, automated decontamination, welding, and so on) has also been effective, and this may be an area where cost savings could be found. However, there is little information documented in the literature concerning the use of automated systems in the industry, except in the area of radiation imaging and sampling equipment. More investigation into the potential use of system automation is required.

Robots and automated systems could also be designed by one manufacturer and used within more than one utility or one sector (for example, operations versus decommissioning, commercial versus government, one country versus multiple countries). This customized approach would support increased, widespread use throughout the industry.

There is, however, a commercial market for robotics and automation, and various engineering companies, specialty decommissioning firms and university research centers are working on robotics and remote systems for use in various industries (for example, mining, marine), including nuclear facilities. This shift towards commercialization has tended to result in some constraints in release of information due to proprietary and competitiveness reasons. Therefore, data regarding cost, failure breakdown rates, and other important information may not be fully shared among vendors and institutions, making it more difficult for end user decision-makers to perform initial cost-benefit analyses to determine

whether to pursue robotic applications. Sharing of information between end users would be beneficial in bridging this gap. Further collaboration between companies and suppliers, and between organizations and countries, would also be a helpful platform to support the industry going forward.

Tokyo Electric Power Company (TEPCO) is working to expedite the application of robotics to many of the challenging tasks associated with decommissioning of the severely damaged units at Fukushima Daiichi. To support this effort, TEPCO is developing a “technical catalogue” for research and development technologies. The catalogue is intended to provide a comprehensive overview of the decontamination and robotics capabilities available in the industry [1].

It is anticipated that this project could facilitate the process of information sharing by reviewing robotics and automation capabilities that have been used successfully on decommissioning projects. Ideally, the cost of development of new technologies could be spread over multiple decommissioning projects, moving from small scale development to standardization that can be continuously employed to improve the efficiency of decommissioning worldwide. This would facilitate continued use of reliable methods from project to project so that the robotics/automation solutions eventually become the standard techniques.

2.2 Desirable Attributes for Robotic and Automated Technologies

The following are considered desirable attributes in the development of robotics and automated technologies [1]:

- The systems should be user-friendly and intuitive so that personnel may be trained as operators within a reasonable time frame. Of particular importance is the interface between the operator and the system. Use of controls similar to those used in gaming systems has proven to be beneficial.
- The system must be flexible and easily adapted to changing conditions, tooling requirements and operational needs. The equipment must be able to perform all tasks within its capabilities safely, effectively and efficiently, with little downtime and no failures that would jeopardize personnel safety or place the system or task in a non-recoverable position.
- Preventive maintenance should be minimal under expected operating conditions. Any required maintenance should be readily performed by site personnel with minimal disruption to the schedule (that is, less than one operating shift). Anticipated replacement parts such as consumables or items prone to wear must be available at reasonable cost.
- The system must be robust and reliable to avoid the delay, added costs and exposure that would result from equipment failures.
- The system must be capable for performing the intended function at least as fast as conventional techniques, including time for equipment set up, periodic maintenance and demobilization. Special consideration may be given for tasks that are particularly hazardous, difficult or impractical to perform using conventional techniques.

2.3 Existing Robotics and Automated Systems

In 2004, EPRI evaluated available robotic systems for application in power reactor decommissioning applications [3]. Since that time, some of the systems identified in the 2004 report – as well as many other robotic systems – have been applied in nuclear plant operations and decommissioning applications, with varying levels of success. Also since 2004, substantial advancements have been made in robotics. Numerous robotic systems have been employed throughout the US and internationally in both the private and public sectors since 2004 to address work involving radiation controls, including in the military and in response to terrorism. The use of robotics also accelerated due to the Fukushima Daiichi accident, and the accident led to the acceleration of plans to decommission nuclear reactors in many countries. The OECD has published two documents concerning robotics [1, 2].

An updated review of robotics and automation use in the nuclear industry in operating commercial nuclear power plants, in decommissioning operations and in emergency clean ups was conducted. Robotic systems have been successfully applied in areas such as component segmentation and structural demolition; site surveys; demolition debris handling; and radioactive waste retrieval, handling, conditioning and packaging.

Another area that may result in cost savings in decommissioning is the use of automation for the performance of decommissioning tasks, whether or not in a radioactive environment. The use of automated systems in non-radiation or radiation environments has been less well documented in the literature. While a few examples are provided, such as the automation of the use of coatings, inspections of underground pipework, and automation of sample collection, there is much room for development in this area.

Table 2-1 provides a summary of the organizations providing robotics and automated systems that were evaluated in this review, along with the applications for which specific systems have been deployed.

Table 2-1
Robotic and Automated Systems at Nuclear Facilities

Manufacturer or Lead Organization	Applications
A.N. Technologies Inc.	Nuclear operations; survey and measurement of hot cell at DOE site.
AREVA	Laser cutting of piping by robot in France; Lower Girth Weld Inspection Tool (LGWIT) used at two U.S. utilities.
ASI Marine	Underwater ROV technology for visual inspection of structures at Canadian and U.S. facilities.
BROKK	Remote-operated equipment for dismantlement and segmentation operations and waste handling. Applied at U.S. DOE sites, U.S. commercial nuclear plants, and UK decommissioning reactors.
California Mechatronics Centre	Wheeled robots for inspection of leaks in steam-affected areas and high levels of N-16.
Chiba Institute of Technology	Tracked robots at Fukushima.
Createc	Remote camera system for radiation imaging at UK sites and Fukushima.
Curtis Dyna-Fog Limited	Application of wetting and contamination control agents used in US facilities.
Cybernetix	Inspection/maintenance in French and Japanese facilities.
Energid Technologies Corporation	Robot used for heat exchanger inspections in nuclear power plants.
FriGeo	Collection of samples by freezing at UK site.
G.E. Hitachi	Robot for movement of rubble at Fukushima; inspection of underground piping at U.S nuclear plants.
H3D	Gamma imaging, identification of sources of radiation, discrete low level contamination.
Idaho National Laboratory (INL)	Remote and automated systems for scanning and characterization of soil contamination at U.S. DOE sites.
IHI Southwest Technologies/IHI Corporation	Underwater robot used for inspection of tanks at nuclear power plants.
Institute for Safety Problems of Nuclear Power Plants	Robots for sampling and monitoring at Chernobyl.

Table 2-1 (continued)
 Robotic and Automated Systems at Nuclear Facilities

Manufacturer or Lead Organization	Applications
International Climbing Machines	Use of crawler robot to remotely inspect tank walls at U.S. DOE Hanford site.
iRobot	Maintenance, material handling and radiation monitoring by robots at Duke Energy plants; material handling and inspections at Fukushima; Wolf Creek bioshield inspections.
KHG	Remote and robotic equipment used in German research and power reactors.
Kinetrics	Robots for radiation measurements and removal of high activity debris at a Canadian nuclear plant.
Kurion	Mechanical systems for monitoring, lifting and cutting operations at U.S. DOE sites and Fukushima.
Magnox	Decontamination and volume reduction of highly contaminated skips; automated shaver decontamination installation and use.
New Millenium Nuclear Technologies International Inc.	System with automated components for the collection of concrete samples at US DOE.
Nova Machine Products	Automated HydraNut tensioning and detensioning system used at U.S. nuclear plant reactor vessels.
NuVision Engineering	Hydraulic robotic arms and equipment, and waste material handling and decontamination at U.S. DOE sites.
OC Robotics	Snake arm robotic equipment for segmentation operations at Swedish and Canadian nuclear plants.
ORTEC	Automated measurement and assay systems for radioactive material and waste.
Pacific Northwest National Laboratory and EIC Laboratories Inc.	Automated chemical analysis of tank contents at DOE.
PaR Systems	Robotic equipment for radioactive material and waste handling at U.S. DOE sites; main crane and mobile tool system for remote operations and cleanup at Chernobyl.
QinetiQ	Robots for material handling and inspections at Fukushima.

Table 2-1 (continued)
 Robotic and Automated Systems at Nuclear Facilities

Manufacturer or Lead Organization	Applications
Rolls-Royce	Cleaning and inspection of small diameter piping.
Savannah River Remediation, LLC	Various robots for tank cleaning at U.S. DOE site (Savannah River Site).
UK Atomic Energy Authority, Ltd	Nuclear operations; development of remote handling equipment for ITER fusion reactor in France.
VideoRay	Mini-submarine ROV for monitoring and retrieval of samples from spent fuel pool at UK nuclear site.
Zetec, Inc.	Robot crawler for inspection of steam generator tubes.



Section 3: NPP Decommissioning Tasks

The decommissioning work breakdown structure for SONGS units 2 and 3 [4] was used as a typical decommissioning task list example. From the work breakdown structure, a task list was prepared for assessment to determine those tasks having a higher potential for automation or use of robotics. This review included a graded approach for automation and robotics. “Ranking” tables were created to identify those tasks offering a substantial benefit with respect to issues such as worker safety, exposure reduction, project cost and overall schedule.

Four criteria were considered:

- The complexity of the task
- The impact on the schedule or cost of the project
- The radiological and industrial safety improvements that could be realized
- The extent of repetition of the task (since tasks with low repetition may not merit the use of a robotics solution and those with high repetition may be well suited for automation)

A matrix was developed to assess each task.

The factors were given equal consideration for assessing the potential for the use of robotics. For automation, the factors were weighted more heavily for repetitiveness in the task and impact on cost and schedule, and less heavily for radiological/industrial safety and task complexity. Each task was given a score based on the criteria and a total overall ranking was found by adding each of the scores. Based on the overall score, the task would either be pursued (>75 % of the possible maximum score), considered (more than 38 % of the possible maximum score) or not considered further (< 38 % of the possible maximum score). These percentages equate to raw scores of 30, 15 and less than 15 for robotics, and 38, 19 and less than 19 for automation.

The ratings and weightings, along with decision points, are shown in Table 3-1 and Table 3-2 below.

Table 3-1
Ranking Table for the Use of Robotics

Potential for Robotics	
Attribute	Score
1 – Work Complexity of Task	Maximum of 10 points
2 – Impact on Schedule/Cost	Maximum of 10 points
3 – Radiological/Industrial Safety	Maximum of 10 points
4 – Repetition	Maximum of 10 points
Maximum Total of 40 points	
(30 – option should be pursued) , (15–30 – consider the option), (<15 – do not consider further)	

Table 3-2
Ranking Table for the Use of Automation

Potential for Automation	
Attribute	Score
1 – Work Complexity of Task	Maximum of 5 points
2 – Impact on Schedule/Cost	Maximum of 20 points
3 – Radiological/Industrial Safety	Maximum of 5 points
4 – Repetition	Maximum of 20 points
Maximum Total of 50 points	
(38 – option should be pursued) , (19–38 – consider the option), (<19 – do not consider further)	

Each of the tasks was assessed against the matrix. The results of the assessment are shown in Appendix A. The results were reviewed and summarized as shown below (with actual scores shown in parenthesis after the task).

Based on robotics metrics, the following items should be pursued (total score more than 30 of a possible 40):

- Load Spent Fuel Canisters and Transfer to ISFSI (35)
- Segment, Package and Dispose of Reactor Internals (35)
- (Spent Fuel Pool) Remove and Dispose of Legacy Class B and C Waste (30)

Based on robotics metrics, the following items should be considered (total score between 15 and 30):

- Remove, Segment and Dispose of Steam Generators (29)
- Segment, Package and Dispose of Reactor Pressure Vessel (26)
- Remove and Dispose of Spent Resin, Filter Media and Tank Sludge (25)
- Remove and Dispose of Reactor Head (25)
- Remove and Dispose of Reactor Coolant Pumps (22)
- Decontaminate Containment Building (22)
- Final Status Survey (20)
- Decontaminate Fuel Handling Building (19)
- Remove, Segment and Dispose of Pressurizer (18)
- Radiological Survey of Structures During Decontamination (18)
- Remove and Dispose of Contaminated Sumps, Trenches and Pavement (18)
- Demolish and Backfill Intake Structure Inside Seawall Below -3 Feet (18)
- Remove Off Shore Intake and Outfall Conduits (18)
- Hot Spot Decontamination (17)
- Decontaminate Auxiliary Radioactive waste Building (17)
- Remove and Dispose of Spent Fuel Storage Racks (17)
- Demolish Containment Building to 3-Feet Below Grade (16)
- Decontaminate Turbine Building (15)
- Reactor Vessel Insulation Removal and Disposal (15)
- Decontaminate Penetration Building (15)

Based on automation metrics the following items should be pursued (total score of more than 38 of a possible 50):

- Segment, Package and Dispose of Reactor Internals (46)
- Load Spent Fuel Canisters and Transfer to ISFSI (45)
- (Spent Fuel Pool) Remove and Dispose of Legacy Class B and C Waste (40)

Based on automation metrics the following items should be considered (total score between 19 and 38):

- Remove, Segment and Dispose of Steam Generators (34)
- Final Status Survey (31)
- Remove and Dispose of Spent Resin, Filter Media and Tank Sludge (29)
- Remove and Dispose of Reactor Head (29)
- Decontaminate Containment Building (29)

- Segment, Package and Dispose of Reactor Pressure Vessel (26)
- Decontaminate Turbine Building (24)
- Remove and Dispose of Reactor Coolant Pumps (24)
- Radiological Survey of Structures During Decontamination (24)
- Demolish and Backfill Intake Structure Inside Seawall Below -3 Feet (24)
- Decontaminate Penetration Building (23)
- Decontaminate Fuel Handling Building (23)
- Remove and Dispose of Contaminated Soil (22)
- Hot Spot Decontamination (22)
- Decontaminate Auxiliary Radioactive Waste Building (22)
- Decontaminate Auxiliary Control Building – Common (21)
- Remove and Dispose of Contaminated Sumps, Trenches and Pavement (21)
- Remove Off Shore Intake and Outfall Conduits (21)
- Demolish and Backfill Turbine Building Structure Below 9-foot (3-meter) Elevation (19)

As can be seen, there was a relatively high degree of commonality between the rankings for robotics and automation. An overall list was developed to identify which was the most appropriate route (that is, robotics, automation or both) to pursue for the item. The list was further categorized to allow grouping of the type of work for further assessment. The overalls groupings and options to pursue are:

Tasks for Potential Robotic/Automated Handling Solutions

- Load Spent Fuel Canisters and Transfer to ISFSI (Pursue for Robotics/Automation)
- Remove and Dispose of Spent Resin, Filter Media and Tank Sludge (Consider for Robotics/Automation)
- Spent Fuel Pool Remove and Dispose of Legacy Class B and C Waste (Pursue for Robotics/Automation)
- Remove and Dispose of Spent Fuel Storage Racks (Consider for Robotics)
- Reactor Vessel Insulation Removal and Disposal (Consider for Robotics)

Tasks for Potential Robotic/Automated Cutting Solutions

- Remove and Dispose of Reactor Head (Consider for Robotics/Automation)
- Segment, Package and Dispose of Reactor Internals (Pursue for Robotics/Automation)
- Segment, Package and Dispose of Reactor Pressure Vessel (Pursue for Robotics/Automation)

- Remove, Segment and Dispose of Steam Generators (Pursue for Robotics/Automation)
- Remove and Dispose of Reactor Coolant Pumps (Pursue for Robotics)
- Remove, Segment and Dispose of Pressurizer (Consider for Robotics)

Tasks for Potential Robotic/Automated Survey Solutions

- Radiological Survey of Structures during Decontamination (Consider for Robotics/Automation)
- Final Status Survey (Consider for Automation)
- Hot Spot Decontamination (Consider for Robotics/Automation)

Tasks for Potential Robotic/Automated Decontamination Solutions

- Decontaminate Turbine Building (Consider for Automation)
- Decontaminate Penetration Building (Consider for Robotics/Automation)
- Decontaminate Containment Building (Consider for Robotics/Automation)
- Decontaminate Fuel Handling Building (Consider for Robotics/Automation)
- Decontaminate Auxiliary Radioactive Waste Building (Consider for Automation)
- Decontaminate Auxiliary Control Building (Consider for Robotics/Automation)

Tasks for Potential Automated Demolition Solutions

- Demolish and Backfill Intake Structure Inside Seawall Below -3 Feet (1 meter) (Consider for Robotics/Automation)
- Remove Off Shore Intake and Outfall Conduits (Consider for Robotics/Automation)
- Remove and Dispose of Contaminated Soil (Consider for Automation)
- Demolish and Backfill Turbine Building Structure Below 9-foot (3 meter) Elevation (Consider for Automation)
- Demolish Containment Building to 3-Feet (1 meter) Below Grade (Consider for Robotics)
- Remove and Dispose of Contaminated Sumps, Trenches and Pavement (Consider for Robotics/Automation)

In other studies [1, 5, 6, 7], potential benefits to automation and robotics in decommissioning applications have been categorized more broadly, and with a focus on emerging technologies and technology needs. Examples include:

- Development and deployment of novel cutting technologies such as laser and plasma cutting [1]
- Development of systems for segmentation of highly irradiated or thick-walled vessels and piping [1]
- In-situ segmentation where the location is difficult to access [1]
- Use of robotics for internal or external demolition [1]
- Underwater capture systems for debris created during underwater cutting [1]
- Improving mechanical decontamination of tank heels [1]
- High speed characterization of soil, and improvement of soil sorting [1]
- Technologies for the application and removal of strippable coatings and other dry decontamination methods [5]
- Systems for superimposing radiation readings and spectrographic information onto visual images of an object [6]
- Methods for automated collection of a large number of surface contamination readings [6]
- The automated visual inspection and thermal/gamma imaging of dry cask storage systems to allow for the reliable detection of changes in fuel configuration [7]

Assigning these items to the groupings above, results in the following:

Tasks for Potential Robotic/Automated Handling Solutions

- Load Spent Fuel Canisters and Transfer to ISFSI (Pursue for Robotics/Automation)
- Remove and Dispose of Spent Resin, Filter Media and Tank Sludge (Consider for Robotics/Automation)
- Spent Fuel Pool Remove and Dispose of Legacy Class B and C Waste (Pursue for Robotics/Automation)
- Reactor Vessel Insulation Removal and Disposal (Consider for Robotics)

General considerations:

- Improving mechanical decontamination of tank heels [7]
- The automated visual inspection and thermal/gamma imaging of dry cask storage systems to allow for the reliable detection of changes in fuel configuration [7].

Tasks for Potential Robotic/Automated Cutting Solutions

- Segment, Package and Dispose of Reactor Internals (Pursue for Robotics/Automation)
- Segment, Package, and Dispose of Reactor Pressure Vessel (Pursue for Robotics/Automation)
- Remove and Dispose of Reactor Head (Consider for Robotics/Automation)
- Remove and Dispose of Spent Fuel Storage Racks (Consider for Robotics)
- Remove, Segment and Dispose of Steam Generators (Pursue for Robotics/Automation)
- Remove and Dispose of Reactor Coolant Pumps (Pursue for Robotics/Automation)
- Remove, Segment and Dispose of Pressurizer (Consider for Robotics)

General considerations:

- Development and deployment of novel cutting technologies such as laser and plasma cutting [1]
- Development of systems for segmentation of highly irradiated or thick-walled vessels and piping [1]
- In-situ segmentation where the location is difficult to access [1]
- Underwater capture systems for debris created during underwater cutting [1]

Tasks for Potential Robotic/Automated Survey Solutions

- Radiological Survey of Structures during Decontamination (Consider for Robotics/Automation)
- Final Status Survey (Consider for automation)
- Hot Spot Decontamination (Consider for Robotics/Automation)

General considerations:

- High speed characterization of soil [1]
- Systems for superimposing radiation readings and spectrographic information onto visual images of an object [6]
- Methods for automated collection of a large number of surface contamination readings [6]

Tasks for Potential Robotics/Automated Decontamination Solutions

- Decontaminate Turbine Building (Consider for Automation)
- Decontaminate Penetration Building (Consider for Robotics/Automation)
- Decontaminate Containment Building (Consider for Robotics/Automation)

- Decontaminate Fuel Handling Building (Consider for Robotics/Automation)
- Decontaminate Auxiliary Radioactive Waste Building (Consider for Automation)
- Decontaminate Auxiliary Control Building (Consider for Robotics/Automation)

General considerations:

- Improvement of soil sorting [1]
- Technologies for the application and removal of strippable coatings and other dry decontamination methods [5]

Tasks for Robotics/Automated Demolition Solutions

- Demolish and Backfill Intake Structure Inside Seawall Below -3 feet (-1 meter) (Consider for Robotics/Automation)
- Remove Off Shore Intake and Outfall Conduits (Consider for Robotics/Automation)
- Remove and Dispose of Contaminated Soil (Consider for Automation)
- Demolish and Backfill Turbine Building Structure Below 9-foot (3-meter) Elevation. (Consider for Automation)
- Demolish Containment Building to 3-feet (1-meter) Below Grade (Consider for Robotics)
- Remove and Dispose of Contaminated Sumps, Trenches and Pavement (Consider for Robotics/Automation)

General considerations:

- Use of robotics for internal or external demolition [1]

In the following sections, categorized according to the task groupings identified above, the items identified by the assessment matrix are examined in more detail to understand where robotics or automation have been used or could be used as appropriate. Existing and potential solutions, conclusions and the outstanding challenges for each task are analyzed in Sections 4 to 9.



Section 4: Handling Operations

The following tasks are reviewed in sections 4.1 to 4.4:

- Load Spent Fuel Canisters and Transfer to ISFSI (Pursue for Robotics/Automation)
- Remove and Dispose of Spent Resin, Filter Media and Tank Sludge (Consider for Robotics/Automation)
- Spent Fuel Pool Remove and Dispose of Legacy Class B and C Waste (Pursue for Robotics/Automation)
- Reactor Vessel Insulation Removal and Disposal (Consider for Robotics)

4.1 Load Spent Fuel Canisters and Transfer to ISFSI

Many facilities have already transferred some of their spent fuel to an ISFSI as part of their routine operations, particularly in the U. S., Spain and Germany.

The steps involved in the operation are for canister-based systems are provided below [8]. Similar steps would be performed for cask-based systems, although separate transportation and storage casks would not be required.

- A spent fuel canister is placed in a separate steel transportation cask. The transportation canister also provides shielding. These are the first of the many operations that require a heavy lift with an overhead crane. Such a crane may already exist in the facility, but upgrading or replacement may be required to meet the rating requirements. It should be noted that crane failures have been a challenge during this type of work. Where new overhead crane installation is required, this may be an opportunity to install robotics. This is discussed further in Section 4.1.3.
- The transportation package is lifted with the heavy crane and is placed in a separate area of the Spent Fuel Pool.
- Spent fuel is placed in the combination canister. This is typically completed by plant personnel using a bridge crane and hoist. This is the part of the operation that is extremely time-consuming. Any improvement that can be made in automation and efficiency of this operation would be important. Likewise improvements in identifying the loading pattern for the casks could be beneficial.

- A heavy stainless lid is then lowered using the overhead crane and secured to the spent fuel canister.
- The dual canister assembly is lifted from the pool using the overhead crane. Shielding may be used at this time to reduce dose to personnel during this evolution. During the process personnel will survey and decontaminate external surfaces of the transport cask as needed.
- The dual canister assembly is placed in a location to allow a permanent lid to be welded on to the stainless steel canister. An automated welding machine is set up to perform this weld. The machine has to be set up and monitored. It should be noted that weld failures (detected through non-destructive testing) can be a challenge.
- After closure welding is completed, all moisture is removed from the canister and it is filled with helium.
- The dual package (spent fuel stainless steel canister and transport cask) is lifted onto a transport cart and winched out of the area using the transporter.
- The transfer cask is transported to the Independent Spent Fuel Storage Installation (ISFSI) via the transporter machine. Prior to the placing the spent fuel stainless steel canister in the ISFSI, an overpack is positioned to receive the spent fuel stainless steel canister.
- The overpack is emplaced with the transfer cask above it. Once this is positioned, the spent fuel stainless steel canister is lowered into the overpack.
- The transfer cask is removed, a lid placed on the overpack, and this is moved to the ISFSI.

4.1.1 Existing Solutions – Automated Welding

Zion Station purchased and deployed an automated remote welding system to perform non-destructive inspections of the fuel canisters after loading to reduce radiological exposure to its workers [9]. This first-of-a-kind robotic welding system was used on both fuel and Greater-Than-Class C canisters, and also has the capability to remotely perform non-destructive testing of the welds. In general, some type of automated nuclear canister welding system has been implemented at more than 10 nuclear power plant sites that are using remote welding as one way to minimize workers' exposure to radiation.

4.1.2 Potential Solutions

4.1.2.1 PaR (cranes)

PaR Systems developed a custom-made Mobile Tool Platform (MTP) that serves as a stable platform for remotely operated tools. The TensileTruss is composed of two triangular shaped platforms, upper and lower, connected by six wire ropes and positioned by six hoists. The hoists raise and lower the platform and can sustain significant horizontal loads and torque generated by tools. This rigid platform provides an ideal delivery system for remote tooling that is required in long-term projects like the dismantling of the Chernobyl Nuclear Plant.

PaR Systems is providing their patented TensileTruss® technology that enables a rigid lightweight extendible Mobile Tool Platform (MTP), along with a full suite of specialized technologies, for the cleanup efforts of the destroyed nuclear reactor at the Chernobyl Nuclear Power Plant in Ukraine. This TensileTruss® technology was also provided by PaR to support the cleanup activities at the Fukushima nuclear site in Japan.

The MTP comprises two triangular platforms with independent wire ropes used to manipulate the lower platform. Hoists on the MTP precisely control the tension of each wire rope, so that the lower platform can handle significant horizontal loads and torques generated by tool usage. The MTP can handle 1.5 tonnes (1.7 tons) of side load capacity at an extension of 44 meters (144 feet) without sway, which would be impossible to achieve with a standard hoist. The MTP allows for remote work to be completed that is otherwise difficult due to the elevation and radioactive environment. The total vertical extension of the MTP is 70 meters (230 feet), enabling it to reach from just below the ceiling all the way to the ground [10].

PaR Systems is developing a tensile truss apparatus for Fukushima. The Overall Gantry will have four lifting devices: two 5T auxiliary hoists, one 1.5T fuel handling mast, and one 1.5T tensile truss.

4.1.3 Unresolved Challenges and Conclusions

Loading Spent Fuel Canisters and Transferring to the ISFSI was identified as highly significant for pursuing for robotics/automation solutions. The item is typically critical path for decommissioning and can take 18 months or longer. Many of the activities involved use an overhead crane and are therefore already considered to be robotic. Proper selection and testing of the crane prior to the commencement of operations is necessary. If the existing crane capacity is inadequate, installation of a new crane system or a crane system allowing more functions for decommissioning may be beneficial.

Making the loading process more efficient, effective or automatic, reducing the time for canister decontamination, and improving the existing automated welding system, are opportunities for improvement. The automated visual inspection and thermal/gamma imaging of dry cask storage systems to allow for the reliable detection of changes in fuel configuration [8] was also previously identified as an item that requires research.

This is an area that requires more research and discussion with vendors to identify whether improvements can be made.

4.2 Remove and Dispose of Spent Resin, Filter Media and Tank Sludge

These operations are carried out routinely during plant operations using normal operating procedures and processes.

The tasks involved are:

- Proper plant system line ups are required to transfer resin into the radioactive storage tanks and finally to a High Integrity Container (HIC) or other approved container for final disposal.
- Once the spent resin is removed from the resin beds, there may be residual resin/sludge in the beds, system piping and storage tanks. Removal of this waste in the tank may be completed via the following avenues
 - Manual entry may be used to remove the sludge/resin via a pump using a water/sludge slurry and transfer to an intermediate container for transport for further processing, packing and final disposal.
 - Not all areas may be accessible via a manway; entrance using robotics or by cutting into the tank will be required.
 - Robotics may be used in this case to limit radiation exposure and confined space entries. Therefore reducing the industrial risk to the worker, for example, robot either entering the area or used for cutting an opening for further access to the area.
- Filter media are placed in an approved container (HIC or other) and sent for final disposal. This can result in potentially high doses and robotic solutions have been used at some sites.

4.2.1 Existing Solutions

4.2.1.1 Removal and Replacement of Filters using Robots

Based on the high visibility of robotic applications used for the inspection of the damaged Fukushima reactors, U.S. nuclear power companies, such as Duke Energy, have started to investigate potential applications at their facilities. The Radiation Protection team at Duke Energy's Robinson Nuclear Plant in Hartsville, S.C. tested several different robots, and in 2012 ordered two 510 PackBot robots and one 710 Warrior from iRobot [12]. The lightweight PackBot is used for tactical operations, such as inspecting objects, and the 710 Warrior robot, which has a higher lift capacity and can travel up to 8 mph, is assigned to perform heavier functions, such as removing and replacing filters in the High Integrity Containers (HICs) located in the plant's four radioactive waste bunkers.

The robots required a few modifications prior to being used. The primary change was equipping the robots so they could be used in areas of the facility that blocked radio signals. In this case, iRobot engineers equipped the 710 Warrior and PackBots with fiber spoolers that allowed operators to control them via a fiber optic tether rather than relying on radio frequencies. The Radiation Protection team at Robinson selected the iRobot units in part because of their ease in learning how to use them with a video-game style control system.

By 2014, workers at Duke Energy's McGuire Nuclear Station were using the iRobot 710 Warrior robot for the replacement of radioactive waste filters [13].

Specifications for the iRobot 710 Warrior include:

- Sealed to IP67 – easy to decontaminate
- Lift capacity in excess of 70 lbs (32 kg) at full extension
- Lift capacity of 300 lbs (136 kg) at close-in position
- 312x zoom camera
- Illumination for dark spaces
- Fiber optic and radio operation
- Up to 11 ft (3.3 m) gripper reach
- Electromagnetic interference characteristics

In the radwaste bunkers, the 710 Warrior was used to characterize and place filters in high integrity containers. During refueling outage 27, the 710 Warrior was used at the cavity edge to remotely remove high dose filters from the pool [14].

To complete this task without the assistance of robots, an enormous amount of planning and preparation would have to be performed, including the placement of barriers and other safeguards to reduce radiation exposure. By using the robots, workers were able to greatly reduce exposure, and work more safely and efficiently [15].

The specific task set performed for moving used filters from the shielded transport container (STC) into the HIC has been published [15]. Typically, these tasks provide the potential for significant collective radiological exposure to workers when moving the filters or during the manipulation of the filters in either the HIC or STC.

For simplicity, the main tasks are numbered and limited to:

1. Removing the cover from the HIC.
2. Determining the “fill” level and configuration of HIC current contents.
3. Removing the lid from the STC.
4. Firmly grasping/hooksing and removing the waste filters from the transport STC.

5. Transferring the filter through the air and into the HIC.
6. Lowering the filter into the HIC and getting it securely inside in the best position possible.
7. Replacing the lids on both the HIC and the STC.

The tasks listed were previously performed by trained Radiation Protection personnel as follows:

- **Tasks 1, 3 and 7.** Removing/replacing the STC and HIC lids was performed using a remotely operated crane and/or a remotely operated tool. This allowed the worker to remain at a distance and at lower exposure, unless there was an issue such as a rigging snag or failure.
- **Tasks 4 and 6.** Grasping/hooking the filter and controlling the filter while removing it from the STC, and then placing into the HIC. In the past, filters were handled and manipulated by the worker using a six foot pole. This is a very challenging maneuver for two reasons:
 - Lack of real time “vision” into the HIC to see current status of contents and how the incoming filter was fitting in
 - Inability of the worker to have constant, consistent or precise control of the actual filter or its movement – typical issues were snagging on other filters or the filter becoming unbalanced while being removed from the STC or introduced into the HIC
- **Task 2.** Viewing, evaluating and manipulating and/or moving the current contents of the HIC prior to adding more filters. Of the task set, this task provides the second highest level of risk and collective radiation exposure. Given the activity level of the HIC contents, using extendable mirrors is critical to seeing the contents and configuration to determine if the incoming filter(s) could fit into a particular HIC. However, a worker cannot use the mirror and move the filter at the same time. The worker checks positions and essentially is moving the filter blindly with stops for checking with the mirror. Another common and continuing problem is filters falling over once placed inside the HIC, blocking space. While some minimal adjustments could be made with extendable poles or rods, precision movement or changing of the filter configuration was not possible. These attempts frequently resulted in the workers receiving collective radiation exposure beyond what was planned for the activity as well as loosely and inefficiently packed HICs, thus increasing the radioactive waste disposal costs.
- **Task 5.** Moving the filter from the STC to the HIC through the air using a six foot (two meter) pole. This is the task that provides the highest levels of risk and exposure for the workers. It is while the filters are moving through the air – in close proximity to the worker – that the highest risk of elevated exposure occurs. This is also the time that provides the greatest opportunity for mishandling of the filter (that is, filter could slide on the extended pole, potential for the filter to be dropped, and so on)

McGuire had previously used robots for this task set before the 710 Warrior. McGuire's prior experience with robots provided insight and helped identify, clarify and prioritize the specifications for movements and capabilities that their next off-the-shelf robot would be required to have. Clearly defined technical requirements included specifications for size, reach and degrees of freedom, "vision", weight and weight lifting capabilities (both within the robot footprint and at full extension of the robotic arm). For operator usability, mandatory requirements included ease and efficiency of operations, speed controls, rapid deployment and small storage profile.

Between uses, the 710 Warrior is stored in the bunker area and can be deployed in a relatively short time. Use of the robot has made significant, positive impacts and changes to this task set by lowering risk and exposure, and increasing safety:

- **Tasks 1, 3 and 7.** Removing/replacing the STC and HIC lids is still being performed using a remotely operated crane and/or a remotely operated tool. Future plans are to use the 710 Warrior to conduct these activities since the lids are well within the robot's weight lifting capacity.
- **Tasks 2, 4, 5 and 6.** Viewing, evaluating and manipulating and/or moving the waste filters. This subset of tasks includes Tasks 2 and 5 – those tasks with the highest levels of risk and exposure for workers. These four tasks are now being performed by the 710 Warrior with the worker behind shielding and operating the robot via wireless controls to remotely view and safely move the filters from the STC to the HIC. From the operator control unit (OCU) screen, the worker:
 - Views and evaluates the contents and configuration of the HIC, and captures a video record. These video records are stored and used to track configuration and number of filters to determine which HIC can accommodate more filters and what size will fit – without re-opening the HICs.
- Moves/manipulates the filters within the HIC to obtain the desired configuration needed to accommodate the incoming filters.
- Firmly grasps the targeted filter, carefully removing it from the STC and places it precisely into the HIC.

Summary of Results of Using the 710 Warrior

Using the 710 Warrior may one day drive changes to setup operations, but it has already had significant ALARA impacts in the day-to-day tasks for handling and packing waste filters at McGuire:

- Reduction in overall risk.
- Increased worker focus on specific waste handling tasks and ALARA planning.
- Reconfiguration of the HIC area, leading to a cleaner (lower background) environment and greater operational efficiencies.

- Recording and tracking of the configuration and number of filters placed in the HICs.
- Development of a new approach to increase control and packing configuration of the filters in the HIC.
- Increased quantities of filters packed into each of the HICs, with an anticipated overall future cost reduction for transport and disposal.
- Reduction in collective radiation exposure to the worker/operator during this evolution.
- Improved overall operations.

Potential system improvements may be increasing the tasks that the robot can perform by adding different tools for the robot to use. For example, tools could be added to aid the robot in removing the fasteners or nuts, and manway covers from the radioactive filter housings or tanks. Wolf Creek used an iRobot 510 PackBot Multi-Mission Robot to look for leaks inside the bio-shield at 100% power to limit personnel dose. A Go-Pro camera was used to capture video, as the system was found to be better than the video system provided by iRobot. Another issue identified by Wolf Creek was that the transmission frequency used to operate the iRobot may potentially affect sensitive equipment. Therefore the travel path was limited due to the use of the tether device and possible issues with retrieval.

4.2.2 Sludge Removal

4.2.2.1 ROV use at Magnox

The fuel ponds at Hinkley Point and other Magnox sites contain large amounts of sludge and other small debris. To avoid the high cost to develop a new remotely operated vehicle (ROV) to assist with underwater sludge removal, an off-the shelf mini-digger was purchased and modified for underwater use. An underwater closed-circuit television (CCTV) was attached to the ROV. The planned lifetime of the unit was three weeks, but it actually operated for 326 days without significant problems. All sludge and fuel element debris was removed, with the only problem being visibility through the CCTV from clouds of disturbed sludge. After successful application at Hinkley Point, the unit was sent to Bradwell NPP to perform the same tasks, where it was operated for an additional 253 days [1]. The mini-digger was modified again to separate miscellaneous debris from sludge using a tool used in the cockle picking industry.

4.2.2.2 Houdini Use in the DOE

Past practice for tank waste retrieval in the DOE was to use large volumes of water to mobilize and remove the waste material. Although this approach has been found to be acceptable for bulk removal of some physical waste forms, it is not appropriate for hard or adhesive wastes, and does not address residual quantities left afterwards (the heel) or the management and removal of in-tank debris. Before remote systems became available for tank remediation projects, the only baseline alternatives were impractical:

- Manned entry through existing ports
- Development and use of long-handled manual tools
- Tank-dome removal, construction of a containment building, and then manned entry

Houdini is a remotely controlled, folding work platform that can pass through 24-in. (60 cm) openings called risers and then expand to become a 4 x 5 ft (1.2 x 1.5 m) mini bulldozer, complete with a plow blade; a dexterous, high-payload manipulator; and remote camera systems. A single-operator control console can be located up to about a hundred meters away [16].

Houdini can deploy a variety of tools fitted with appropriate grasp points and can manipulate objects up to 250 lb (114 kg). It can shovel waste or deploy localized sluicing systems for heel removal, cut and remove in-tank debris, deploy tools to obtain core samples, and perform characterization and inspection missions. It has successfully and extensively manipulated a localized sluicer that uses high-pressure water to dislodge and then pump a variety of physical waste forms. Houdini is lowered from an enclosed and shielded deployment package that houses the tether reel and the robot for stowage and maintenance.

Houdini's in-tank remote hardware is provided by an external unit. Hydraulic fluid and electrical power pass to Houdini through a customized tether. If there is a loss of power, the system has a fail-safe feature that allows the robot chassis to collapse under gravity so that it can then be extracted from the tank. The system is designed for full submersion in radiological and hazardous environments, although the tethers on both Houdini-I and Houdini-II have experienced some in-leakage. Houdini's primary limitations are that it can reach only about 6 ft (1.8 m) up tank walls, its capability to travel over or through deep waste is currently uncertain, and it requires frequent maintenance. Though training is straightforward with no special qualifications needed, inexperienced operators can also easily damage the system. Therefore, the need for operators to practice in cold tests is critical to mission success.

Houdini was developed to provide mobile waste retrieval capability for remediating radioactive waste storage tanks across the DOE complex. It is designed to be relocated between tank risers and can be deployed in enclosed spaces as well as fully exposed to the elements. The system has been designed to

be outfitted optionally with a sensor technology that can precisely report vehicle position within the tank. With the exception of expendable camera elements, Houdini is designed to operate in radiation fields of up to 100 R/hr (1 Gy/hr) with cumulative exposures of up to 105 R (1 Gy).

The principal waste retrieval tool used by Houdini is the Confined Sluicing End-Effector (CSEE). Operation of the CSEE is analogous to a high-performance carpet cleaner in which rotating water jets mobilize dirt and a vacuum then removes the dirty water. It weighs about 45 lb (20 kg) and has two grasp handles so that it can be operated by or exchanged between the Houdini (see Figure 4-1) and the Modified Light Duty Utility Arm (MLDUA).

The MLDUA is capable of deploying up to 200-lb (91 kg) payloads through risers as small as 12 in. (30 cm) in diam. The MLDUA has a vertical reach of nearly 50 ft (15 m) and a horizontal reach of 15 ft (4.5 m). With a gripper and the CSEE attached, the effective reach is 17.5 ft (5.3 m). The MLDUA can be operated remotely, using a joystick, and in preprogrammed sequences. A tool interface provides utilities and communications to support multiple end-effectors.



*Figure 4-1
Houdini Remotely Operated Vehicle (left) with Confined Sluicing End-Effector Tool (right) [16]*

Houdini can be broadly applied to retrieve highly radioactive and/or hazardous waste stored in both underground and aboveground tanks. It is best used where access to tanks is limited through 24-in. (0.6 m) diameter penetrations and in tanks where the waste is neither deep nor viscous. Houdini deploys tools to support nearly all in-tank tasks ranging from waste removal to hardware disassembly and sizing.

Houdini-II represents the final design revision necessary to bring the technology from demonstration to implementation. The technology is now available from RedZone Robotics in Pittsburgh.

4.2.2.3 Tank Cleaning

An example of a tank cleaning robot that was used to remove tank bottom residuals with a high pressure water jet system in the DOE is the Sand Mantis. The robot is 8 feet (2.4 m) long and weighs approximately 800 pounds (360 kg). The cross-shaped body can be collapsed into a straight piece for insertion through small openings at the top of a tank. Once inserted, the robot unfolds and accomplishes its functions through remote control. The robot was used in the last phase of waste removal from Tank 18 and contributed to the removal of over 99% of the original waste and approximately 99% of the highly radioactive radionuclides [17]. It took 4 years to design, procure and test the Sand Mantis, and after operating in Tank 18 for 415 hours, it reached its limits of effectiveness in removing the residual heel of radioactive material at the bottom of the tank. Its high pressure (4,500 psi) hydro-lance broke up the waste mounds and its 17,500 psi eductor suctioned the dispersed waste from the floor of the tank.

However it is estimated that the direct costs for equipment, testing, operation, sampling, and other activities associated with sludge retrieval systems such as the Sand Mantis could be approximately \$10 to \$40 million. This is likely to be prohibitively expensive for nuclear power plant decommissioning, unless this can be used on a large scale.

While the equipment worked satisfactorily, repairs to the wheel assembly and forward blades were required to extend its operational life. Figure 4-2 depicts the Sand Mantis during testing and operation.



Figure 4-2
Sand Mantis [18]

4.2.3 Potential Solutions

The OECD [1] has identified the need to develop systems for removal of tank heels and residues in preparation for tank removal or dismantlement. The ideal system would be remotely operated and have versatile end effectors to perform the desired activities.

4.2.3.1 Tank Heel Removal

Clean-up of tanks containing highly radioactive wastes is an inherently difficult process. After removal of bulk materials, these tanks typically contain residual liquids (heels) and settled solid particulates (sludge). Chemical treatment of heels produces large quantities of liquid waste. Since these are concentrated high-level wastes, high dose rates are encountered when handling and processing these materials. Some current techniques for removal of tank heels involve the use of aggressive chemical or mechanical processes that can compromise the integrity of the tank or peripherals components (pumps, pipes, pressure vessels, and so on). Better decontamination and techniques to fix contamination are required.

In nuclear plant decommissioning, improved decontamination techniques for tanks could be applied to reactor water storage tanks, spent resin tanks, and sump collection and equipment drain tanks where there may be sludge heels with radiation levels in the mSv/hr to hundreds of mSv/hr range.

A versatile remote manipulator was recently developed in the UK for use at the Trawsfynydd nuclear power station. S.A. Technology, in cooperation with Magnox Ltd. and ACTUS, designed and constructed two long-reach manipulators for retrieval of the heels from radioactive liquid storage tanks at the site. These tools were designated as the Rotary Deployment Arm (RDA1 and RDA2). The RDA is designed to complete a variety of clean-up tasks in tanks of different sizes and technical constraints. The RDA is capable of being deployed

through penetrations with diameters of 10 inches (25 cm) and larger. The RDA has a vertical reach of 32 feet (9.8 m), and a horizontal reach of 15 feet (4.5 m) when fully extended. The RDA consists of mast and forearm assemblies constructed from carbon fiber and stainless steel components, as well as electromechanical and hydraulic components to provide actuation. These mast and forearm assemblies reside inside the tanks during decontamination operations.

At the plant room floor level, the RDA is mounted inside a stationary support frame that allows the RDA to be deployed into and retrieved from the various tanks, and provides cable management for the variety of required services. The RDA support frame also provides containment for operation, and wash-down capability for contamination control, as well as wheeled transportation. When retracted, the RDA fits within the support frame (roughly the size of a large refrigerator). The RDA system includes a hydraulic power unit, electrical enclosure and integrated control system to provide motive power and control. End effector tooling for the system is designed to perform a variety of operational tasks.

4.2.4 Unresolved Challenges and Conclusions

The removal and disposal of spent resin, filter media and tank sludge was designated as an item to be considered for robotics/automated solutions. While there are existing and potential robotics/automated solutions to all of these tasks, they tend to be expensive compared with the typical budget allocated to the work.

Except in cases where sludges and residues are a particular challenge (as for example, as found in Magnox sites in the UK), or in cases where significant radiation exposures may result, the use of these robotic solutions in nuclear power plant decommissioning is considered to be typically cost prohibitive. Simpler robotics solutions may be more cost effective in such cases.

Working together with other organizations or as a fleet, and especially if the technique can be used in both operations and decommissioning (for example, the iRobot units), then it may be more appropriate to deploy these techniques. However careful cost and safety benefit analysis should be conducted prior to investment. Further work is not considered appropriate in this area, except in increasing the potential capability of widely available commercial robots, and the use of a simpler camera system.

4.3 Remove and Dispose of Legacy Class B and C Waste from the Spent Fuel Pool

There will be various items left in the spent fuel pool over the years of operation. Possible items could include:

- Used control rods
- Radioactive sources for example, reactor startup source

At José Cabrera NPP, for example, a substantial amount of legacy wastes (activated fuel related hardware, such as plug devices, control and source rods, and so on) was removed from the spent fuel pool. Activated hardware elements were classified as “Special Waste” and segmented by mechanical shearing to fit inside custom designed baskets.

The process for removal and disposal of these items would be as follows

- Characterization of all items in the pool
- Determining the nuclides of concern
- Dose rates of items as needed
- Determining packaging requirements
 - Shielding needed for transport
 - Type of container required for shipping/burial
 - Type C/high level waste may be required to be placed in special containers and managed in a manner similar to used fuel (for example, temporary storage at an ISFSI)

For high activity waste, the process should be the same as for the spent fuel, however the difference would be the different physical shapes and weights. Therefore, special tooling would be needed to assist in the removal and packaging of the material on a case-by-case basis.

4.3.1 Existing Solutions

Characterization and inspection of spent fuel storage pools requires mobile equipment capable of operating underwater to perform close-up inspection and radiation measurements in confined spaces. Typically this will involve mounting an underwater camera or underwater radiation detector to a cable or a long (15 to 20 ft [4.5 to 6.1 m]) rod to locate and measure levels of radioactivity, or to collect samples to identify specific radioisotopes through laboratory analysis. The process is tedious and time-consuming, involving worker exposure, contamination control measures, long turn-around times for analytical results, and costs involved with the time spent performing the work and making decisions.

4.3.1.1 ISUGS

ISUGS is a technology operated underwater that provides dose rate and isotopic details for the characterization of objects stored in the reactor canals [16]. The technology is based on Canberra’s In-situ Object Counting System (ISOCS) placed in a watertight vessel (see Figure 4-3). Objects to be characterized are brought to the unit while shielded by the water, using the same instrumentation and computer software as used in ISOCS. The dimensions of the submersible unit are 30 inches (0.76 m) in length and 11 inches (28 cm) in diameter. Depending on the levels of radioactivity in the canal, the count time for the individual scans (measurements) will vary from 90 to 300 seconds. This

technology can operate in a relatively high radiation field (dose rates ranging from 0.050 to >1,000 R/hour [0.5 to 10,000 mGy/hour]). Once data have been recorded on the computer, the file can be downloaded and interpreted through the Canberra software to visually display characterization results.

The ISUGS System has been designed with the following components:

- Canberra GL0515 Low-Energy Germanium Detector, with an energy range of 3 keV to 2 MeV
- Canberra detector electronics, including transistor reset pre-amplifier and high-voltage power supply
- Single-port, multiattitude liquid nitrogen cryostat and remote detector chamber
- Custom submersible housing with electronics/vent umbilical, and 10 externally mounted interchangeable shielded collimators
- Canberra *InSpector*TM Multi-Channel Analyzer

Specific advantages include:

- Cost reductions for object characterizations – reduction in labor hours and sampling. For a job that requires characterizing 10 pieces of equipment, the technology was estimated by the DOE to cost approximately one-fifth the amount of using traditional technology, although this cost reduction will vary widely depending on the specific application.
- Accelerated schedule due to shorter characterization times and reduced sampling needs. According to users and recipients of the data, the technology is much faster and easier to use than surveying and sampling.
- Near real-time in situ radiological measurements.
- Reduced exposure of personnel to radiation – due to the lack of sampling and underwater operation
- The system provides better quality documentation including isotopic results.
- No secondary waste stream created.

The technology is fully developed and commercially available. Operating the unit requires vendor support, which is part of the service typically provided. The technology is available as a service from the vendor if the end user cannot afford to purchase ISUGS or does not have sufficient work scope to justify purchase of the ISUGS.

Daily instrument checks are required on the detector to ensure the unit is performing properly, and preventative maintenance is required on the detector and underwater components. The ISUGS technology is limited to underwater applications and should not be deployed directly over fuel rods due to concerns over accidental breakage. Another limitation is the inability to use the system on objects that cannot be moved to the ISUGS unit for scanning due to weight, size, radiation and safety concerns, or deteriorating condition.

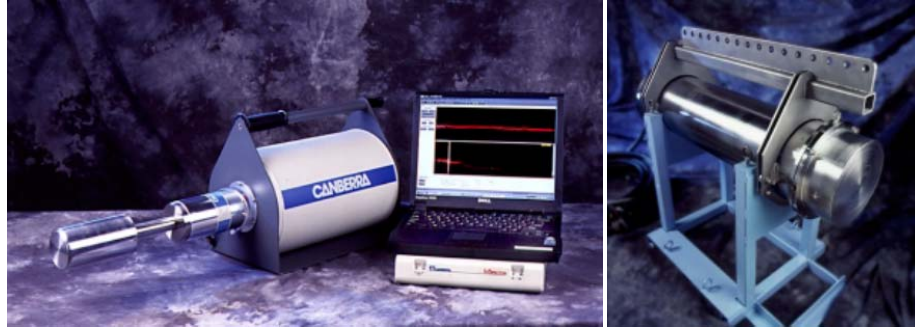


*Figure 4-3
ISOCS Unit (left) and Watertight Vessel (right) [16]*

4.3.1.2 Underwater Monitoring and Inspection Equipment

The Remote Underwater Characterization System (RUCS) is a small, remotely operated submersible vehicle intended to serve multiple purposes in underwater operations (see Figure 4-4). It is based on the commercially available “Scallop” vehicle produced by Inuktun Services, Ltd., British Columbia, Canada [16]. The U. S. Department of Energy modified the commercially available system to add radiation sensors and auto-depth control to the submersible, and to add vehicle orientation and depth monitoring at the operator control panel. RUCS is designed to provide visual and gamma-radiation characterization, even in confined or limited-access areas. RUCS has been used to visually survey reactor canals and to gather characterization data on the reactors and equipment on the floor of the canal. It is simple to deploy and its small size and maneuverability allowed it to operate beneath overhead structures and behind the reactors.



*Figure 4-4
Scallop Remotely Operated Underwater Vehicle [16]*

At the Sellafield nuclear site in the UK, a mini-submarine ROV was used in 2014 to remotely monitor and retrieve samples from the bottom of the First Generation Magnox Storage Pond (FGMSP) [19]. The FGMSP technical team wanted to understand the spent fuel pool sludge, water and visibility conditions to support decommissioning planning and deployed the ROV probe. James Fisher Nuclear (JFN) worked with the site to plan, perform trial runs, and send a Video Ray Pro 4 ROV into the FGMSP for the monitoring and sample collection activities. This technology was taken from the oil and gas industry.

The VideoRay ROV system was a preferred system due to the resistance of its electronic components to the high radiation fields during use. The VideoRay Pro 4 has the following features for versatile operations in underwater environments:

- Depth rating of 300 meters
- Tether length of up to 500 meters
- 3D compass and MEMS gyro navigation
- Video camera and high intensity LED lighting
- Intuitive VideoRay Cockpit control software

Magnox also mounted survey equipment on this technology and used this for the conduct of remote underwater surveys.

4.3.2 Potential Solutions

4.3.2.1 iRobot

As previously described in Section 4.2.1, Duke Energy ordered two 510 PackBot robots in 2012. The iRobot's PackBot was used to achieve remote positioning and inspections of containers inside the Defense Waste Processing Facility (DWPF). It was also used to separate some LLW materials from HLW materials.

Specifications for the iRobot 510 include:

- Main portable system – 60 lbs (27 kg)
- Sealed to IP67 – easy to decontaminate
- 30 lb (14 kg) lift capability
- 312x zoom camera
- While and IR illumination for dark spaces
- 7 ft (2 m) camera reach and 4 ft (1.5 m) gripper reach
- Support for multiple sensors including hazardous materials and radiation detection
- Compliance with a wide variety of EMI standards

4.3.2.2 Avexis

The Sellafield site in Cumbria, UK has 290 active facilities in a 6 km² area and a 100-year decommissioning plan. There are a significant number of challenges in starting the process due to lack of accurate data regarding the facilities and their contents. The University of Manchester is leading the development of a number of robotic systems for remote characterization of these storage facilities. The Aqua Vehicle Explorer for In Situ Sensing (AVEXIS) has been developed for the exploration and characterization of wet storage facilities [22].

There are currently four ongoing projects relating to different aspects of the AVEXIS design: the AVEXIS MiniROV, design of collaborative control, analysis of the effects of radiation on the electronics and the development of an acoustic communications and positioning system.

4.3.3 Unresolved Challenges and Conclusions

The removal and disposal of Legacy Class B and C Waste from Spent Fuel Pools was designated as an item that was ranked as being important to pursue. There are currently available solutions to support identification and characterization of materials. ISUGS can be used through the use of a vendor and may result in cost savings over traditional characterization methods without requiring purchase of the system. Its use may still need to be supplemented by sampling work. The RUCS system, Videoray, AVEXIS or other similar systems can also be used to support identification of materials. It is judged that there is not a pressing need for additional work in this area.

In terms of packaging materials, some of the same issues apply as discussed in Section 4.1 for dry cask loading, and more options should be considered for this.

4.4 Reactor Vessel Insulation Removal and Disposal

The tasks involved in reactor vessel insulation removal and disposal are:

- Removal of the reactor vessel insulation underneath and on the sides; typically performed manually and involves high radiation exposure.
- The space where the RCS piping exits/enters the reactor vessel is limited. Therefore limiting the radiation exposure would be preferred.
- Usually the insulation is designed to fit the contour of the piping and reactor vessel, and it is usually fitted together like a puzzle and held in place with buckles/clips.
- Due to tight spaces in these areas, maneuverability is usually difficult.
- The process for removing the insulation would be as follows:
 - Enter area and unbuckle or unfasten the insulation as needed.
 - Remove the insulation and transfer the piece out of the area.

- Depending on contamination levels, personnel may be required to wear protective clothing, and use respiratory protection.
- Also due the dose gradients, personnel may be required to wear multiple dosimetry.

Robotics could potentially be used to perform this task. The robot would need to have excellent dexterity to unbuckle and remove the clips. The areas usually have limited space, so this would be a consideration for remote operation.

4.4.1 Potential Solutions

At Brunswick, the iRobot 510 PackBot discussed in Section 4.3.2.1 is used to monitor radiation hazards, complete maintenance in tight spots and replace pipe insulation [21]. Based upon the experience of these robots at operating plants, robots could be used to perform some standard operations and achieve worker dose savings.

4.4.2 Unresolved Challenges and Conclusions

The removal and disposal of reactor vessel insulation was designated as to be considered for the use of robotics. Based on the fact that this is a manual operation and incurs significant dose, this would appear to be an appropriate ranking. Based on use at Brunswick for removal of piping insulation, iRobot's PackBot could potentially be used for reactor vessel insulation removal as well, although this may be cost prohibitive for a single decommissioning project. A more cost effective or simpler solution is needed.



Section 5: Robotic/Automation – Cutting

The major existing and potential cutting techniques are reviewed in Section 5.1 on *Segment, Package and Dispose of Reactor Internals*, and then the information is applied in the remaining applications in Sections 5.2 and 5.3. Due to overlapping similarities, removal of the reactor head, steam generators, reactor coolant pumps, pressurizer and the spent fuel storage racks are treated together in Section 5.3 on *Removal, Segmentation and Disposal of Large Components*.

- Remove and Dispose of Reactor Head (Consider for Robotics/Automation)
- Segment, Package, and Dispose of Reactor Internals (Pursue for Robotics/Automation)
- Segment, Package, and Dispose of Reactor Pressure Vessel (Pursue for Robotics/Automation)
- Remove, Segment, and Dispose of Steam Generators (Pursue for Robotics/Automation)
- Remove and Dispose of Reactor Coolant Pumps (Pursue for Robotics)
- Remove, Segment, and Dispose of Pressurizer (Consider for Robotics)
- Remove and Dispose of Spent Fuel Storage Racks (Consider for Robotics)

5.1 Segment, Package and Dispose of Reactor Internals

There are several reactor internals that need to be cut, packaged and removed:

- The upper internals package, including control rod guide tubes. These components are typically only moderately activated.
- The lower internals, which may include a core barrel, baffle structure, and/or shrouds, dependent on plant design. These are the most highly activated components, and are thus typically segmented remotely under water. Cutting occurs either in the reactor cavity or in the spent fuel pool, depending on the original design of the facility and any modifications made prior to segmentation. Cut pieces must be placed in shielded containers, then transported for conditioning and packaging for disposal. There may be neutron pads or shields that will also be highly activated and may need to be separated from the other parts of the core barrel.
- In-core instrument nozzles.

The selected cutting technology will influence the attributes of the remote deployment system. Critical parameters include the weight of the cutting head and associated reaction forces; required degree of articulation and number of degrees of freedom; the accuracy, stability and repeatability of positioning; accessibility; and ease of use/training of operators [1].

Cutting equipment can readily be adapted for remote use. Typically used techniques such as circular saws, nibblers, plasma arc cutters, reciprocating saws, laser cutters, friction saws, grinders and rotary hammers have successfully been adapted for remote operation. In fact, some equipment is already designed for remote application (for example, plasma arc cutters), so that extending these to a remote underwater application is straightforward. Cutting tools originally designed for manual operation may require design and fabrication of special fixtures, equipment or custom designed tools to support remote operation [2].

Maintaining water clarity is critical, and the management of cutting debris is challenging. High airborne activity and hazardous material is a potential concern, dependent on cutting method used. Cutting methods and methods of handling debris are discussed in a separate EPRI document [23]. Precise cuts are required for packaging efficiency. Waste management, and the safe handling and packaging of cut sections are performed underwater. The project typically requires two or more years for planning, and as long as two years for execution. Technology development can reduce both cost and schedule, worker radiation exposure and waste generation.

Enhancements to the current methods are needed in all areas:

- Cutting techniques and deployment
- Ventilation systems for control of airborne activity and hazardous species (for example, hexavalent chromium that may be generated if thermal cutting methods are used)
- Systems for management of cutting debris
- Systems for maintaining water clarity
- Systems for safe transfer of cut segments to waste packages

Automation of existing robotic systems and maximum integration of related sub-processes would be desirable. Basing the automation of the system on an established successful cutting technique may be appropriate, whether the entire process or select aspects, or whether the system is designed for cutting all of the reactor internal components or only the most highly activated ones. The minimum or maximum degree of automation acceptable also should be considered. A key consideration is the justifiable cost for an automated system.

An example of technology improvement that could be considered is in making the precise cuts required. The cutting device is often positioned using remote manual control. A possible improvement might be the use of Computer Numerical Control (CNC) where a precise component drawing and a

pre-defined cutting plan may be loaded into a computer program, then the computer program could control the manipulator that locates the cutting device and controls the cuts to the plan dimensions. New cutting methods such as underwater laser cutting may also be appropriate.

Additionally, improved techniques for the underwater collection, separation and filtration of cutting debris from reactor vessel internals segmentation should be developed [1]. An optimal system may include a fully remote skid module for separating and filtering the debris, and for packaging the filter unit for disposal without direct operator contact. If required, the system could also include a remote method for grouting the final container for disposal.

While this section will focus on cutting operations, improving the efficiency of cutting operations is not solely about cutting speed. The cutting time is about 20% of the time required for cutting operations. In automating cutting operations, it is important to be able to stop the cutting program at any time and to be able to repeat the cut. There is also potential for improvement in the use of a cutting technology that would enhance packing density. Any improvements that can be made to the automation of the packing process would also increase efficiency.

5.1.1 Existing Solutions

5.1.1.1 Mechanical Cutting at José Cabrera

The segmentation of the José Cabrera internals by Westinghouse by mechanical means will be used as an existing and successful example of cutting the reactor internals mechanically that could be used as a base case to make improvements. Details of the project are available in Reference [24] and are summarized here.

As in all Westinghouse reactors, the reactor vessel internals at José Cabrera comprised two basic assemblies: Upper Internals, removed at refueling to get access to the core fuel; and Lower Internals, which hold and support the core. All internal components are constructed of stainless steel.

All cutting for both Upper and Lower Internals took place inside the SFP, on top of a stand over a dedicated turntable resting on its floor. The placement and control of the different cutting and handling tools was performed manually by operators from a purposely built bridge crane over the SFP, riding on the same rails as the old bridge crane, and making use of the two updated Reactor Building cranes.

The cutting tools used in the RVI segmentation were a band saw, a disc saw, a drill tool and shear tools. All tools were hydraulically powered and controlled, and could be easily reconfigured, for example, to change cut direction. They were manually controlled by the operators on the bridge, via control boxes that monitored and modified parameters such as cutting speed and force.

Lifting and handling of cutting tools and segmented pieces was performed under manual operator control from the bridge, with the help of both the bridge and Reactor Building cranes. Standard pneumatic and hydraulic powered clamp type tools were used to lift the cut pieces, in combination with bayonet connected extension poles, while heavy pieces (up to 5 Tm) were handled by heavy duty mechanical grippers.

Every segmented piece was physically and radiologically characterized once cut. The segmented pieces, once characterized, were placed inside either CE-2B baskets or special inserts for more highly activated pieces that were handled in the same manner as used fuel. These containers were placed at several locations in the reactor cavity and SFP. Filling of the containers took place underwater. Once filled, the containers were closed and either transferred out for conditioning and packaging, or introduced into storage canisters similar to those used for fuel, using the same transfer cask and tools.

The project duration was 36 months. The total collective dose received by workers and operators was 283 man-mSv, and the maximum individual dose was 11 mSv.

Lessons learned from the project include [24]:

- A good upfront characterization of the vessel and internals is key for an accurate waste packaging and acceptance for waste transportation and final disposal.
- A detailed cutting and packaging plan, based on a 3-D model, is needed for facilitating the segmentation operation on site.
- In old plants, some plant functions do not exist or do not fit the specific needs anymore: for example, electricity, compressed air, water filtration, working bridge.
- The optimum dismantling strategy sometimes requires significant civil work modifications.
- Maintenance and repair of equipment must always be considered

Each RVI is different and not standard, so the process must be automated on a project-specific basis. Precision and repetition are required and the project is complex and challenging. A solid experience base, has however been achieved on the remote operation. Therefore some further automation may be possible, resulting in potential schedule and cost reductions. As an alternative to automation of the whole process, some sub-processes may be able to be optimized, such as spare parts replacement, characterization or waste handling.

5.1.1.2 Non-Mechanical Cutting Methods

Cutting of internals and vessels using non-mechanical methods such as Plasma Arc, Contact Arc Metal and Abrasive Water Suspension Jet (WAS) techniques has been conducted in Germany [25] and in earlier decommissioning projects in the U.S. [23]. During these applications, the reactor internals were cut under water, with cuts typically observed from different angles by several cameras, as is done during mechanical cutting.

As an example of use of robotics and automation in existing systems, multi-axial manipulation systems were used to perform WAS cutting of complex structures [26]. All axes were remotely operated individually and were either servo-hydraulically or servo-electrically driven. The linear manipulation system was flexibly fixed by pneumatic clamping mechanics in the holes of the different grids and plates to be cut. The cutting nozzle could be moved by 3 axes in x, y and z direction, allowing cutting of individually shaped sections. A position sensor was an integrated component to the Control Unit. It reported the current location of the cutting nozzle. Targeted to meet the flexibility requirement and to allow cutting complex shaped sections, a ring chassis was positioned outside the reactor pressure vessel. A servo-electric driven carriage allowed 360° rotations in the circumferential direction to allow both horizontal and vertical cuts. The manipulation systems were controlled by a single customized PLC-based 4-axis servo-control unit. The operator communicated the commands to the servo-control through a touch-screen on a mobile control panel.

Prior to an actual WAS cut, reference runs were conducted and recorded. The recorded profiles were used in future cutting tasks of the same kind. Reproducible cutting profiles offer the benefit of reduced set-up times.

During reference runs and actual cuts, the mobile control panel reported the direction of movement, traversing speed and actual position of the cutting nozzle. Together with live stream images of the cameras, the operator had full control of the WAS cuts. Confirmation that the corresponding section was completely cut through was generally determined visually. If the view of the section to be cut was obstructed, an under-water acoustic sensor (hydrophone) was used to confirm that the cut was completed.

5.1.2 Potential Solutions

5.1.2.1 MAESTRO

Cybernetix, based in France, has been providing remote operated systems for the past fifteen years to the French nuclear industry for the maintenance, inspection and repair of nuclear research and reactor facilities. Working with the CEA (French Atomic Energy and Alternative Energies Commission), Cybernetix has engineered various “slave” arm telemanipulation systems such as MAESTRO, which has been used for applications in France and other countries [27]. The MAESTRO system, depicted in Figure 5-1 comprises a toolbox of various components that can be assembled to perform virtually any telerobotic task in a nuclear environment.



Figure 5-1
MAESTRO System Slave (a) and Master (b) Arms [27]

The MAESTRO system includes:

- A 2.34m long, 60 kg payload capacity, slave hydraulic manipulator with 6 degrees of freedom, and a tool changer
- An embedded hydraulic power pack
- An embedded electronic controller
- A complete set of tools for dismantling and maintenance (nibbler, gamma camera, drill, laser torch, offset screwdriver, video camera, IF104 radiation probe, screwdriver, disk grinder, hydraulic shears, alternating saw)
- A control system with a wide range of control modes, including 3D model based control
- Two pan and tilt cameras with a specific controller to automatically follow the tools

Large components at the Belgian research reactor BR3, including the RPV head and bottom, pressurizer and steam generator, were segmented using high pressure water jet cutting deployed by a MAESTRO arm manipulator.

The CEA is also exploring use of laser cutting technology that could potentially be deployed using the MAESTRO system. CEA noted benefits of laser technology are [27]:

- Cutting capability in air of ~1cm/kW and complex geometries
- Less secondary waste than most of other thermal techniques, especially for spray and dust
 - Power can be optimized to minimize aerosol production

- High flexibility on cutting tool positioning for better control of cuts
- Limited production of kerf (loss of mass of the cut piece) due to the thin cut line
- Easily automated - no mechanical stress in the robotic arm and possibility to transport the laser power up to 100m with a coupler and two fibers
- Robustness and simplicity of tools
- Use of compressed air to clear cuts (minimizes secondary waste generation)

CEA noted that disadvantages include

- Difficult to start a cut in the middle of a piece
- Attention should also be paid to the structure behind the item to be cut to avoid damage by the laser.

5.1.2.2 Laser Snake 2 – OC Robotics Trials

A collaborative research and development pilot project, building upon LaserSnake feasibility, study was undertaken by OC Robotics, co-funded by Industry, Innovate UK, the Nuclear Decommissioning Authority and the Department of Energy and Climate Change to develop long reach snake-arm robots to operate in nuclear environments (air and water); development of laser cutting process heads, optics, and diffractive optics for nuclear decommissioning; and to integrate snake-arm robots and mobile platforms for the exploration of complex spaces [27]. Consideration was also given to the regulatory and certification issues associated with tele-operated delivery of laser cutting solutions for the nuclear sector.

The project purpose was to:

- Demonstrate that a 5kW laser can cut material representative of that found in redundant nuclear plant
- Demonstrate that the snake-arm is capable of deploying the laser head in a controlled manner, with sufficient dexterity to exploit the versatility of laser cutting
- Demonstrate the ease with which the arm can be deployed into desired plant areas
- Demonstrate that the technique can be used safely in an area not specifically designed for laser cutting
- Investigating the damage caused to surrounding plant as a result of laser cutting
- Investigating the effect of airborne particulate on local ventilation filtration

Gouge cutting and under water laser cutting was conducted by TWI. The articulated reach of the snake arm was increased from 1.5m to 4.5m. Submerged trials were conducted during 2015 and early 2016 using sleeved and pressurized snake arms. The goal was equipment deployment at FGRP at Sellafield in the spring of 2016.



*Figure 5-2
Gouge Cutting and 1.5m, 100mm Diameter Snake Arm [27]*

5.1.2.3 CHARLI

Designed by AREVA, the CHARLI robot equipped with a robotic arm fitted with a laser cutting head and cameras was used to cut piping in 2013 during the decommissioning of the Superphenix fast neutron reactor in France [28]. The robot was designed to move around confined pipework structures and function in very harsh environments with high levels of radiation, high temperatures, and the presence of sodium, aerosols, and argon.

5.1.3 Unresolved Challenges and Conclusions

Reactor internal segmentation has not yet been standardized or optimized to the extent that it can be operated automatically and routinely. Techniques using currently available systems have been effective, but require significant operation and oversight, and have often been challenged. There is significant room for opportunity to both further automate existing cutting methods, and also to test and use new techniques.

Further automation of successfully deployed mechanical cutting should be pursued. Additionally, the support systems and activities to these operations, including repair and maintenance of the system, should be further explored as these may take up to 80% of the cost. Automation of the collection and removal of cutting debris is an area where improvements could also be made.

Investigation of the potential benefits of alternative cutting technologies such as laser cutting or the arc saw should continue to be pursued. A commitment to continuous improvement of technology and the desire to invest and develop better methods is required for the nuclear industry to develop effectively, especially in this most expensive, time consuming and safety sensitive task.

5.2 Segment, Package, Dispose of Reactor Pressure Vessel

In some cases, the reactor vessel does not have to be segmented and can be treated as a large component (to-date, primarily in the U.S.). Where a decision is made to segment the reactor vessel, it would have to be segmented and shipped in different packages, and it is a high exposure task. Shielding is needed for personnel radiological concerns. Some similar thought processes are required for segmentation of the reactor vessel as are required for the reactor internals. Cutting technologies (existing and potential alternatives) have previously been discussed, including how these can be automated, issues with water clarity and handling of cutting debris. The items discussed in Section 5.1 will not be repeated here. Rather specific items relating to segmenting the reactor vessel will be explored.

5.2.1 Existing Solutions

5.2.1.1 José Cabrera Reactor Vessel Segmentation

The José Cabrera reactor vessel was lifted remotely and placed in the spent fuel pool for segmentation [27]. Preparatory activities for vessel cutting included:

- Installing new heavy load movement equipment
- Installing a vessel support structure to keep the reactor vessel vertical
- Cutting intra-nuclear instrumentation tubes
- Removing the reactor cavity sealing ring
- Removing the neutron shield ring and supports
- Preparing the floor of the spent fuel pool
- Cutting the vessel connection pipes (safety injection and main pipes)
- Transferring the vessel to the spent fuel pool
- Removing the reflective insulation
- Mounting lifting elements in the vessel flange
- Securing the vessel on its support
- Sealing the reactor cavity
- Increasing the water level in the spent fuel pool

The vessel was segmented into 120 pieces according to a segmentation plan developed based on the initial characterization results and the size of the concrete containers acceptable at the disposal facility. All packages were grouted before disposal. Cutting was performed under water using the band saw, disc saw, drilling tool and shear tools. These tools were manually monitored, and operated hydraulically from the spent fuel pool bridge as was done for cutting the reactor vessel internals. The tools were configured to easily change cut direction.

José Cabrera report that the reuse of some of the equipment utilized previously for the segmentation of the reactor internals helped the vessel segmentation project to be performed less expensively and on a shorter schedule. Additionally, the collective dose was minimized and waste volume reduced by using an optimum cutting pattern. A hexagonal cut was made with disc saw of the vessel bottom to install the band saw column, then vertical and horizontal cuts of the vessel wall were made with the band saw tool.



*Figure 5-3
Making Vertical Cuts to the Vessel at José Cabrera [27]*

For packaging pieces of the vessel, different types of containers were used depending on the size, weight and radiation level of the pieces: 6 CE-2a baskets with a load of between 7,400 and 8.500 kg (Vessel); and 1,000 kg (chip boxes). Packaging of the vessel is shown in Figure 5-4.

Potential activities that could have used robotics are the cutting of the intra-nuclear instrumentation tubes, the vessel connection pipes and the vessel, potentially using robotic arms.

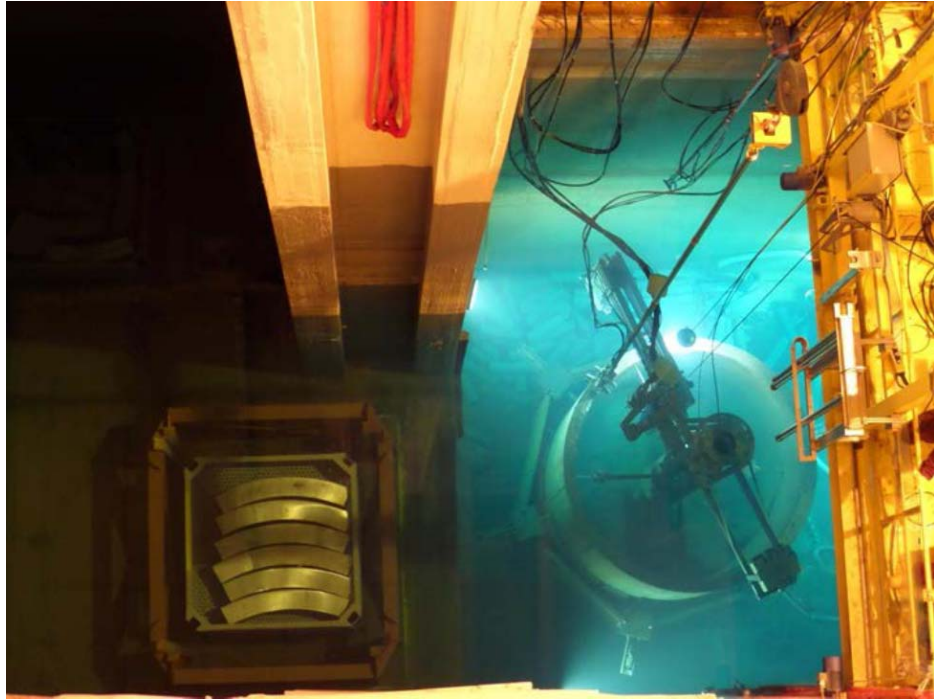


*Figure 5-4
Packaging the Segmented Reactor Vessel Pieces at José Cabrera [27]*

5.2.1.2 Diamond Wire Cutting

Engineers at the Princeton Plasma Physics Laboratory (PPPL) undertook an investigation of diamond wire cutting technology for the dismantlement of the Tokamak Fusion Test Reactor (TFTR) vacuum vessel [29]. In August 1999, this technology was successfully demonstrated and evaluated on vacuum vessel surrogates. Subsequently, the technology was improved and redesigned for the actual cutting of the vacuum vessel. Ten complete cuts were performed in a 6-month period to complete the removal of this unprecedented type of dismantlement activity.

Diamond wire cutting is performed remotely after the initial setup of the wire and hydraulic control systems. A hydraulic motor drives the main drive saw, which is aligned with the direction of the cut. The wire is wrapped around the drive wheel and object to be cut. An electro-hydraulic power unit drives the saw and puts force on the wire. This power unit can be placed up to at least 25 feet (7.6 m) from the cutting location, depending on the length of hydraulic hose selected. This arrangement minimizes the risk of injury.

To successfully cut the complex TFTR vacuum chamber safely at the lowest cost while maximizing worker health and safety, several devices and controls had to be developed. An automated pulley system was designed and installed to control the approach angle of the diamond wire to the vacuum vessel. The approach angle was critical to proper cutting while eliminating the possibility of wire failure due to the extremely sharp edges created when cutting the various layers of metals.

The pulleys were mounted on a control shaft and moved by remote control using servomotors. The design provided for two types of cutting approaches. The more common approach of pulling the wire toward the saw and then what is referred to as a “push cut,” where the wire cuts into the object and moves away from the saw. This is much like a band saw.

The automated pulley system further improved the cutting and also prevented wire failure. It is possible that this technique could be further automated.

5.2.1.3 Greifswald NPP, Germany

Remote dismantling was performed using a band saw for the reactor pressure vessel, plasma arc for the upper part of the reactor cavity, and disc cutter for the upper part of the protection tube unit. All of this work was performed dry. Cutting was performed using a band saw for the core basket, contact arc metal cutting for the lower part of the protection tube unit, plasma arc for the lower part of the reactor cavity, and a fret saw for the cavity bottom. All of these operations were performed wet [2].

5.2.1.4 Karlsruhe Research Center

Dismantlement of the reactor vessel at the sodium cooled 21MW KNK reactor at Karlsruhe was performed using remote equipment. This included the following components used for the cutting, transport and conditioning steps [2]:

- Milling machine
- Crane to position the milling machine
- Load manipulator to handle cut pieces and tools
- A second crane to handle transport baskets
- Master-slave manipulators to handle smaller tools

The milling machine was used to segment the reactor vessel from the inside-out. The milling machine comprised a disassembly manipulator system that provided six axes to allow access to all required cutting positions using end mills or side milling cutters.

Key features of the milling machine included:

- A hydraulic self-centering system to fix position within the reactor vessel
- Four-coordinate electrical drives
- Hydraulic drives for the milling modules
- Displacement and rotation sensors for each axis
- Control console to pre-set process parameters and control axis position
- Video and audio capability to monitor the milling process

The cutting process was slower than expected because the rigidity of the manipulator arms was insufficient to counter the reaction forces of the milling cutters. This greatly affected the efficiency of the milling process. In fact, in some cases the milling tool became too hot and started glowing.

This experience underscores the importance of a robust engineering phase and mock-up testing program for new cutting systems that include an in-depth study and critical assessment of equipment capabilities and limitations. The Karlsruhe team generally concluded that preference should be given to well-proven conventional tools – customized if necessary – unless the performance of alternative equipment can be clearly established.

5.2.1.5 Chicago Pile Reactor, Argonne National Laboratory

A Dual Arm Work Platform (DAWP) was used to perform mechanical dismantlement of the radioactive reactor and bio-shield structures [16]. The DAWP manipulated standard, commercially available tools (that is, circular saws, jackhammers, and so on) using two Schilling Titan III six degrees of freedom hydraulic, tele-operated manipulator arms controlled from a remote location. The two arms were mounted to a steel work platform designed to hold the associated tooling, utilities, and cameras supporting the operation of the manipulator arms.

The DAWP provided for control of five electrical and two hydraulic tools, had a remote viewing system, a lighting system, and a tool control system. The DAWP was designed to minimize the on-board electronics and hydraulic valves for radiation tolerance, and to facilitate decontamination and so a relatively large diameter tether linked the platform to the hydraulics source and control system.

The control hardware rack and the hydraulic power unit (HPU) were mounted in the basement away from the radiation and contamination hazards expected in the reactor shell. The DAWP operator control station consisted of a video console, control chair, master controller station, and the Virtual window stereo viewing system.

Based on the application at the Chicago Pile 5 reactor, the following lessons learned and areas for improvement were identified:

The following are highlights of the lessons learned:

- Setup time and complexity were considerable; improvements could be achieved through use of a control trailer for the operator station and standardized pallets for in-facility control hardware to minimize impact on the facility where the equipment is to be used.
- Relatively expensive, environmentally sealed electrical connectors were used for the electrical tool connection to the base platform in order to permit wash-down decontamination of the system. Practical experience in operation and decontamination has shown that standard covered AC outlets rated for outdoor use should be sufficient.

- Commercially available dome cameras were used on DAWP in order to control cost and to permit greater field of view coverage. These cameras have had some problem with glare and bloom due to the lighting in the reactor shell and have also had mechanical failures in the motorized lenses. More robust cameras could be considered but have roughly a cost increase factor of three. The cheaper cameras have not had any radiation related failures.
- Control tether management is one of the most difficult and critical issues when maneuvering DAWP; improvement could be achieved through use of a custom made tether and tether management system.
- Some maintenance activities required that the manipulator arm be sent back to the manufacturer for repairs, and a considerable source of down time was attributed to shipping out one or both arms for maintenance. A field system should include a third spare arm, and the field team should include a nuclear technician trained in the maintenance of the DAWP.

5.2.2 Potential Solutions and Unresolved Challenges

Generally, very similar considerations discussed in Sections 5.1.2 and 5.1.3 for segmentation of reactor internals also apply to segmentation of the reactor vessel. The primary difference in the two components is that the vessel is relatively less activated. This provides additional flexibility in segmentation techniques, including the potential for segmentation in air as opposed to underwater, as described in Section 5.2.1.3 for operations at Greifswald.

5.3 Remove, Segment and Dispose of Large Components

Large components include the reactor head, steam generators, reactor coolant pumps and the pressurizer. For completion, removal and disposal of the spent fuel storage racks is also considered in this section.

5.3.1 Existing Solutions

In Reference [30], the NEA provides a good overview of the various approaches to the decommissioning of large components including reactor heads, steam generators, pressurizers, and reactor coolant pumps. Segmentation of large components requires cutting of metals in a variety of geometries and configurations, from thick-walled vessels to thin-walled piping. Additionally, component access may be difficult and handling the components or cut segments may be challenging due to space limitations and obstructions. Further, waste minimization requires optimization of waste packaging, which places further constraints on cutting operations.

At Belgian Reactor 3 (BR3), large contaminated components including the pressurizer and the steam generator were segmented into large pieces using high-pressure abrasive water-jet cutting. The cutting head was positioned using the MAESTRO arm. The steam generator was placed upside down in the reactor pool and was cut with the high pressure abrasive water jet cutting tool in a static

position. Segmentation of the steam generator tube U bends was performed with the cutting tool in a fixed position. The straight sections of the steam generator tubes were segmented using diamond-wire cutting. Automation could be considered for this process.

The upper portions of the Unit 1 steam generators at Zion were segmented in place to facilitate the future removal of the lower portions. The upper portions were packaged and loaded into railcars for transport to and disposal at EnergySolutions' low-level waste disposal facility located in Clive, Utah.

Diamond wire cutting was used to cut the steam vessels at Winfrith's Steam Generating Heavy Water Reactor in England. A single operator controlled the cut of the nose of the steam vessel remotely.

The SFP racks at José Cabrera were removed and water jet decontaminated before being cut by mechanical shearing and managed as LILW. [24]. The spent fuel racks were removed from the Spent Fuel Pool at Zion and directly loaded into supersacs for disposal where possible. Other racks were coated with fixative, segmented in the dry cask pit using diamond wire saw cutting, cooled with water to control airborne contamination. This resulted in contamination challenges. Fixative was again applied prior to disposal. At Humboldt Bay, the spent fuel pool storage racks were coated with fixatives and grouted prior to shipment to prevent movement of contamination during transportation. Robotics or automation may be used to cut, remove and place the spent fuel pool racks in final storage containers for final burial.

5.3.2 Potential Solutions

5.3.2.1 Size Reduction Machine

The Size Reduction Machine (SRM) is a hydraulic shear attached to a hydraulically controlled arm that is mated to a manually deployed base unit (see Figure 5-5). It allows shearing from 1' (0.3 m) below floor level to 15' (4.5) above the floor without requiring the direct physical movement and placement of the shear head by the operator [16].

The shear can handle stainless steel components including pipe up to 4" in (10 cm) diameter. The base unit contains the electronics, hydraulic pumps, tanks, servos, and actuators needed to move the shear positioning arm, and operate the shear head and material gripper (handler). The functions are controlled by a tethered control panel that uses individual joysticks to control directional movements. The hydraulically controlled moveable arm provides the ability for the shear head to have 6 axis of movement and to cut to within 4" (10 cm) of a wall surface. The unit is electrically powered using a 220-volt, single phase, 60-amp source. The unit has an electrostatic capture coating finish that assists in external decontamination of the surface. Internal contamination of the unit is controlled by using a HEPA filter on the equipment cooling air inlet. Access to the equipment in the base unit is through two hinged doors with quick release

closures. The unit is small enough to go through standard 3' (0.9 m) wide doors to access work areas. Despite the SRM's weight of approximately 1400 pounds (636 kg), it is easily moved by two operators. A power source must be available at work location or extension cords must be long enough to reach the desired location.

The SRM has a niche between the hand held technologies and larger platforms such as Brokk units. It allows remote and fast cutting with reduced potential for injury.

Because of its inability to perform certain cut locations and configurations because of the shear jaw size, it would be used in conjunction with and supplement manual cutting technologies, and where size reduction of piping, conduits, and components less than 4" (10 cm) is necessary. Orientation of component being cut is also sometimes critical to cut success.

The DOE reported that motorizing the base unit would reduce overall setup and cutting time, and that a laser range pointer with a homing device on the shear head would assist in rapid placement and final maneuvering of the shear head. An onboard computer would also make it possible for the unit to automatically cycle through repetitive motions. A larger shear (8-inch [20 cm]) could also easily be accommodated on the SRM in place of the current 6-inch (15 cm) size, increasing the cutting capacity.



Figure 5-5
Size Reduction Machine

5.3.2.2 DOE Tri Tool Inc. High-Speed Clamshell Pipe Cutter

The High-Speed Clamshell Pipe Cutter is used to cut large-bore piping and conduits [16]. The high-speed units are portable split-frame pipe lathes that can sever and/or bevel in-line pipes 25- cm to 61-cm nominal diameter. A key feature of the high-speed units is field-adjustable bearings that pre-load and stabilize the rotating head to improve life, stability, and precision, and reduce the amount of maintenance required. The improved technology demonstrated can sever pipe with higher cutting speeds than conventional clamshell lathes.

The equipment is relatively easy to use where pipes are somewhat close together and near walls. It is relatively easy for two persons to set up and workers can learn the cutting technique quickly without having to be qualified as welders. An alternating current power source is required for the hydraulic pump.



*Figure 5-6
High Speed Clamshell Cutter During Demonstrations at Hanford [16]*

Clamshell lathes are portable and especially useful for segmenting fixed pipe for size reduction of large pipe sections. The cutter technology is equally well-suited for indoor and outdoor work. The technology can be applied in environments where flame cutting is unsafe or not useable. This technology is of particular value at sites where piping and conduit may be internally or externally contaminated because it can be operated remotely.

The High-Speed Clamshell Pipe Cutter technology is competitive with other cutting and segmentation technologies such as using an oxyacetylene torch. Cutting time using the high-speed clamshell lathe for 3-cm walls and 61-cm diameter pipe is approximately half that required for the baseline oxyacetylene torch technique. Similar high-speed clamshell pipe cutters are available from

PCI Energy Services (Lake Bluff, Illinois). The method is, however, expensive, both in terms of equipment costs, either to rent or own, training (considered to be necessary for proper operation), and the time required to attach and detach from the pipe.

The technology can be used for interior and exterior conduit and is well-suited for cutting exposed pipes located more than 18 cm (7 in.) away from the wall. Because there is no heat or smoke generation, Clamshell Pipe Cutters reduce the risk of creating airborne contamination while segmenting internally or externally contaminated pipes and conduits. It is therefore particularly useful where the piping is highly contaminated. A similar cutter manufactured by E. H. Wachs was successfully used for pipe segmentation at Humboldt Bay where there was significant alpha contamination, for example [23]. It may also be particularly useful in applications where a very even and/or symmetrical cut is needed (that is, where precise welding to the cut pipe is to be performed).

To optimize operations, future efforts should focus on reducing setup and cutting time, and increasing cutting bit life.

5.3.2.3 ARTISAN

West Valley Environmental Services, in partnership with Nuvision Engineering, Inc., developed a robotic arm (ARTISAN) to remove thousands of feet of small diameter piping (5 cm to 20 cm), and structural steel (up to 20 cm) from a chemical processing cell [2]. The robotic arm was fitted with a mechanical shear for 5 cm piping, a band saw for 15 cm piping, and a circular saw for structural steel. The arm was fitted with a remotely operated wrench to allow disassembly and removal of bolted tanks. The ARTISAN arm performed beyond expectations, and substantially reduced personnel radiation exposure during the dismantling operation.

There may be a possible use for this manipulator for removal and cutting of piping, although the system deployed at West Valley had limited capabilities for larger diameter piping. The equipment may be useful to crimp or shear the piping for increased contamination control and could potentially be deployed by a mobile robot to limit set up.

5.3.3 Unresolved Challenges and Conclusions

The increased use of 3D imaging and laser modelling may be appropriate for segmentation of large components to allow for the planning of the segmentation of these items or for their cutting prior to removal intact. Segmentation of large components other than the reactor vessel and internals is generally less challenging due to lower dose rates. This provides greater flexibility with respect to technology selection, but also correspondingly reduces the potential benefit from use of robotic and automated systems. Making cutting systems that can be used on multiple components and types of components would be useful. This would allow deployment costs to be distributed between multiple components and activities.



Section 6: Conduct of Surveys

The following tasks are reviewed in sections 6.1 to 6.2.

- Radiological Survey of Structures during Decontamination (Consider for Robotics/Automation)
- Final Status Survey (Consider for Automation)

6.1 Radiological Survey of Structures During Decontamination

6.1.1 Existing Solutions

In situ object counting systems (ISOCs) use a high purity germanium gamma detector with modelling software to provide highly accurate estimates of activity in volumetric sources. ISOCs has been widely used in decommissioning to characterize concrete structures and land-areas. An example is the recent application at Zion to assay 28 m² areas of un-impacted lands to verify there were no plant-related radionuclides in the un-impacted survey units.

New Millennium Nuclear Technologies supported Southern California Edison with the deployment of a system with automated components for the collection and profiling of concrete samples from the bioshield, concrete slabs and containment walls [32]. The system comprises a drill with a specialized cutting and sampling head, a tungsten carbide drill bit, a sample collection unit, a vacuum pump, and calibrated portable radiometric instruments. The equipment pulverizes the bulk concrete material and transmits representative powdered samples to a two-stage vacuum sample retrieval unit, and subsequent optimal counting by gamma spectroscopy. The result was an estimated cost savings of \$300,000 for overall waste management sampling and planning efficiency for every 3 inches of annulus concrete proven to be Low Level Waste prior to disposal.

6.1.2 Potential Solutions

Detection equipment is generally light weight and highly adaptable for remote operation. This includes radioactivity measurement, detection and imaging systems, as well as sampling equipment. Additionally, this equipment can be combined with positioning and recording units such as Global Positioning System (GPS) units, cameras, LIDAR and wireless data transmission units to create self-contained survey systems.

6.1.2.1 Gamma Imaging Techniques

There is a number of new gamma imaging technologies on the market that are similar but with subtle differences. This technology could be used to change the way survey data is gathered, or at least to complement the data and reduce the amount of survey information required.

Polaris-H

Polaris-H is a battery-operated system that weighs less than 5 kg, with an integrated optical camera that overlays a gamma-ray image for each isotope the system identifies. Individually selected isotopes or all isotopes can be displayed. The energy resolution is near 1% FWHM at 662 keV and the detector can localize gamma-ray sources in all directions simultaneously. It is ready to use within two minutes of pressing the power button. It is airtight and watertight for easy decontamination. A tablet connects wirelessly for real-time display of the spectrum and image some distance away. The detector technology is CdZnTe (CZT) [33]. The Polaris-H gamma-ray camera can be set up for remote use for multiple purposes.

The system can be used to image a large region in a single measurement and hot spots will appear over any discrete particles, which can be difficult to identify with a survey meter. This was used in several cases at the DC Cook plant to identify discrete particles not previously identified. The system could be used for site characterization prior to decommissioning to gather data relevant to decommissioning.

The high imaging efficiency of the detector means that it can make an image of gamma-ray intensity isotope-by-isotope in a reasonable time, even near background levels. Given enough count time left in an area, the detector is capable of detecting and imaging sources weaker than natural radiation background.

Although there is no recorded use of the Polaris in decommissioning, the portability and capability of the system would allow the system to have significant potential use. The LLDs of the system have not, however, yet been defined. Use of the system in the free release of an area (see Section 6.2) would require calibration of the system, which to date has not been accomplished, but this is an area that could benefit from further investigation and work.

N-Visage™

Createc, based in Cumbria, UK, designed a camera system, N-Visage, that was mounted onto remote-controlled drones and caterpillar-tracked robots for the visualization of radiation inside the Fukushima reactor buildings [37]. N-Visage operates the identical product in the US under the name “RadVision” [34]. The

£150,000 (approximately \$199,000) system is able to create a real-time, three-dimensional image of the area being surveyed and identify hot spots of radioactivity. Figure 6-1 shows one of the hot spots inside a reactor building. Specifications of the N-Visage Camera include:

- Semiconductor elements, laser range finders (LRF) and fish-eye cameras are installed to enable 360-degree spherical scanning
- Size: 110 mm (D) x 700 mm (H)
- Weight: 17 kg (with a Control Box of ~ 6 kg)
- Detection Element: Semiconductor sensor
- Measurable Range: 0.05 mSv/h to 500 mSv/h
- Scanning Time: Approximately 2.5 to 3.0 hours/scan

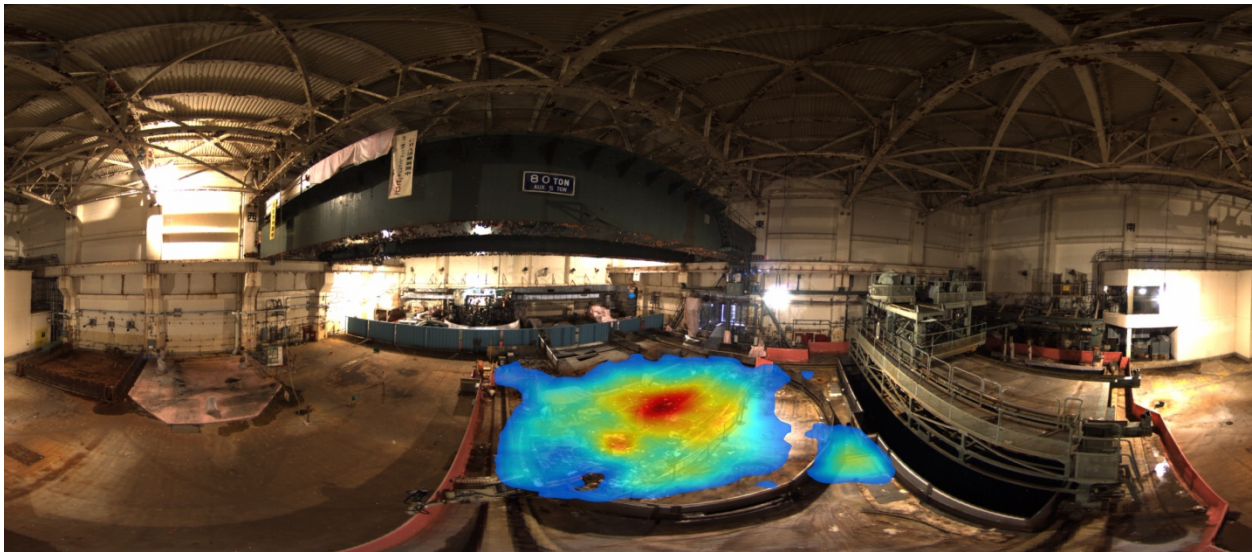


Figure 6-1
Image of a Hot Spot Mapped inside a Fukushima Reactor
Photo courtesy of Createc

The N-Visage software system combines laser scanning and gamma camera radiation data to generate a 3-D map of where the radioactive sources are potentially located within a building [1]. The 3D point cloud data can be obtained from the N-Visage Camera or input from an existing survey.

The Sellafield Separation Plant [1] used the NVisage gamma camera in concert with a Laser Scanner modelling system to perform radiological characterization of a processing cell. The system was used to create a 3-D radiological map of the shear cell by integration of laser scanning data with radiological data from the gamma scanner. This is an example of work that can be used to remotely survey and construct 3D files for use in decommissioning planning and site characterization, (including, for example, geostatistical evaluation of radiological and geometrical data).

RadSearch Gamma Camera

The ANTECH RadSearch radiation detection, survey and measurement device was demonstrated during a campaign of measurements at the Alpha Gamma Hot Cell Facility at Argonne National Laboratory [35]. The instrument contains a sensitive and highly collimated LaBr scintillation detector with a video camera and a laser range finder. The detector head with pan/tilt function is normally mounted on a tripod or wheeled cart, but can also be mounted on vehicles or a mobile robot for delivery to high dose rate and/or high contamination areas. The operation of RadSearch is controlled from a remote monitoring station and can be connected via cable or operated remotely by wireless up to 80 meters away.

RadSearch was shown to quantify multiple distributed sources (Co-60; Cs-137; and Eu-152), determine surface activity, and identify and quantify different radionuclides during testing at a hot cell in Argonne National Laboratory, which validated its ability as a tool for decommissioning.

RadSearch Specifications include:

- One-inch lanthanum bromide (LaBr) gamma-ray scintillation detector
- Energy range: 30 keV to 2,000 keV
- Energy resolution: 2.5 to 3% FWHM
- Pan/tilt with range of motion +/- 180 degrees pan; +/- 90 degrees tilt
- Total weight: 53.2 kg
- Set-up time: 10 minutes
- Power supply: 110 or 240 VAC

3D GammaModeler

The 3-D GammaModeler™ visual and gamma ray imaging system was developed by AIL Systems Inc. to remotely survey large areas for gamma-ray emissions and display the results as combined 3-D representations of the radiation sources and the equipment [16]. The GammaModeler™ system is an upgrade of the AIL GammaCam™ system that provides 2-D images of the radiation environment overlaid on the video picture of the scene.

The 3-D GammaModeler™ system comprises four modules: a sensor head, a portable computer, a pan and tilt controller, and a 3-D workstation. The sensor head incorporates a coded aperture gamma ray imaging detector, a high-resolution video camera, a laser range finder, and a pan and tilt assembly. The sensor head is controlled remotely by the computer and the pan and tilt controller. The pan and tilt assembly allows the sensor head to be panned a full 360° and tilted +/- 73°. Remote operation and control of the sensor head allows for safe image acquisition in high radiation environments, minimizing operator exposure. During image taking operation, a pseudo-color image of gamma ray emitting sources is overlaid on the video picture of the scene.

At each camera location with observed gamma ray emissions, additional images are taken of key reference features in the scene along with the measured range, and pan and tilt directions to these features. Viewing the same features from another location allows the relative camera positions to be calculated. These calculated camera positions are adjusted to place the object at a desired position or an absolute position if known. Knowledge of the camera locations is essential to triangulating the observed gamma sources in the 2-D images in order to position the sources in three dimensions. The visual and gamma radiation results are saved in digital format and can be easily archived for a permanent record of the measurement survey. This may be useful in characterization.

RadScan

British Nuclear Fuels Ltd. (BNFL) developed the RadScan 600 gamma-ray imaging system to perform surface characterization of contaminated sites. This system operates at stand-off distance of up to 30 cm, and provides real-time data on surface gamma concentration levels. The single-detector system performs gamma spectroscopy to identify contamination levels, isotopic concentrations and dose rates [1].

6.1.2.2 Imaging Systems

Laser imaging acquisition and data processing systems are available on the open market and have applications in the characterization of complex and/or hazardous facilities for the purposes of planning decommissioning projects [16].

A simple robotic platform integrated with a commercially available laser imaging/surveying system was used to generate as-built configurations of complex piping and equipment at the DOE Savannah River Site. Use of this equipment reduced radiation and conventional risks to personnel. This approach also avoided multiple dress-out events and possible personnel contamination to obtain comparable information. Wireless communications would have been desirable but could not be used because of the thick concrete walls in the reactor building. Wireless data transfer may not be essential if the robot must be tethered for adequate power supply.

A series of 200 photographs were used to create 3-D models of a robotic manipulator and cell systems and structures in France [1]. The 3-D model was used to develop a virtual reality mock-up that was used to practice and plan for the use of a robotic arm and end effectors to demolish the cell components.

An approach for autonomous robot navigation being developed at MIT uses an inexpensive, Microsoft Kinect sensor to map the entire 3-D space a robot would navigate. A feedback mechanism is used to store spatial data and use the information to identify changes in the memorized 3-D image. The navigation system is based on a technique called simultaneous localization and mapping (SLAM). The original system was based on robots fitted with more expensive laser scanners, but additional development testing has demonstrated that a robot can locate itself simply using a low-cost Kinect-like camera [1]. During testing,

the MIT team demonstrated that the robot could locate itself within a 3-D map of its surroundings while traveling at up to 1.5 m/sec. This approach to robot navigation is particularly promising for aerial robots, or those designed to operate in environments with stairs, ramps and other indoor architectural elements. 3-D modelling of a room or space may be as simple as driving a robot around and then downloading the image map from its memory [1].

6.1.2.3 Pipe Crawler

The Pipe Crawler comprises a visual inspection system (a high-resolution micro color camera with light heads, a monitor, and a video recorder) along with radiological detectors coupled to a dose rate meter [16]. Pipe Crawlers are available for 4.8 cm, 5 cm, 7.5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, and 60 cm pipe sizes. The crawler/detector is capable of visually and radiologically inspecting the inside of pipes, and pinpointing where in the pipe contamination exists. Individual detectors can be isolated for separate readings if necessary. The system is well suited for inspecting the interior of most types of piping. For applications performed to date, the camera and detectors have been pulled through a pipe using a tether or a push-pull fiberglass rod. As the assembly is pulled through the pipe to be inspected, the operator at the console looks for the presence of visual contamination and monitors the rate meter for radiological contamination. The operator at the console can give the camera operator directions about the required movements in the pipe in order to properly inspect the entire interior.

A crew of six workers would typically be used for pipe inspection with the Pipe Crawler: two workers would move the pieces of pipe into position for the camera, and would segregate the pieces based on the inspection results; one worker would operate the crawler; one would operate the video unit; and a fork lift operator and a radiological technician would also provide support, either part-time or full-time. The capital cost of the Pipe Crawler, including all components, is approximately \$130,000.

In tests on the pipe crawler, visible inspection of the inside of pipes that would otherwise have been impossible with the human eye was possible, allowing less expensive waste disposal options to be pursued. The Pipe Crawler could be used to monitor inaccessible pipes (for example, underground lines) and verify the absence of radiological contamination.

6.1.2.4 Other Remote Monitoring Techniques

OC Robotics snake arms (discussed earlier in Section 5.1.2.2) are also being tested with an omni-directional, untethered and Wi-Fi controlled vehicle so that a range of tools could be mounted at arm tip, providing additional freedom to explore complex structures. Oxford Mobile Robotics Group are currently demonstrating survey and inspection technologies using this technique [27]

Other developments include tiny spheres to monitor pipe internals, designed with the nuclear industry in mind. Tiny flexible robots are also being developed to perform surveillances in tight spaces, and silicone-based autonomous jellyfish robots that use water to generate energy, and synthetic muscles to propel themselves, have been developed by the United States Navy. The robotic jellyfish prototypes are also being evaluated for environmental monitoring and spill remediation [1].

6.1.2.5 Stack Characterization System

The Stack Characterization System (SCS) is a collaborative project with the Robotics and Energetic Systems Group (RESG) at Oak Ridge National Laboratory (ORNL) and the Applied Research Center (ARC) at Florida International University (FIU) [36]. The SCS is a robotic system that will be deployed into off-gas stacks located around the central campus at ORNL.

The SCS is a remotely operated, articulated radiological data recovery system designed to deploy down into off-gas stacks from the top when inserted using a crane. The battery-powered SCS is designed to stabilize itself against the stack walls and move various data recovery systems into areas of interest on the inner stack walls. Stabilization is provided by a tripod structure; sensors are mounted in a rotatable bipod underneath the tripod. Sensors include a beta/gamma/alpha detector, a removable contaminant multi-sample automated sampler, and a multi-core remote core drill. Multiple cameras provide remote task viewing, support for sampling and video documentation of the process. The system consists of surveying equipment capable of taking surface contamination samples, radiation readings and core samples as well as transmitting live video to its operators.

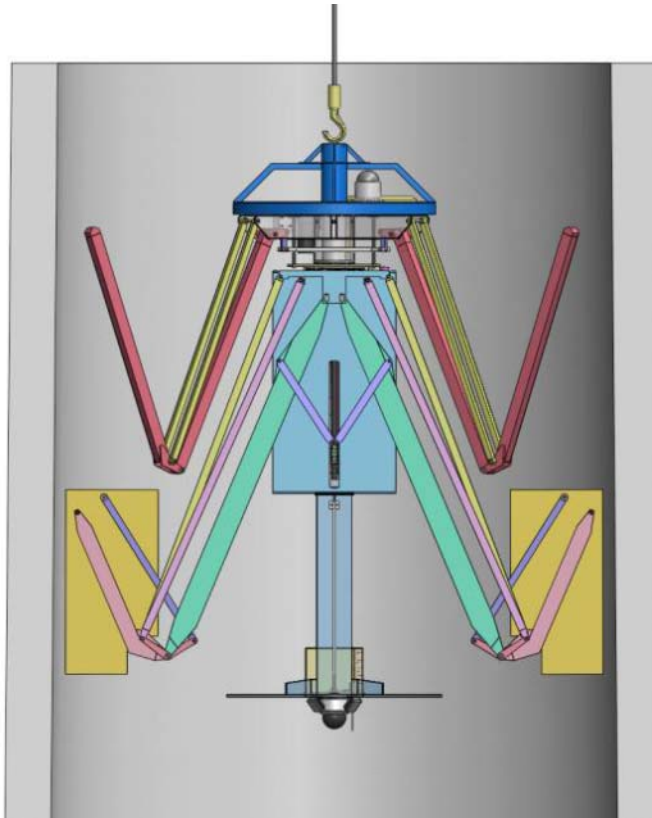


Figure 6-2
SCS in Retracted Position Inside Stack [36]

6.1.2.6 Monitoring and Robot Development at Fukushima

Existing robotics systems were deployed in a variety of applications within weeks after the accident at the Fukushima Daiichi Nuclear Power Station. Systems from S.A. Robotics/Technology, iRobot and QinetiQ Talon were outfitted with various sensor kits (chemical, biological, radiological, and explosivity) and cameras to perform inspections and monitor conditions inside the facility [1].

In a collaborative effort, Tokyo Electric Power Company (TEPCO), Toshiba, and International Research Institute for Nuclear Decommissioning, (IRID) developed a scorpion-shaped robot to investigate conditions of the melted-down fuel debris and the Unit 2 Primary Containment Vessel (PCV) at Fukushima Daiichi Nuclear Power Station in 2017. [11] About 54cm long, 9cm high and 9cm wide, and weighing about 5kg, the robot was designed to enter the unit's PCV along a pipe about 10cm in diameter. LED lights and cameras are attached to both the front and rear of the robot. The rear section, “like the tail of a scorpion,” can be raised to record video to obtain high spatial perception vision during investigation, (reason for calling it scorpion). The robot can operate for around ten hours in an environment with a dose rate of 100 Sieverts per hour and cumulated radiation tolerance is 1000 Gy or more. It is also fitted with a radiation dosimeter and a thermometer to measure conditions within the PCV [37].

During deployment, the robot passed along the control rod drive (CRD) rail within the containment vessel towards the pedestal area. However, when it was about three meters away from the pedestal, one of its crawler belts became stuck and the robot could not move. TEPCO decided to leave the robot where it was and disconnected the cable [38].



*Figure 6-3
Scorpion [37]*

A shape-changing robot began surveying conditions within the primary containment vessel (PCV) of the damaged unit 1 of the Fukushima Daiichi plant. However, the robot stopped working before completing its mission. The robot comprises a main body and two compact crawlers. The robot can assume a long, straight shape for passing through narrow spaces, such as pipes. Alternatively, it can rotate its crawlers by 90 degrees in relation to its central body to assume a U-shape, with the crawlers providing better stability when travelling over flat surfaces. The robot is 9cm in height. Depending on the position of its crawlers, it is 25cm to 64cm in length and between 6.5cm and 27cm in width. Weighing 7.5kg, the robot is operated via a 40m cable.

The robot travelled through a 10cm-diameter pipe to reach the inside of Unit 1's PCV. Although various robots have already been used in the investigation and clean-up of other parts of unit 1, as well as the other units at the plant, this marked the first time that a robot has entered any of the damaged units' PCVs.

After entering unit 1's PCV, the robot was lowered by cable onto the grating on the first floor outside the pedestal (the structure that supports the reactor containment vessel). Here it assumed a U-shape. It measured radiation and temperature levels, photographed the interior of the vessel. However, after taking measurements at 14 out of 18 planned points, the robot stopped working [39].

Toshiba Corporation and IRID have also developed a compact submersible robot to inspect the damaged primary containment vessel (PCV) of Fukushima Daiichi Nuclear Power Station Unit 3. The robot provides a platform for front and rear facing video cameras and their LED lights, and is powered and remotely controlled via wire. The operators can control its progress through the coolant and the PCV using four rear mounted and one front mounted thrusters. It delivers a video feed intended to determine the degree of damage to the PCV interior and information on how best to retrieve fuel debris. [40]

Finally, to inspect areas significantly contributing to radiation dose rates (hot spots) on the 1st floor of the Reactor Building in Units 1 to 3, a remote-control robot (crawler crane) mounted with gamma cameras has been deployed in the upper areas of the relevant floors. [41]

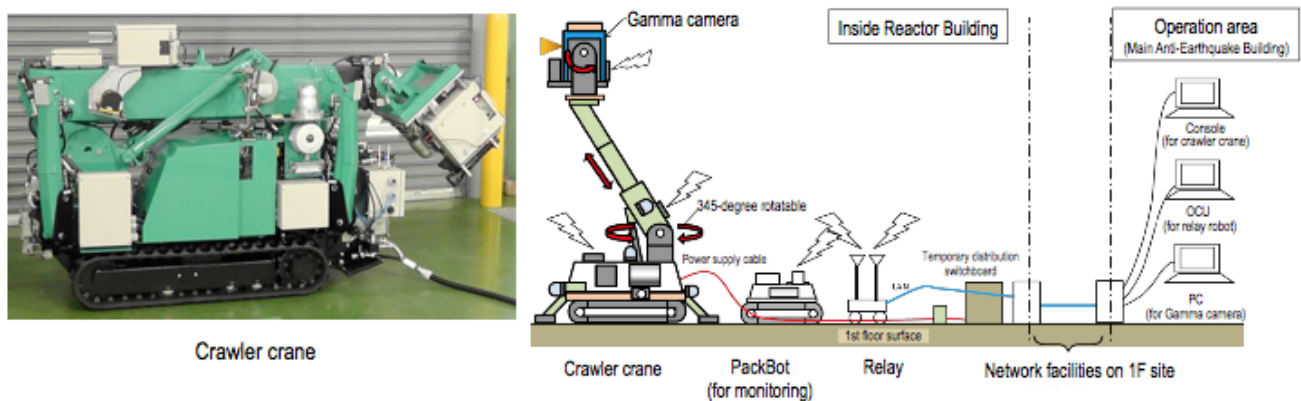


Figure 6-4
Crawler Crane [41]

6.1.3 Unresolved Challenges and Conclusions

Currently available systems for in-situ measurement have proven to be beneficial and use of these systems is becoming standard practice. The same trend could occur with gamma imaging systems, but they need to be more fully evaluated and demonstrated for use in a decommissioning environment to determine whether their use is cost effective. This includes consideration of how the systems may be combined with manual surveys to be the most beneficial. The combination of laser imaging along with the survey performance also looks particularly interesting.

OECD recommends the development of communication technologies including repeaters and routers to move signals in, out and within concrete structures and rooms, the use of RF power such as Wi-Fi Backscatter and Arbabian Radios, unique identifiers on transmitters and embedded in signals to enable assigning transmitter to a location, object, or person and integrated with RFID (radio-frequency identification) technologies for communication/storage/computation capacities in attachable tags. They recommend research to be conducted on wireless monitoring and reporting capabilities for decommissioning laboratory and field equipment.

6.2 Final Status Survey

Most countries have adopted a sampling and survey regimen that is statistically based for final status surveys and sampling to demonstrate compliance with established site release criteria. These regimes typically require both scans and sampling of the full site, with 100% scans of areas that are likely to exceed the site release criteria. These efforts are very time consuming, and thus result in large labor costs.

6.2.1 Existing Solutions

6.2.1.1 GATOR

The Idaho National Laboratory, working with the U.S. DOE Office of Environmental Management Technical Assistance Program, developed and deployed a suite of remote and automated systems for the rapid scanning, characterization and analysis of surface soil contamination [42]. This included an advanced sodium iodide based data acquisition and management system, known as the GATOR. This was a gasoline-powered all-terrain utility vehicle manufactured by John Deere and modified by INL. The base vehicle costs approximately \$10,000 to \$15,000, and additional costs are incurred for the procurement and installation of the radiation detection system and other support equipment.

The system comprises a $4 \times 4 \times 16$ inch sodium iodide detector computer-based multichannel pulse height analyzer, global positioning system (GPS) and laptop computer integrated by INL software. The detector is suspended from the front of the vehicle at a height of 31 cm and the electronics are mounted on the vehicle bed, behind the driver. The GATOR was used to perform radiological scanning of large flat areas.

6.2.2 Potential Solutions

6.2.2.1 Spectral Gamma Probe

A Spectral Gamma Probe designed for the in situ detection of radionuclides was developed by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) under the sponsorship of the U.S. Department of Energy for use as a site characterization tool at DOE waste sites containing radionuclides in the subsurface [16].

The enhanced Spectral Gamma Probe consists of a gamma radiation detection system that is driven into the subsurface using a Site Characterization and Analysis Penetrometer System (SCAPS) or other cone penetrometer truck. The sensor uses a NaI (sodium iodide) scintillation crystal to detect gamma radiation in the subsurface at the probe tip. Gamma rays emitted by the radioactive material are collected and this energy spectrum is analyzed to identify radioactive constituents and their relative concentrations.

The spectral gamma system comprises a sensor deployed in the subsurface by cone penetrometer rods, and a data acquisition system at the surface. The downhole system consists of a sodium iodide (NaI) detector and photomultiplier tube; a temperature sensor; and a custom-designed preamplifier. The data acquisition system is equipped with industry-standard, rack mounted nuclear instrument modules (NIMs) capable of data processing and storage. The spectral gamma probe is deployed with a cone penetrometer truck (CPT). As the CPT rods are advanced into the ground, the probe transmits analog signals, which are recorded in the data acquisition system. As the CPT rods are retracted, grout is injected effectively sealing the hole. A decontamination system is also used for the rod system.

The use of CPT and in situ measurement eliminates the requirement for sample collection, transportation and analysis and can reduce secondary waste from sampling. The use of the spectral gamma probe also results in a significant reduction risk of exposure during sample collection and analysis. However, the data reduction process for quantitative results is lengthy, requiring a trained nuclear physicist to perform the calculation. An automated data reduction program was under development at the time of the demonstration and would be required for this system to be of viable use.

Practical testing of the system showed that areas of gross radioactive contamination were easily detected and semi-quantitative results for Cs-137 could be determined directly in the field. The cost savings for the collection of 180 measurements using the Spectral Gamma Probe system was \$800,000. The in situ measurements made with the spectral gamma probe were found to be comparable to the laboratory measurements on the core samples, and the spectral gamma probe provides a more detailed profile of the contamination. The gamma probe was also able to detect areas of activity not identified by the grosser sampling method used for the laboratory analysis. The lower limit of detection (LLD) for Cs-137 appeared to be approximately 5 pCi/g (0.2 Bq/g). Weaker gamma emitters will have higher LLDs. The density and moisture content of the soil also affect the detection limit.

The use at the R-Reactor Basins at the Savannah River Site required only relatively shallow measurements. Pushing to greater depth (for example, > 130 ft [40 m]) or pushing in sites with challenging geology may require use of a heavier CPT truck and/or the use of the sonic head.

6.2.2.2 Soil Sampler

The Hanford Site C Reactor Technology Demonstration Group evaluated a compact subsurface soil investigation system developed by Geoprobe Systems of Salina, Kansas, for retrieving soil samples from below the C Reactor fuel storage basin concrete floor [16].

The fuel storage basin held large quantities of contaminated water for many years. Consequently, the possibility existed that the soils beneath the concrete floor were contaminated by water leaks. While it was agreed with the regulatory agencies that the parts of the concrete basin more than 4.6 m (15 ft) below ground level could remain in place, the soils below the basin presented an unknown risk because it could not be proven that the basin did not leak. A mobile yet rugged soil probe delivery system was required that could access the inside of the basin and take soil samples (through holes predrilled through the floor) from multiple depths under the floor. The improved technology demonstrated was a Geoprobe Model 540M, which is a compact direct push soil sampler mounted on a two-wheeled cart.

The Geoprobe Model 540M is a hydraulically operated sampler with a remote power pack. The unit hydraulically pushes and hammers a metal sampling tube into the soil from which a sample can be withdrawn to the surface. The sampling tubes incorporate inner plastic sample holders that have a 1.25- or 2-in. (3 or 5 cm) inside diameter. Samples up to 2 ft (0.6 m) long may be obtained at multiple depths with the compact Geoprobe unit.

The following describes the truck-mounted Geoprobe sampling unit:

- Probing unit is permanently mounted on a full-size, 1-ton capacity, diesel-powered truck.
- Total weight of the unit is about 5,700 lbs (2,586 kg) (probe weight is 1,700 lbs [771 kg], truck weight is about 4,000 lbs [1,815 kg]).
- Unit dimensions (including vehicle) are approximately 22 ft (6.7 m) long, 8 ft (2.4 m) wide, and 8 ft (2.4 m) high.
- All tooling and supplies are stored on the truck.
- Two people are needed to operate this unit efficiently.

The site at C Reactor where the demonstration was conducted was the floor of the fuel storage basin, which was dry and had a number of high concrete parallel curbs that had limited clearance between them.

The goal of the sampling effort was to obtain samples at two depths (5 ft [1.5 m] and 10 ft [3 m]) from up to five different core holes. Before deploying the Geoprobe's Model 540M, five randomly selected 8 in. (20-cm) diameter holes were drilled in the fuel basin's floor slab to permit sampling probe access to the soil below.

By using Geoprobe Model 540M, soil samples can be obtained quickly and efficiently at locations that do not have direct truck access to support soil characterization that is required for decommissioning activities.

The Geoprobe Model 540M sampler is useful for sampling in congested areas or areas that are inaccessible to large and/or heavy vehicles. This equipment has difficulty in probing heavy-cobble gravel and strongly cemented formations.



Figure 6-5
GeoProbe Sampler [16]

6.2.3 Unresolved Challenges and Conclusions

There is a need to reduce the costs of final status survey activities. While there are existing systems that offer improvements to manual surveying and sampling methods, there is generally a need for calibration of these systems to confirm their suitability for use in conducting final status surveys so that commercial use may be expanded. Additionally, it would be beneficial to improve and automate the storage, transmission and handling of data generated from the survey and sampling systems.

Particularly in the area of radiological characterization, it may be possible to use robots that are pre-programmed, are capable of functioning autonomously, and are able to make decisions and alter actions in response to various sensory inputs. Robots performing these tasks offer significant reductions in cost and schedule. Thus, increased automation in the deployment of advanced systems for radiological characterization is technically feasible and should be pursued.



Section 7: Decontamination Automation

The following tasks were identified for automated decontamination solutions:

- Hot Spot Decontamination (Consider for Robotics/Automation)
- Decontaminate Turbine Building (Consider for automation)
- Decontaminate Penetration Building (Consider for Robotics/Automation)
- Decontaminate Containment Building (Consider for Robotics/Automation)
- Decontaminate Fuel Handling Building (Consider for Robotics/Automation)
- Decontaminate Auxiliary Radioactive Waste Building (Consider for automation)
- Decontaminate Auxiliary Control Building (Consider for Robotics/Automation)

Since the decontamination activities are somewhat similar, this section provides a general discussion of automated options for decontamination.

Contamination levels in the turbine building and penetration building would typically be low and likely in spots, as opposed to widespread. Contamination levels may be present in paint or coatings of concrete and also within the concrete itself. Contamination is typically on the surface and not at depth [43].

Contamination levels in the Containment, Fuel Handling, Auxiliary Radioactive Waste and Auxiliary Control buildings may be higher, more widespread and potentially deeper in nature, especially in the floors of buildings that housed systems that contained radioactive fluids. Contamination again may be present in paint, but also may be deeper in the concrete surfaces, and may exist in cracks or associated with metals or rebar in concrete. Contamination has been reported up to 0.5cm on the walls and up to 3 cm on floors. Contamination in cracks can go as deep as one meter [43].

Building contamination typically involves removing the surface of the concrete that contains the contamination, or the use of gels or decontamination agents to draw out contamination from the concrete/paint. Decontamination activities are often carried out using manual techniques and can be quite time consuming.

7.1 Existing Solutions

7.1.1 Hot Spot Removal

Simple, single purpose robots were used to successfully extract debris in the drain line in Unit 4 of the Pickering A Nuclear Plant CANDU reactor heat exchanger. The debris was creating a radiation source that prohibited personnel entry to the area and was contributing to high radiation dose rates in the plant. The exact location of the source was not known, and it was in a maze of pipe and conduits of the primary coolant system which, if breached, could have led to the loss of the debris.

A simple four stage solution using small robotic vehicles performed in sequence was developed by Kinectrics to detect the source, cut the insulation around the pipe, freeze the coolant and radiation source in place, cut the ice bar and transfer the ice bar plus source to a shielded shipping container. The design strategy was for the tooling design and operations to be as simple and reliable as possible, based on proven designs and technologies, but flexible enough to allow for as-found conditions and to eliminate all single points of failure. A contingency robot was also designed.

Issues that affected the operation were that insulation was different than anticipated, taking longer to remove than anticipated, and video cameras were difficult to use and would require enhancement in future applications. However, the simple robots were effective and operated well, proving that simple solutions can be highly effective.

7.1.2 Concrete Decontamination Techniques

Concrete decontamination may be required to achieve residual activity removal goals ranging from situations where decontamination is required to meet limits for open air demolition of the structure, to situations where all or part of the building will remain intact and decontamination is required to meet license termination criteria, clearance levels or even levels below detectability.

7.1.2.1 Concrete Decontamination at DOE Facilities

The En-vac Robotic Wall Scabbler used by the DOE [16] is a remote-controlled scabbling unit with individually motor-controlled wheels that moves horizontally and vertically along floors, walls, and ceilings, adhering to the surface with the help of a high-vacuum suction created at its base. The scabbler uses stainless steel shot in an abrasive blasting technology which recycles the shot. Walls can be scabbled to 0.3 cm (1/8 inch) within 20 cm (8 inches) of piping and obstructions. The scabbler leaves a rough finish.

The En-vac system is heavy, with the heaviest piece weighing 6,800 pounds (3,090 kg). All of the equipment is capable of being lifted by industrial forklift or mobile carry crane. Future development might include downsizing and combining the three larger components (vacuum unit, filter, and recycling unit)

to make it more mobile. This would enhance the capability of this technology and assist with the transportation process. Another enhancement might be to place a radiation-monitoring probe on the system so that radioactive measurements can be made to determine if the debris is radioactive.

The Pentek, Inc., remotely-operated scabbler, the Moose[®], used by the DOE [16] is designed to scarify large concrete floors and slabs in environments that require stringent control of airborne contamination and debris. The Moose[®] scabbler utilizes a single-step floor scarification process with three integral subsystems: the scabbling head assembly, the on-board high efficiency particulate air (HEPA) vacuum system, and the six-wheeled chassis. Remote operation of the Moose[®] is performed using a small control panel attached to the Moose[®] by up to 300 ft (91 m) of tether. The system has a 0.7 m turning radius.

The scabbling head utilizes seven 2 ¼ in (5.6 cm) diameter independent reciprocating scabbling bits, each 9-point tungsten carbide-tipped, which pulverize the surface delivering 1,200 hammer impacts/min. The system removes 1/8 inch (0.3 cm) concrete. Dust and debris are captured by the two-stage positive filtration HEPA vacuum system that deposits the waste directly into an on-board 23 gal (87 liter) waste drum, although the system is typically used inside a containment tent.

The shortcoming of the Moose[®] is the fact that it will only accommodate 23 gallon (87 liter) drums. The drums become filled after 45 minutes of scabbling, and it requires two people to don PPE, enter the area, and change the drum. While the majority of the 5-minute drum change-out can be completed with only one person, the second person is required to help lower the heavy (over 200 lb [91 kg]) drum to the floor.



Figure 7-1
En-Vac Remote Wall Scabbler [16]



*Figure 7-2
Pentek Moose® Scabbler System [16]*

7.1.2.2 Automated Shaver Systems

Automated shaving systems, which can be mounted on walls or floors and then programmed to operate automatically within a specific area have been developed at Magnox in the UK and also by Studsvik [43].

A remote clamping system using a suction and vacuum technique was developed with a contractor to hang a shaving jig during spent fuel pool decontamination at Hinkley Point. The jig, two square meters in area, contained a shaving head made by Hydrostress and required to be remotely clamped to the wall of the pond (see Figure 7-3) to perform decontamination, thereby reducing worker dose from mounting the system. The mounting frame was hung from a crane, the vacuum was turned on remotely and the frame was then fit to the wall.



*Figure 7-3
Remotely Wall Mounted Shaving System [43]*

Once mounted, the shaver operates automatically within the scope of the mounted frame, removing the surface of the wall. The automation of the shaving operation reduced the dose associated with manual decontamination using a shaver.

Studsvik reports the use of completely encapsulated large area shaver units on gantry and fork lift systems [44]. Such systems are reported to have been used at Kahl Nuclear Power Plant for the decontamination of concrete blocks from the reactor area and at the Karlusche Reprocessing Plant for the decontamination of concrete surfaces.

The tool system is reported to be able to decontaminate concrete at a depth of 3 mm at approximately 15 m²/h, and measurement systems can also be used in conjunction with the unit. For the gantry system, the tool can be dismantled into sections and transported by hand. The tool can be used in rooms that are inaccessible to vehicles. An area of 17.3 m² can be treated at each location and heights can be extended if required. For the fork lift system, the tool can be fixed at any lift with a DIN 15173 fork, and the maximum working height can be adjusted.

7.1.3 Coating Mechanisms

InstaCote supported Humboldt Bay with the engineering and application of remote fogging technology to disperse Instacote wetting agents. These were used to stabilize the primary turbine and primary and secondary heat exchangers and associated ducts to prevent loose radiological particles from becoming airborne during demolition [45]. The fogging technology allowed for the reactor turbine and heat exchangers to be stabilized remotely. Dynafogger equipment was used at Humboldt Bay and also at DOE sites such as the Oak Ridge National Laboratory for contamination control during decontamination and demolition operations.

FIU conducted a demonstration at their mock hot cell of a remote fixative sprayer platform that was integrated onto an existing remote platform developed by International Climbing Machine (ICM) (see Figure 7-4) [16]. This integrated platform has the capability of climbing up vertical surfaces. The ICM system was selected for the initial technology demonstration based on the company's work experience in nuclear decontamination, technology capabilities, and previous technology demonstrations. The integrated technology platform was successfully demonstrated to remotely enter into a mock hot cell facility and to spray a fixative on the ceiling, walls, and floor surfaces. The spraying rate for the remote sprayer platform ranged from 3.4 to 4.3 square feet per minute (0.3 to 0.4 m²/min) based on area covered, spraying time, and product used. This is designed for hostile environments.



*Figure 7-4
CM Climbing Machine Spraying Fixative [16]*

Robot guidance was used in recoating a Torus for the DOE [46]. A complete 3D model of the Torus was constructed from design drawings and the model was corrected using data gathering robots and photogrammetry. All robot movements were simulated in simulation software, and then those predetermined movements were programmed into the robots. Unanticipated objects or conditions found in the actual Torus were then compensated for by the use of machine vision, with human override from outside the containment area as the final back-up to the system. Robots were designed to clean, strip the original coating, and then recoat the entire Torus. This approach is very similar to the methodology that would be used to apply a fixative on the walls of a fuel storage pool. In this case, the use of robots rather than the traditional human painting crews has been estimated to have reduced dose by up to ninety-five percent.

In this particular task, several teams of ten robots each performed the torus recoating task in far less time than the traditional human recoating methods. This use of multiple teams of robots illustrates one great advantage of robotic services; if time is an important component of the project, simply by adding additional robots the time on task can be reduced without significant changes to project dose.

General surface preparation robots using both mechanical and laser ablation were planned to strip the old coating coupled with machine vision to determine if the coating is fully removed. Pipe inside and outside diameter surface preparation robots also used both mechanical and laser ablation to strip the old coating, and machine vision for quality control, but were able to effectively navigate curved surfaces with a variety of radiuses. A self-movable robot platform equipped with a six axis arm with multiple heads prepared all areas not accessible to the main surface preparation robot.

A surface coating robot used precise machine vision control of spray heads to prevent over spray and confirm all surfaces were properly coated. Design variations allowed robots to accommodate curved surfaces. Self-movable robot platforms in this team are capable of placing, or removing and replacing, any other robot in the team that many encounter difficulty.

7.1.4 Dry Ice Decontamination

The decontamination work in the reactor buildings at Fukushima Daiichi is challenging because radiation doses are currently high, limiting the permissible worker stay times. Radiological surveys have shown that more than 70% of the area dose in the buildings is due to contamination of non-structural commodities (duct work, cable trays, piping, and so on) located in upper elevations. Decontamination of these components is thus expected to provide significant dose reduction benefit. (For reference, 20% of the overall dose is estimated to come from floor surfaces and 10% from walls and ceilings.)

Under the initiative of TOSHIBA Corporation, IRID developed dry ice blast decontamination equipment. To verify movement and decontamination performance of the robot in narrow or uneven places or in the dark, demonstration tests were conducted at a purpose-built mock-up facility that simulated a portion of the reactor building.

The robot is designed to decontaminate surfaces by spraying on dry ice powder and then scraping it off. This technique produced less secondary waste and is less likely to damage parent material because the dry ice itself is sublimed. The robot is equipped with a suction feature, and may be remotely operated using a total of 22 cameras to direct movements, lifting operations and decontamination work; and to determine the robot's location. It is designed to function at a height of up to 8 m. [47]

Other basic specifications are as follows:

- Dimensions (total length x width x total height): 2,069 mm x 930 mm x 1,961mm
- Weight: Approximately 1,700 kg
- Movement system: Electric-driven crawler
- Movement speed: 0.8-7.5 m per minute (five-step variable speed)



Figure 7-5
Dry Ice Decontamination Robot [47]

7.2 Potential Solutions

The OECD considers that there is benefit to continued development of *ex situ* techniques for decontamination of contaminated concrete, as well as techniques for the effective separation of the cement (typically contaminated) from the aggregate (typically not contaminated) [1]. A number of these types of techniques are under development.

7.2.1 Nitrocision

A remote technique to remove concrete contamination is under development by Nitrocision that uses the patented method of cooling and pressurizing liquid nitrogen to create an ultra-high pressure jet of liquid nitrogen with a density comparable to water. By regulating the pressure and velocity, the jet of liquid nitrogen can be used to clean surfaces, remove coatings or contamination, cut materials, and scabble concrete. The NitroJet® system is a dry process that provides a more aggressive process relative to technologies such as water jet, and dry ice and grit blasting. This is accomplished with the combination of high pressure, low temperature, and the 650-x liquid-to-gas expansion factor of liquid nitrogen. Table 7-1 [48] shows the equipment used in the NitroJet® technique.

Table 7-1
Equipment Needed to Run the NitroJet® Technology [48]

Equipment	Description/Function
Power utility (fuel)	250 kVA – power supply
Nitrogen tank	16 000 L – nitrogen storage
NitroJet® kkid	Core of the technology
Heat exchanger	Final cooling of the nitrogen jet
Air compressor and drier	Rotation of the nozzle, valve operation
Insulated low pressure pipes	Transportation of low pressure nitrogen from the tank to the skid and from the skid to the heat exchanger
High pressure pipes	Transportation of high pressure nitrogen from the skid to the heat exchanger and from the heat exchanger to the gun
Gun mounted with rotary nozzle	Distribution of the nitrogen
Two axis bearer (carrier)	Motorized axis for automatic operations
Shroud system	Collection of the nitrogen and of the concrete dust
Cyclonic vacuum system, HEPA filter	Separation of dust; aspiration of the nitrogen, purification of the gas

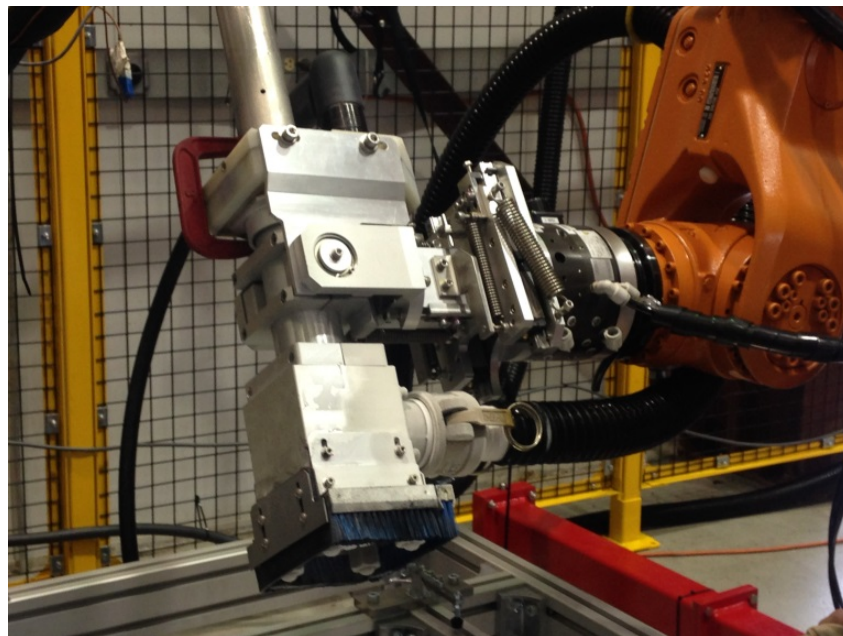


Figure 7-6
Remote Blasting of Concrete with Nitrocision Jet and Use of Vacuums [43]

The level of surface material removed can be precisely set to match the depth of contamination removal to actual depths of contamination concern. The depth of contamination removed affects the speed of the technique.

Deployment of the system would need to be addressed for the specific circumstance. The system can be deployed manually, semi-manually or automatically. The choice depends on the environment (radiation dose rate and contamination levels) as well as the accessibility and the configuration of the concrete to be decontaminated. It is likely for decontaminating reactor concrete that a robotic deployment would be required.

The implementation of the NitroJet® technology at the SICN nuclear facility by AREVA [48] was considered a success. The three different configurations (manual, semi-manual and automatic) were all tested. The first phase consisting of transferring, setting up, connecting and testing all the equipment took one week. The technology then ran for several weeks, 5 hours per day, with no major maintenance problems. Deployment of the technology to hundreds or thousands of square meters of concrete was therefore concluded to be technically viable. The collection of nitrogen, and active dust by the vacuum system was found to be excellent with a collection efficiency of more than 99%.

AREVA compared their results to the speed of decontamination of concrete by mechanical means. By using the NitroJet® technology, AREVA concluded that the technology would be cost effective for concrete walls and ceilings for contamination more than 5 mm deep and more than 500 m² in area. However, they concluded that the new technology would not be cost effective for floor decontamination due to the low cost of conventional scabbling equipment compared with Nitrocision's equipment, unless the recovery/recycling of the aggregate was off-set against the disposal cost of the concrete.

7.2.2 Laser Scabbling

The laser scabbling technique relies on the generation of temperature gradients in the cement and aggregate, expansion of the cement, micro cracking of the aggregate and rapid expansion of residual water in and at the periphery of the aggregates. In 2009, the UK NDA commissioned a project to develop a prototype laser scabbling system to determine how the technology might be implemented for remote use in nuclear decommissioning environments. The conclusions from the work extracted from a report by TWI Limited [49] were:

- For scabbling of limestone aggregate based concrete, a maximum material removal rate of 63 cm³/min was observed, using a laser power of 4000 W. This is equivalent to removing 1 m², to a depth of 5 mm, in about 80 minutes.
- A surface wetted or soaked with water improved the efficiency of the scabbling process.
- Under the conditions examined, no conditions were found to laser scabble the concrete containing basalt aggregate. The resultant surface was however, degraded and so easier to remove using modest mechanical techniques, relative to untreated concrete.

- Partial surface scabbling was observed on the concrete containing siliceous aggregate. As with the basalt material, the surface was degraded.

For future laser scabbling applications, an assessment of the composition of the concrete should be performed to verify its suitability for this process. Continued development of this technology should include laser output and fiber length [1].

Use of laser scabbling is also being investigated for concrete decontamination at Fukushima Daiichi. Testing performed using 5-10 kW lasers demonstrated that the time required to decontaminate a 100 m² area at a depth of 0.5 millimeters was approximately 20 hours, and decontamination to a depth 1.7 millimeters required 48 hours [1]. These decontamination rates are slower than rates typically achieved using conventional machines and end effectors.

The OECD recommend development of higher power laser end effectors and remote delivery systems to enhance cutting and scabbling. Integrated safety interlocks, and airborne radioactivity and waste collection systems should also be part of the technological improvement effort. AREVA has performed research on particle sizing and distribution in aerosols generated by laser ablation that should aid in the efficient design of ventilation capture systems to minimize secondary wastes associated with laser ablation coating stripping [1]. The laser scabbling process shows promise, but challenges remain with cost, production rate and laser safety. The benefit of investing and using this technology along with its limitations compared with standard processes for shipping and disposing the entire structure as radioactive is likely to result in this process not becoming standard in decommissioning applications.

7.3 Unresolved Challenges and Conclusions

Decontaminating contaminated concrete is an area where significant savings can be made. The deployment of automated shaving systems and the use of decontamination foams and gels deployed in an automated manner should continue to be developed. Additional trials and enhancements are needed to demonstrate that these techniques are effective on a large scale.



Section 8: Automation of Demolition

The following tasks were identified for automated demolition solutions:

- Demolish and Backfill Intake Structure Inside Seawall Below -3 Feet (Consider for Robotics/Automation)
- Remove Off Shore Intake and Outfall Conduits (Consider for Robotics/Automation)
- Remove and Dispose of Radiologically Contaminated Soil (Consider for Automation)
- Demolish and Backfill Turbine Building Structure Below 9 Ft Elevation. (Consider for Automation)
- Demolish Containment Building to 3-Feet Below Grade (Consider for Robotics)
- Remove and Dispose of Contaminated Sumps, Trenches and Pavement (Consider for Robotics/Automation)

Since the demolition activities are somewhat similar, this section provides a general discussion of automated options for demolition.

8.1 Existing Solutions

Heavy equipment, which is usually used for material handling, is now being converted for remote operation. An example includes remotely operated backhoes with a ram implement attachment used for breaking concrete. Brokk has been developing demolition robots since the 1980s, and they were extensively used during the Connecticut Yankee decommissioning for small scale scabbling, demolition and excavation work in an area next to the Spent Fuel Building. Brokk equipment can be outfitted with many different types of end-effectors such as concrete crushers, scabblers, drills, hydraulic hammers and buckets.

Brokk equipment was also procured and used during decommissioning operations at the Humboldt Bay Power Plant (HBPP) and Zion Nuclear Station. The Brokk mini-excavator 400 series was purchased for \$1M and deployed at HBPP for remote cutting and shearing. However, it was determined that the concrete walls were too thick for widespread use of the equipment. The Brokk machine could be operated remotely, at distances ranging from 2 to 20 feet using a remote control console.

During 1997–1998, a Brokk 250 was purchased by the Idaho National Engineering and Environmental Laboratory (INEEL) Large-Scale Demonstration and Deployment Project (LSDDP) for a comparison of performing manual versus remote dismantlement activities, such as concrete sizing and removal. The Brokk family of demolition equipment is manufactured by Holmhed Systems AB of Sweden and uses a teleoperated, articulated, hydraulic boom with various tool-head attachments [17].

The Brokk 250 comprises a revolving table, capable of continuous rotation, mounted on a tractor-like base. Solid rubber wheels mobilize the equipment, and hydraulic outriggers extend beyond the tires to add stability during operation. The unit requires a 480-V ac, 50-A circuit for its power source. The Brokk 250 may be operated from 400 ft (120 m) away using either a tethered portable controller or a wireless radio frequency (rf) portable controller. In the baseline mode, the Brokk is controlled by an operator standing in relatively close proximity of the machine with line-of-sight vision of the work site.

To perform activities from a truly remote non-line-of-sight location, the Brokk 250 was retrofitted with two image-stabilized cameras mounted in a pan-and-tilt aluminum enclosure. These two cameras were mounted on two actuated arms located on the Brokk 250's cover. The actuated arm system allowed the cameras to be positioned in the optimal viewing position during work activities and to be retracted while the Brokk was being moved throughout the remote area.

An auxiliary camera system was developed that could be placed anywhere in the facility and used for remotely viewing work activities from a different perspective. This system was developed using a third DRaySEETM camera system that was mounted on a 5 ft (1.5 m) pole and enclosure.

INEEL developed the Compact Control Operator Console (CRC) to condense a typical multi-monitor, multi-rack large operator control console into a single, easy-to-relocate ergonomic station. The CRC measures 30 in. (0.75 m) wide by 61 in. (1.5 m) long and 76 in. (1.9 m) tall, and includes a 4-panel video array that is mounted on a mast in front of an ergonomic chair. These are subsequently mounted on a base that serves as an enclosure for associated power, video switchers, and control and fiber-optic electronics. Also mounted on a swivel arm on the CRC is a control computer with a touch-screen that serves as an intuitive graphical user interface (GUI) to the Modified Brokk Demolition Machine.

The teleoperated Brokk 250 provides increased capability over the manual and heavy equipment systems (manual jackhammer, cutters and saws, backhoe mounted equipment, robotics with various attachments and explosives). Benefits include moving the operator out of harm's way, the ability to work in small areas, documented reduction in cost, schedule, and worker exposure on a wide range of tasks in various work conditions. The Modified Brokk Demolition Machine with Remote Console adds to these benefits the ability to remotely operate existing equipment from an increased safety zone in hazardous environments or increased remote capability in the case where hands-on, line-of-sight work is prohibitive because of constraints, such as radiological contamination. Working time is

reported to be less than half that of most manual tools, significantly reducing cost, schedule, and worker radiation exposure. The cost comparison concluded that production rates could potentially reach the same level in remote operation as in non-remote operation while providing a safer operator environment. Therefore, after the initial capital outlay for the remote demolition equipment, no additional cost or loss in productivity would be incurred.

Optional joystick control of the camera functions would be preferable to just a touch-screen interface. The operators were more familiar with joystick controllers and the need to continuously touch the operator interface touch screen on a specific button to move the cameras proved to be occasionally frustrating. The operators felt a system with the option of joystick or touch screen would be preferred. The facility camera is designed to transmit video via an RF transmitter to the Brokk, where the signal is passed via the fiber-optic tether to the operator. Commercially available RF video transmitters at the time the original project was performed were very limited to line-of-sight operations and very susceptible to noise and interference. These limitations plagued the operator with frequent dropouts of the overview picture and caused some significant frustration under these operating conditions. It was suggested that an optional coaxial cable be installed from the facility camera to the Brokk 250 and then passed via the fiber-optic cable to the operator to reduce these video problems.

Either the Modified Brokk camera system or the CRC is readily available for commercialization. Both systems used commercially available subsystems when possible to minimize cost and development time. Based on the INEEL demonstration, the Modified Brokk Demolition Machine with Remote Console is suitable for dismantlement activities requiring completely remote operations. It is safer to operate, provides increased distance when operating in a radiological environment, allows continued higher productivity than manual operations, and costs nearly the same to operate. When completely remote operations are not required, when 100 ft (30 m) line-of-sight provides adequate distance to protect the operator, and when the possibility exists for falling debris to damage the Brokk camera and electronic systems or extremely dusty environments preclude the use of cameras, then the use of a Brokk without the modifications described would be preferable.

The DOE has also used the robot, Rosie, at the CP-5 reactor site to perform mechanical dismantlement of radiologically contaminated structures. Rosie is a mobile platform used to support reactor assembly demolition through its long reach, heavy lift capability and its deployment and positioning of a Kraft Predator dexterous manipulator arm. Rosie is a tethered, 165 ft (50 m) long, robotic system controlled via teleoperation from a control console that is located outside of the radiological containment area. The operator uses Rosie to move, lift or “offload” radioactive materials using its integral lifting hook or to position the Kraft Predator arm in locations where the arm can be used to dismantle parts of the CP-5 reactor. Mobilization, demolition, and demobilization costs are each much greater for Rosie than for manual demolition due to its hourly equipment rate, which is about three times the rate of a typical crew.

Remotely operated construction vehicles such as bobcats, dump trucks, bulldozers and full-size excavators were effectively used during the initial clean-up at Fukushima Daiichi. Much of this equipment was provided by the Japanese firm Yoshikawa Co. In some cases, equipment already configured for remote operation was used, and in others, standard equipment was adapted for remote operation using off-the-shelf conversion kits. For example, QinetiQ North America offers kits to convert Bobcat loaders into unmanned vehicles in 15 minutes. The kits permit remote operation of standard vehicle attachments, including shovels, buckets, grapples, tree cutters and tools to break through walls and doors [1].

KHG (Kerntechnische Hilfsdienste GmbH), founded in 1977 by nuclear plant operators in Germany, maintains a large fleet of robots and is specializing in the support for the decommissioning of the Germany nuclear power reactor fleet. Their equipment ranges from twenty-two ton radio-controlled excavators, to small radio-controlled inspection vehicles.

8.2 Potential Solutions

The French group INTRA previously developed a series of robots for emergency response that can be operated from distances of more than one kilometer. The INTRA inventory ranges from exploratory robots to giant earth removal trucks, bulldozers and excavators, all of which can be operated in hostile environments. With assistance from the CEA, INTRA is replacing 15-year-old operating and controls systems with Pentium 4 based boards, linked to specialist interface and communications boards, and also moving to a new software architecture. This combination will allow the systems to be updated quickly and efficiently without introducing software flaws or other operating system issues. This upgrade is expected to foster the continued development and broader applications for these remotely operated machines by enabling the rapid integration of autonomous and semi-autonomous software capabilities as they are developed [1].

OECD recommend procuring remotely operated excavators, haulers, concrete and rebar processors for building D&D testing, deploying to decommissioning(s) and testing interior and exterior demolition using teams of machines [1].

8.3 Unresolved Challenges and Conclusions

Given the substantial cost savings that could be possible, the use of automated demolition techniques should be considered for all larger concrete structures.



Section 9: Other Activities Considered

Robotics or automated solutions have been used for other activities such as sampling and waste assay. These existing techniques are reviewed in this section.

9.1 Sampling

9.1.1 Dual-Remote Raman Technology

A new Raman spectroscopic system for in situ identification of the composition of solid nuclear tank waste was developed by Pacific Northwest National Laboratory (PNNL) in collaboration with EIC Laboratories, Inc. [50]. Raman spectroscopy is a vibrational spectroscopic method that provides information on molecular structure and allows for each mineral or chemical compounds in a sample material to display a characteristic “fingerprint” in the Raman spectrum.

For the testing of Tank C-111 at the DOE Hanford Site, the Raman probe was installed on top of the tank riser and sent an incident laser beam to the bottom of the tank approximately 15 meters below. The returning light containing the chemical information was collected by the probe and transmitted via fiber optic cable to the spectrometer located outside the tank farm area. Further development of the dual-remote Raman technology will provide personnel radiological and safety benefits compared to grab sample collection, and also enable rapid and cost-effective in-situ chemical analysis of tank waste.

9.1.2 FriGeo

The UK Sellafield site worked with a Swedish company, FriGeo, to develop a self-sinking probe for the freezing and collection of samples of radioactive sludge from the bottom of its 5-meter deep legacy fuel storage pond [51]. The Sellafield Ltd decommissioning team worked with FriGeo to develop a technical solution to collect radioactive sludge samples while preserving most of the sample qualities. FriGeo reviewed technologies from the construction industry and evaluated the idea of using a vibrating probe to facilitate the self-sinking function and collection of samples from predetermined depths.

With operation at temperatures down to -40°C the sludge sample is rapidly frozen on the probe in minutes, which both helps to protect sample integrity and prevent contamination spread from the probe when it is lifted out of the water. Testing of this concept was performed in 2012 and 2013 with deployment of the

freeze sampler from a ROV mini-submarine and collection of a 40 cm-deep sample. The freeze technology could have broad applications within the nuclear industry for the sampling of various materials such as sludges, wastes, contaminated oil, and so on.

9.1.3 Vadose Zone Characterization System

The DOE has used 100- to 150-ft (30 to 45 m) deep boreholes for the characterization of contaminant distributions at Hanford. However conventional drill rigs cannot be located over plumes in tank farms because of surface piping, instrument lines, and utilities. Drilling and analysis is expensive (costs have exceeded \$1 million per borehole), secondary waste is produced and the sample analysis may take months to complete. Additionally, boreholes produce localized measurements unsuitable to characterize an entire plume and additional characterization of entire plumes by use of new boreholes is cost-prohibitive.

In response to these challenges, the Vadose Zone Characterization System (VZCS) was developed. This system uses a cone penetrometer with gamma sensors to characterize gamma contamination under tank farms [16]. A magnetometer in the cone penetrometer tip reduces the probability of contacting subsurface utility or instrument lines during use. A truck-mounted VZCS can be driven into tank farms and located in any area the size of a parking space. A platform-mounted VZCS can be lifted by a crane into locations that have no vehicle access.

The VZCS consists of multifunction probes within a cone penetrometer that is pushed from a stand-alone or truck mounted platform into the ground to depths up to 150 ft (45 m). The multi-sensor probe configuration includes X-ray fluorescence and gamma spectroscopy sensors; sensors for soil stratigraphy, for the detection of subsurface ferrous structures, and for monitoring vertical alignment during penetration; and sensors for soil moisture content and soil resistivity. A multipoint soil sampler probe to retrieve soil samples in a separate push and a grouting tip to close the cone penetrometer hole is also available.

During a demonstration at Hanford, eight test locations were investigated to a depth of 33 to 51 ft (10 to 15 m). The VZCS successfully indicated the presence or absence of radiological contamination. This information was useful to direct follow-up soil sampling with the VZCS to depths of interest at specific locations. The VZCS can be used at sites where geologic conditions permit subsurface penetration using forces up to 40 tons (36 metric tons), except those characterized as difficult to drill because of large boulders or cemented layers. The VZCS can sample between boreholes to verify the presence of contaminants, including pushing at the bottom of existing boreholes to obtain information on the lower vadose zone. The VZCS can penetrate as deep as 300 ft (90 m) but is generally limited to depths up to 150 ft (45 m), but greater depths can be reached when used in conjunction with drilling methods. It is best used for initial site characterization data, confirmed by collecting samples for analysis in the laboratory.

Conventional techniques generally require the emplacement of a borehole using drilling, driving, or pushing techniques. Dry-well gamma logging is then used for measurements and then samples are taken with a device known as a split spoon, which captures material from the bottom of the hole as the hole is drilled. Samples are then analyzed in the laboratory. Spectral gamma logging measurements are taken inside the casing when the well is completed. The VZCS has several advantages: the footprint of the VZCS is smaller than a conventional drill rig; the VZCS contains sensors to help detect and avoid metal subsurface objects; and the VZCS disturbs only a 2-inch diameter core of soil, compared to 6 inches or more for conventional drilling; the VZCS generates no waste, compared to conventional sampling that generates contaminated drilling mud, which must be disposed of as either radioactive or mixed waste. Dry-well gamma logging also cannot detect the presence of radionuclides other than gamma emitters, but the sensors in the cone penetrometer come in contact with soil directly to enable a broader range of analytic capability.

A total of 371 ft (112 m) of soil was characterized in the S Tank Farm for \$323,000, in contrast to approximately \$1.2 million for a typical 150-ft (45 m) borehole. The VZCS can characterize a foot of soil for about one-tenth the cost of cable tool drilling. Additional cost savings accrue from the use of the VZCS to optimize the location for future boreholes.

9.1.4 Tank Sampler

The DOE is responsible for cleaning and closing more than 300 small and large underground tanks across the DOE complex that are used for storing over 1-million gallons of high- and low-level radioactive and mixed waste. The contents of these aging tanks must be sampled to analyze for contaminants to determine final disposition of the tank and its contents. Access to these tanks is limited to small-diameter risers that allow for sample collection at only one discrete point below this opening. To collect a more representative sample without exposing workers to tank interiors, a remote controlled retrieval method must be used. Many of the storage tanks have access penetrations that are 18 in. (0.45 m) in diameter and, therefore, are not suitable for deployment of large vehicle systems like the Houdini (see Section 4.2.2.2). Often, the tanks offer minimal headspace and are so cluttered with pipes and other vertical obstructions that deployment of long-reach manipulators becomes an impractical option.

A smaller vehicle system was needed to deploy waste retrieval, sampling, and inspection tools into these tanks, so the Oak Ridge National Laboratory, along with ROV Technologies, Inc., and The Providence Group, Inc., developed the Scarab III remotely operated vehicle system [16] (see Figure 9-1). The system also includes a containment and deployment structure and a jet pump-based, waste dislodging and conveyance system to use in these limited access tanks. The Scarab III robot addresses the need for a vehicle based, rugged, remote-controlled system for collection of representative samples of tank contents.

The remotely operated vehicle system comprises three primary components: the vehicle (Scarab III), the Deployment and Containment Module (DCM), and the control consoles. The Scarab III remote vehicle is designed to operate either submerged under water or in several inches of waste material.

The vehicle has four rubber-treaded wheels for traction on slick surfaces, and four metal wheels for biting into thin layers of waste material which can climb over 8-in. (20 cm) obstacles. There is a manipulator arm that can grasp objects up to 2-in. (5 cm) in diameter and has a wrist capable of 360° rotation and an elbow capable of moving 90° up or down. The manipulator arm is used to grasp the sample collection device and maneuver it to collect the sample. The manipulator gripper end-effector has a payload limit of 5 lb (2.3 kg). The Scarab III chassis is stainless steel for corrosion resistance, and the overall dimensions are such that the unit can be deployed through an 18-in. (0.45 m) riser opening. Three on-board cameras provide viewing for deployment, retrieval and driving operations. Two of these cameras are mounted on the front and rear of the chassis. The third camera is mounted on a turret that provides 270° of pan and 90° of tilt. This camera can also be placed atop an extendible boom for surveying tank walls.



*Figure 9-1
Scarab III Remote Sampling Vehicle [16]*

The DCM provides containment and storage for the Scarab III vehicle. Two winches are used to deploy the vehicle and ancillary equipment through an access port at the bottom that interfaces with the tank riser. There are also access ports mounted at either end of the containment structure for sending equipment in and out of the DCM. Piping and quick disconnect fittings are provided for connecting to a high-pressure washer for decontamination of vehicle and ancillary equipment inside the DCM. The control consoles are lightweight, modular units that are portable for ease of setup within a small area. The main console provides power to the other consoles that contain the joystick and levers for operation of the Scarab III vehicle and the monitors for the onboard cameras.

Observations from cold testing and in-tank operations indicated that the vehicle could operate effectively in radioactive sludge up to about 8 in. (20 cm) in depth. Operating time for retrieval of nine waste samples was 7.6 hours. The Scarab III vehicle requires an 18-in. (0.45 m) diameter or larger access to enter the tank.

Total field deployment costs fall dramatically from \$147,000 for an initial deployment to less than \$30,000 for follow-on deployments.

9.2 Automated Waste Assay System

The El.Se.Srl firm in Italy, in collaboration with ORTEC, designed and deployed an automated measurements system for checking radioactive waste at the SOGIN decommissioning sites at Caorso, Trino, and Latina, Italy [52]. The system is highly automated for measurement of a variety of sample sizes and forms: bags, boxes, and B25 containers, with densities approximately in the range of 100 kg/m³ to 2,000 kg/m³; these items are generally loaded by a fork lift or overhead crane.

The assay system uses four ORTEC Interchangeable Detector Module (IDM) mechanically cooled high purity germanium (HPGe) spectrometers. A computer-controlled automatic Cart-On-Track conveyor capable of moving weights up to 6,000 kg moves the container past the 4 HPGe detector systems positioned in two tower structures on either side of the containers.

Testing at the Italian nuclear facilities showed that the system was capable of meeting below clearance or “free release” requirements for radionuclides under consideration. Clearance limits of 0.1 to 1.0 Bq/g were readily met for radionuclides such as Mn-54, Co-60, Cs137, Eur-152, Eu-154, and Am-241.

In the medical field, gamma camera imaging systems have been used to create detailed 3-D images of areas of localized radionuclide concentrations in patients undergoing positron emission tomography (PET) scans. Similar X-ray tomography systems have been effectively used in the nuclear industry for a number of years for characterizing waste containers [1].

9.3 Unresolved Challenges/Conclusions

Sampling and waste assay are important but fairly standardized techniques. However, for time consuming activities such as sampling and analysis associated with site characterization and final status survey, benefit may be realized from use of automated systems. Thus, available sampling and assay systems should be evaluated further for cost effectiveness at NPP decommissioning sites.



Section 10: Conclusions

It is generally accepted that use of automation and robotics offers potential benefits for many tasks involved in nuclear power plant decommissioning. Although many tasks may readily be automated or performed remotely using robots, inherent risks to use of such technology with respect to overall project cost and schedule should be balanced against the perceived value of the benefits. To this end, Section 3 of this report provides an assessment of the relative benefits that may be derived for specific decommissioning tasks through use of automated or robotic systems.

The results of this assessment may be used to focus automation and robotics research and development efforts on those tasks that would most clearly benefit from use of such systems. The results indicate that research and development efforts in both automation and robotics may optimally be focused on the following main tasks:

- Load Spent Fuel Canisters and Transfer to ISFSI
- Segment, Package and Dispose of Reactor Internals
- (Spent Fuel Pool) Remove and Dispose of Legacy Class B and C Waste

These tasks are complex, radiation dose intensive, and are typically on the decommissioning project critical path.

As importantly, the results of the task assessment provide guidance for prioritizing development efforts for automation or robotics use in other tasks where the benefits may also be substantial.

As discussed in Sections 4 through 9, many robotic and automated systems already exist both within the nuclear industry and in other industries that may either be used directly or readily modified to perform specific decommissioning tasks. This information may be used by decommissioning project engineers in development of decommissioning work plans, or by research and development groups to adapt existing solutions to decommissioning tasks

It is anticipated that as use of automated and robotics systems becomes more commonplace in decommissioning projects, some common barriers such as questions on equipment reliability, maintenance, ease of use and high development costs will be overcome. Focusing development efforts on solutions for those tasks for which the benefits are most profound will assist in fostering wider acceptance of the use of robotics and automation in additional decommissioning tasks.

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Appendix A: Assessment of Decommissioning Tasks for Robotics and Automation

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Perform Primary System Decontamination	4	4	1	2	11
Discount; not very repetitious, 1-time activity/unit					
Load Spent Fuel Canisters and Transfer to ISFSI	9	9	8	9	35
High rad; critical path; lifting/rigging; high reps, complex but routine/repetitive, critical path					
Segment, Pkg, Dispose of Reactor Pressure Vessel	8	7	9	2	26
Complex, segmentation tasks repetitive, RVs are few					
Decontaminate Turbine Building	2	5	2	6	15
Routine, repetitive scope					
Removal, Segmentation, Disposal of Pressurizer	6	3	8	1	18
Removal of Reactor Coolant Pumps/Disposal	6	3	8	5	22
Repetitive					

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Remove and Dispose of Rad Contaminated Soil	2	3	2	7	14
Routine, repetitive scope					
Final Status Survey	4	5	2	9	20
Large areas and time; low rad and safety; high reps					
Hot Spot Decontamination	4	3	4	6	17
Complexity and type of task can vary					
Segment, Package and Dispose of Reactor Internals	8	10	8	9	35
Complex – many parts, segmentation scope repetitive					
Removal and Disposal of Spent Resin, Filter Media and Tank Sludge	8	4	6	7	25
Complexity varies, filtering/desludging frequent					
Remove and Dispose of Turbine Gantry Crane	2	2	4	1	9
Low complexity, few cuts, only one component					

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Decontaminate Auxiliary Radwaste Building	4	4	4	5	17
Complexity varies; potential repetitive approach					
Radiological Survey of Structures During Decontamination	4	4	4	6	18
Low complexity, high repetition					
Rx Internals Removal Prep, Modify Containment Access	4	5	4	1	14
One time activity/unit; heavy equip use					
Remove and Dispose of Missile Shields	2	3	2	1	8
One time activity/unit; no major industrial/rad issues					
Remove and Dispose of Reactor Head	8	6	6	5	25
Reactor head detensioning and cutting repetition					
Remove and Dispose of Spent Fuel Storage Racks	4	2	8	3	17
Very repetitive					

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
(Spent Fuel Pool) Remove and Dispose of Legacy Class B and C Waste	9	6	9	6	30
Numerous materials and packages and tasks involved					
Drain Spent Fuel Pool and Process Liquid Waste	4	2	4	2	12
Limited repetition and low complexity/safety					
Segment, Package and Dispose of Spent Fuel Pool Island Equip	6	2	4	2	14
Segment and Dispose of Fuel Bridge Crane	2	1	4	1	8
Limited segmentation tasks and only 1 crane					
Reactor Vessel Insulation Removal and Disposal	4	2	8	1	15
Limited low-rad material being removed for disposal, high dose rates under vessel					

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Remove and Dispose of Steam Generators	8	6	8	7	29
Numerous SG components and cutting					
Decontaminate Containment Building	6	5	4	7	22
Consider repetitive and large areas to decon					
Decontaminate Penetration Building	2	3	3	7	15
Consider repetitive and large areas to decon					
Decontaminate Fuel Handling Building	6	2	4	7	19
Consider repetitive and large areas to decon					
Decontaminate Safety Equipment and MSIV Building	4	1	4	4	13
Discount should be a small decon effort based on secondary systems					
Decontaminate Auxiliary Control Building – Common	3	1	4	6	14
Consider repetitive task					

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Decontaminate Condensate Area and Tunnels	4	1	4	5	14
Discount should be small decon effort					
Excavate, Remove and Dispose of Yard Area Drains	4	1	2	6	13
Discount should be small decon effort					
Remove and Dispose of Contaminated Sumps, Trenches and Pavement	4	2	6	6	18
Consider repetitive task/contamination control					
Dispose of Contaminated Decontamination Equipment and Tooling	2	1	4	6	13
Discount not repetitive and low complexity					
Remove Protected Area Security Fencing	2	1	2	7	12
Very repetitive, low complexity					
Remove Protected Area Pavement	2	1	2	8	13
Very repetitive, low complexity					

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Detension and Remove Containment Building Tendons	4	1	2	5	12
Demolish Fuel Handling Building to 3-Feet Below Grade	4	1	4	5	14
Demolish Penetration Building	4	1	4	5	14
Demolish Safety Equipment and MSIV Building	2	1	2	5	10
Demolish Containment Building to 3-Feet Below Grade	4	1	6	5	16
Demolish Auxiliary Radwaste Building – Common	2	1	6	5	14

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1-10)	(1-10)	(1-10)	(1-10)	(Max = 40)
Demolish Auxiliary Control Building – Common	2	1	6	5	14
Demolish and Backfill Fuel Handling Building Below -3 Feet	4	1	4	5	14
Demolish and Backfill Radwaste Building Below -3 Feet	4	1	4	5	14
Demolish and Backfill Turbine Building Structure Below 9 Ft Elev.	2	4	2	5	13
Consider due to cost					
Demolish and Backfill Safety Equipment Building Below -3 Feet	2	1	2	5	10

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1-10)	(1-10)	(1-10)	(1-10)	(Max = 40)
Demolish and Backfill Penetration Area Below -3 Feet	4	1	4	5	14
Demolish and Backfill Containment Building Below -3 Feet	4	1	4	5	14
Demolish and Backfill Intake Structure Inside Seawall Below -3 Feet	6	5	2	5	18
Consider due to cost					
Remove Off Shore Intake and Outfall Conduits	8	6	2	2	18
Consider due to cost					
Remove Sheet Piling and Excavation Shoring	4	1	2	3	10
Remove Dewatering System and Effluent Treatment	2	1	2	1	6

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Finish Grading and Re-Vegetate Site	4	1	2	3	10
Remove Temporary Structures	2	1	2	1	6

Automation Attributes and Scoring Metrics					
Automation Attributes and Scoring Metrics	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition Efficiency	Total
	(1–5)	(1–20)	(1–5)	(1–20)	(Max = 50)
Perform Primary System Decontamination	2	8	2	3	15
Discount; not very repetitious, 1-time activity/unit					

Automation Attributes and Scoring Metrics					
Automation Attributes and Scoring Metrics	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition Efficiency	Total
	(1–5)	(1–20)	(1–5)	(1–20)	(Max = 50)
Load Spent Fuel Canisters and Transfer to ISFSI	5	18	4	18	45
Complex but routine/repetitive, critical path					
Segment, Pkg, Dispose of Reactor Pressure Vessel	4	14	4	4	26
Complex, segmentation tasks repetitive, RVs are few					
Decontaminate Turbine Building	1	10	1	12	24
Routine, repetitive scope					
Removal, Segmentation, Disposal of Pressurizer	3	6	4	3	16
Removal of Reactor Coolant Pumps/Segmentation/Disposal	3	7	4	10	24
Remove and Dispose of Rad Contaminated Soil	1	6	1	14	22
Routine, repetitive scope					

Automation Attributes and Scoring Metrics					
Automation Attributes and Scoring Metrics	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition Efficiency	Total
	(1–5)	(1–20)	(1–5)	(1–20)	(Max = 50)
Final Status Survey	2	10	1	18	31
Prescriptive scope/objectives, repetitive tasks					
Hot Spot Decontamination	2	6	2	12	22
Complexity and type of task can vary					
Segment, Package and Dispose of Reactor Internals	4	20	4	18	46
Complex — many parts, segmentation scope repetitive					
Removal and Disposal of Spent Resin, Filter Media and Tank Sludge	4	8	3	14	29
Complexity varies, filtering/desludging frequent					
Remove and Dispose of Turbine Gantry Crane	1	4	2	2	9
Low complexity, few cuts, only one component					
Decontaminate Auxiliary Radwaste Building	2	8	2	10	22

Automation Attributes and Scoring Metrics					
Automation Attributes and Scoring Metrics	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition Efficiency	Total
	(1–5)	(1–20)	(1–5)	(1–20)	(Max = 50)
Complexity varies; potential repetitive approach					
Radiological Survey of Structures During Decontamination	2	8	2	12	24
Low complexity, high repetition					
Rx internals removal preparation, modify Containment Access	2	10	2	2	16
One time activity/unit; heavy equip use					
Remove and Dispose of Missile Shields	1	5	1	2	9
One time activity/unit; no major industrial/rad issues					
Remove and Dispose of Reactor Head	4	12	3	10	29
Reactor head detensioning and cutting repetition					
Remove and Dispose of Spent Fuel Storage Racks	2	4	4	6	16
Discount; limited number of racks					

Automation Attributes and Scoring Metrics					
Automation Attributes and Scoring Metrics	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition Efficiency	Total
	(1–5)	(1–20)	(1–5)	(1–20)	(Max = 50)
(Spent Fuel Pool) Remove and Dispose of Legacy Class B and C Waste	5	15	5	15	40
Numerous materials and packages and tasks involved					
Drain Spent Fuel Pool and Process Liquid Waste	2	4	2	4	12
Limited repetition and low complexity/safety					
Segment, Package and Dispose of Spent Fuel Pool Island Equipment	3	4	2	4	13
Segment and Dispose of Fuel Bridge Crane	2	2	2	1	7
Limited segmentation tasks and only 1 crane					
Reactor Vessel Insulation Removal and Disposal	2	4	4	3	13
Limited low-rad material being removed for disposal/ high dose rates under vessel					
Remove and Dispose of Steam Generators	4	12	4	14	34
Numerous SG components and cutting					

Automation Attributes and Scoring Metrics					
Automation Attributes and Scoring Metrics	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition Efficiency	Total
	(1–5)	(1–20)	(1–5)	(1–20)	(Max = 50)
Decontaminate Containment Building	3	10	2	14	29
Consider repetitive and large areas to decon					
Decontaminate Penetration Building	2	5	2	14	23
Consider repetitive and large areas to decon					
Decontaminate Fuel Handling Building	3	4	2	14	23
Consider repetitive and large areas to decon					
Decontaminate Safety Equipment and MSIV Building	2	3	2	7	14
Discount should be a small decon effort based on secondary systems					
Decontaminate Auxiliary Control Building – Common	2	3	2	14	21
Consider repetitive task					
Decontaminate Condensate Area and Tunnels	2	2	2	10	16
Discount should be small decon effort					

Automation Attributes and Scoring Metrics					
Automation Attributes and Scoring Metrics	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition Efficiency	Total
	(1–5)	(1–20)	(1–5)	(1–20)	(Max = 50)
Excavate, Remove and Dispose of Yard Area Drains	2	2	1	12	17
Discount should be small decon effort					
Remove and Dispose of Contaminated Sumps, Trenches and Pavement	2	4	3	12	21
Consider repetitive task					
Dispose of Contaminated Decontamination Equipment and Tooling	1	1	2	12	16
Discount not repetitive and low complexity					
Remove Protected Area Security Fencing	1	1	1	15	18
Very repetitive, low complexity					
Remove Protected Area Pavement	1	1	1	15	18
Very repetitive, low complexity					

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1–10)	(1–10)	(1–10)	(1–10)	(Max = 40)
Detension and Remove Containment Building Tendons	2	2	1	10	15
Demolish Fuel Handling Building to 3-Feet Below Grade	2	2	2	10	16
Demolish Penetration Building	2	1	2	10	15
Demolish Safety Equipment and MSIV Building	1	1	1	10	13
Demolish Containment Building to 3-Feet Below Grade	2	3	3	10	18
Demolish Auxiliary Radwaste Building – Common	2	3	3	10	18

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1-10)	(1-10)	(1-10)	(1-10)	(Max = 40)
Demolish Auxiliary Control Building – Common	1	2	3	10	16
Demolish and Backfill Fuel Handling Building Below -3 Feet	2	2	2	10	16
Demolish and Backfill Radwaste Building Below -3 Feet	2	2	2	10	16
Demolish and Backfill Turbine Building Structure Below 9 Ft Elev.	1	7	1	10	19
Consider due to cost					
Demolish and Backfill Safety Equipment Building Below -3 Feet	1	1	1	10	13

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1-10)	(1-10)	(1-10)	(1-10)	(Max = 40)
Demolish and Backfill Penetration Area Below -3 Feet	2	1	2	10	15
Demolish and Backfill Containment Building Below -3 Feet	2	2	2	10	16
Demolish and Backfill Intake Structure Inside Seawall Below - 3 Feet	3	10	1	10	24
Consider due to cost					
Remove Off Shore Intake and Outfall Conduits	4	11	1	5	21
Consider due to cost					
Remove Sheet Piling and Excavation Shoring	2	2	1	5	10
Remove Dewatering System and Effluent Treatment	1	1	1	2	5

Robotics Attributes and Scoring Metrics					
Work Description	Work Complexity	Schedule and Cost Impact	Radiological and Industrial Safety Impact	Repetition	Total
	(1-10)	(1-10)	(1-10)	(1-10)	(Max = 40)
Finish Grading and Re-Vegetate Site	2	1	1	5	9
Remove Temporary Structures	1	1	1	2	5

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