Innovative Manned and Robotic Techniques that Reduce Dose and Increase Decontamination and Decommissioning Efficiency and Safety – 10132

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ABSTRACT

The Department of Energy (DOE) constructed over 20,000 facilities to support nuclear weapons production and other activities. Thousands of these facilities are currently in the process of, or slated, for deactivation and decommissioning (D&D). Many are contaminated with radioactive materials and other hazardous materials. Deactivation stabilizes each facility and reduces maintenance costs. Decommissioning includes clean-up of radioactivity and demolition of the site as well as the administrative and technical actions that release the Licensee from regulatory control and relieves them of the responsibility for nuclear safety. Areas within DOE facilities such as tanks, spent fuel pools and other containments present extreme challenges in an already challenging work environment. Issues such as high radiation and contamination levels, limited access, underwater environments, toxic materials, and confined spaces make an already difficult job even more so. Innovative approaches to D&D can offer new ways to reduce radiation exposure and other health risks while reducing cost and schedule. Nuclear facilities are committed to the principals of ALARA (As Low As Reasonably Achievable) for radiation exposure to workers while at the same time minimizing the cost of a D&D project. Two innovations have proved extremely effective in this regard: the use of robots and divers. This paper will address both of those methods of reducing risk to human workers while increasing efficiency and reducing dose, time, and costs.

INTRODUCTION

The Department of Energy (DOE) constructed over 20,000 facilities to support nuclear weapons production and other activities. Thousands of these facilities are currently in the process of, or slated, for deactivation and decommissioning (D&D). Many of these facilities are contaminated with radioactive materials and other hazardous materials, such as mercury, asbestos, and lead. They require continued monitoring and maintenance because deterioration either has or could eventually make them unsafe for workers to enter or increase the risk of a release of contaminants to the environment.

Although the DOE's site cleanup program is one of the largest environmental cleanup efforts ever undertaken, other countries are facing similar challenges. In many cases, the D&D effort includes the decommissioning of commercial nuclear sites and research reactors as well. There is essentially a two-part strategy: Deactivation stabilizes each facility and reduces maintenance costs; Decommissioning includes clean-up of radioactivity and demolition of the site as well as the administrative and technical actions that release the Licensee from regulatory control and relieves them of the responsibility for nuclear safety. Once a facility is decommissioned, there should no longer be any risk of a radioactive accident or danger to the public. Facilities that will eventually undergo D&D include commercial power reactors, research reactors, chemical processing buildings, uranium, plutonium, and tritium production facilities, and gaseous diffusion plants.

Areas within DOE facilities such as tanks, spent fuel pools, and other containments present extreme challenges in an already challenging work environment. Issues such as high radiation and contamination levels, limited access, underwater environments, toxic materials, and confined spaces make an already difficult job even more so. For example, workers using long handled or remotely operated tools to access an underwater work site typically perform decontamination, characterization, size and volume reduction, and disposition of sludge and debris. However, even distanced from the work, it is not uncommon for workers to accumulate undesirable levels of exposure or experience skin contaminations. Many OSHA recordable injuries due to difficult or awkward working conditions also occur. Moreover, distance makes it difficult to perform the tasks accurately or efficiently and remote tooling, cutting equipment, and sludge removal systems often prove ineffective. Innovative approaches to D&D can offer new ways to reduce radiation exposure and other health risks while reducing cost and schedule.

All nuclear facilities are committed to the principals of ALARA (As Low As Reasonably Achievable) for radiation exposure to workers while at the same time minimizing the cost of a D&D project. Two innovations have proved extremely effective in this regard: the use of robots and divers. This paper will address both of those methods of reducing risk to human workers while increasing efficiency and reducing time and costs.

Because water serves as an excellent radiation shield, the use of divers has long been recognized by commercial nuclear plants as a valuable component of an ALARA program. Commercial plants also recognized that divers are frequently able to perform work at a fraction of the cost and schedule required to design and build remote tools or do work in the dry. In addition, the protective equipment worn by divers isolates them from other possible hazards such as asbestos, lead, and toxic chemicals. The ability of divers to operate safely in all sorts of hazardous environments is well documented.

A second alternative is the use of robots to replace some or all human activity in hazardous areas. In dry applications, robots can often replace all human workers, while in many underwater instances, it is simply impossible to deploy divers due to access restrictions, contamination levels or high dose rates; thus robots provide the best alternative. In fact, as robotic technology has evolved, it is now becoming apparent that some or all of the underwater tasks previously performed by divers can be more effectively performed by robots; thus providing significant advantages in meeting dose and schedule goals. Working in tandem with, or in lieu of divers, robots excel at complex repetitive tasks and are, of course, immune to the radiation and hazardous material exposure potentially harmful to human operators. The use of actual robots as opposed to the older technology of Remotely Operated Vehicles (ROV's) is a significant step forward in efficiently performing these hazardous and complex tasks without exposing humans to the associated risks.

MANNED INTERVENTION BY DIVERS

Commercial nuclear plants and a number of DOE sites have successfully used divers in spent fuel storage pools, suppression chambers, rad-waste tanks, and even in the reactor vessel. Extensive experience in commercial plants and recent work at DOE sites has shown that divers working within the water shield can approach highly radioactive materials while receiving minimal exposure. At close range, sometimes within arms reach, divers can perform tasks safely, quickly, and accurately. These are often tasks difficult or impossible to perform using surface workers with long handled tools or complex, expensive remote tooling. Divers have a number of cost effective underwater tools at their disposal. These include underwater video for work management and project documentation, high-efficiency vacuum systems for desludging, and plasma arc cutting systems for rapid segmentation and size reduction of bulky equipment.

Radiological Diving Procedures

Radiological diving procedures specific to the types of environments present at D&D sites are designed to prevent skin contaminations, reduce dose, and ensure safe and efficient work evolutions. Divers are fully encapsulated in heavy-duty dry suits with an attached supplied-air helmet. A constant positive pressure is maintained to prevent leakage. Divers are in continuous hard-wire radio communication with surface support personnel. Helmet mounted cameras 'see' what the diver sees and transmit live vide images to a video monitor at the dive control station.

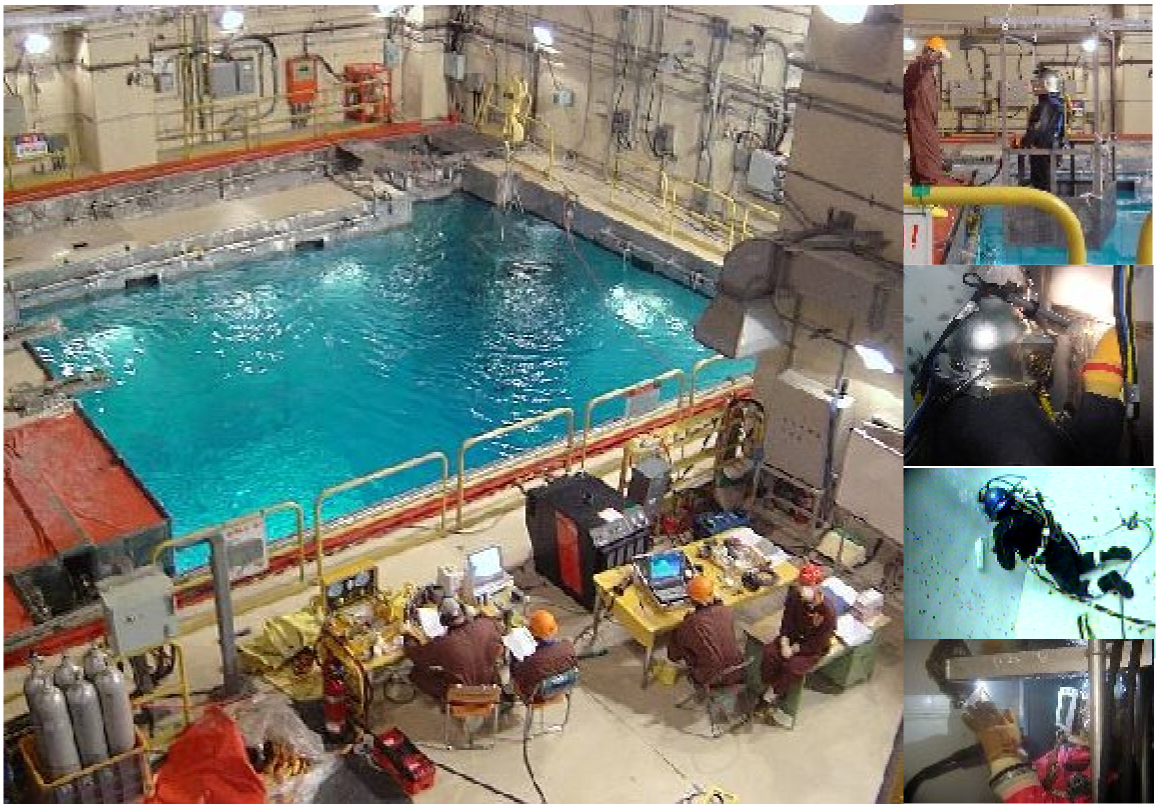

Fig. 1. Typical diving operation. Clockwise from left: dive control station, diver entering fuel pool, diver inspector, diver applying fixative, and diver welding.

Divers wear electronic dosimetry that provides real-time dose tracking during dive operations. Radiation technicians know at any given time the dose rate and accumulated whole body and extremity dose. Utilizing radio communication and video, the diver can be instantly directed to change position or exit the area if dose rates change.

The techniques for preventing skin contaminations are simple but effective. The dive suit, of course, provides the first line of defense. Prior to diving, it is carefully leak checked. A leak check is repeated as the diver enters the water. Dive equipment is very robust, but additional suit protection can be added when working around equipment or components that might damage the suit. During the dive, a positive suit pressure is maintained so that a leak would be visibly apparent and the escaping air would prevent water intrusion.

The most critical time in the dive evolution is diver egress. As soon as the diver breaks the surface, surface support personnel begin a wash-down. The diver is thoroughly rinsed as he emerges from the water to remove any loose contamination. Radiation Technicians carefully check the diver for signs of contamination prior to removal of any dive equipment. Once cleared, equipment is dried and cautiously removed following the basic procedures for removing protective clothing in any contaminated environment.

Diver Tools

Divers have a variety of tools at their disposal. Many of these are common tools used by surface workers, but because the diver is able to approach irradiated components more closely due to the water shield, these tools can often be employed more effectively. Cleaning and sludge removal is typically performed using submersible vacuum/filtration systems. The entire system including the pump and filters is submerged making it easily accessible to the divers for maintenance and filter change out with minimal exposure. For example, a bank of eight filters with dose rates of up 20 Rem can be changed by a single diver in a few minuets with total whole body dose of just a few milirem.

As the example project below illustrates, removal of existing coatings can be performed using high-pressure water jetting, mechanical abrasion, or aggressive scrubbers. Application of fixative can be performed underwater using plural components pumps to force a two-part epoxy through rollers designed to evenly distribute coating over various surface geometries. Underwater coatings are formulated to remain cohesive in immersion, cure rapidly, and achieve a high degree of adhesion.

Cutting and segmentation of ferrous components can be performed efficiently using both thermal and mechanical cutting tools. Thermal cutting can be done using plasma arc, oxy-arc torches, thermite lances and arc saws. Mechanical tools such as shears, nibblers, saws, and abrasive cutting discs have all been used successfully. Careful selection of the proper tool is essential. Consideration must be given to the material to be cut, access, dose rate, and contamination levels. Choosing the wrong tool may hamper productivity, spread contamination, or increase exposure.

Example Diving Projects

One DOE site faced the major challenge of cleaning and preparing aging spent nuclear fuel basins for closure by removing highly irradiated sludge and debris in the flooded pools and then removing the water to eliminate potential environmental risks to the adjacent aquifer. In addition, an underwater fixative had to be applied prior to dewatering to prevent the release of embedded radioactive materials during draining.

The project included cleaning and removing water from four basins. There were three concrete epoxy-coated basins of up to 770,000 gallons and one stainless steel-lined, 118,000-gallon reactor canal used so support reactor operations and store spent nuclear fuel. One of the main challenges to removing water from the basins was the risk of contamination from the walls and floors of the basins becoming airborne as water was removed. Having divers apply a fixative underwater eliminated this risk.

The original plan was for workers standing at the edges of the basins and on rafts or bridge cranes to use long-handled tools to manually scrub the walls and basin surfaces. There was significant risk of skin contamination, of workers falling into the basin, or sustaining injuries from the awkward working position. Surface workers would also be required to handle and package highly irradiated materials as they were removed from the water. The diver option mitigated or eliminated these risks.

It was initially assumed that the majority of sludge and debris in the basins would be removed prior to commencing diving operations. Pre-job planning and surveys showed that this would be very inefficient and would result in unacceptable exposure to surface workers. It was determined that using divers to assist facility operations personnel would reduce dose, cost, and schedule. Divers used commercially available underwater cleaning tools to remove loose contamination and coating from underwater surfaces. Existing basin sludge and debris produced by cleaning operations was removed using an underwater vacuum system configured for use by divers. The entre system, including the pump and filters, was deployed underwater. This allowed divers to service the system and change filters with the benefit of the water shield.

Debris removal was particularly problematic due to high dose rates and small size of some components. Together, divers and support personnel removed approximately 31,000 pounds of service equipment and other spent fuel-handling debris. The divers were able to locate and deal with tiny but highly radioactive debris particles that otherwise would never have been found before water was removed. In one case, divers located and removed a small screw head reading 90 R per hour. The screw head was placed in a container underwater with the diver receiving only 5 mR during the disposal operation.

A fixative was applied underwater using a modified epoxy pump delivery system. The epoxy material was specially formulated for underwater application and reached full cure underwater in twelve to twenty-four hours. This approach eliminated the need for the installation of extensive scaffolding and of course significantly reduced dose to the applicators while preventing the risk of airborne contamination.

The dive team completed 411 dives. Divers averaged about 6.5 mR per dive, with two dives a day, well below the dose estimated in the original work plan. The estimated total person-rem project dose was 12.5 Rem. Actual person-rem project dose was 3.3 Rem for a savings of 9.3 person-rem.

There were two incidences of skin contamination. The team completed 265 dives before the first occurred at 3,000 disintegrations per minute (dpm). The contamination was immediately removed. A second skin contamination occurred at 4,200 dpm. The contaminations presented virtually no dose to the diver and were attributed to donning and doffing of the dive suits.

Prior to cleaning and application of the fixative, basin walls read as high as 12,000 dpm/100cm^2. Post application contamination levels were approximately 1,000 dpm/100cm^2. An added benefit occurred during application of the fixative. Divers found a small leak in the basin when the fixative was drawn into a three-millimeter crack in the basin wall. Work was temporarily halted while the team patched the leak. It is unlikely that the leak would have been found has the fixative application not taken place underwater by divers.

The overall cost of the project was $1.6 million versus an estimate of $1.9 million. Divers were able to clean the pools and apply the fixative in less time than planned.

In some cases, it may be advantageous to flood an otherwise dry component for D&D work. A commercial nuclear utility is considering this in support of replacement of the steam generators (SG). The current plan is to remove the four steam generators from containment and place them in temporary facilities on site. Dose from the tube bundles inside the generators will be quite high. Once the steam generators are in place, they will be filled with water so that divers can enter and remove components that will clear the way for segmentation and packaging of the generators.

The SGs will be placed horizontally and a diver access will be cut in the outside wall of the steam dome. Divers will enter and begin cutting and removing the separator cans and separator support plate to provide access to the tube bundle support beams. Several cutting methods are being considered. Plasma arc cutting is suitable for both carbon and stainless steels up to one inch thick. It is also a relatively clean thermal cutting process that will help to maintain the water clarity essential for safe diving operations. For cuts such as the drain tubes or thinner wall plate, reciprocal saws or shears may be the better choice.

Cutting the large tube bundle support beams will place the diver in proximity to the tubes and potentially in a high radiation field. This area must first be carefully surveyed so that the cutting plan remains consistent with ALARA goals. Divers will wear teledosimetry for real-time dose assessment. Additional shielding over the tubes may be required.

Segmented pieces of the support beams must be removed from the SG. Since there is the potential for contamination on these components, removal will require careful coordination with radiation protection personnel to prevent the spread of loose contamination or unnecessary exposure to irradiated components.

The final planned cut will sever the upper portion of the tube bundle shroud from the lower portion. Divers can access both sides of the shroud at the cut location. Cutting from within the shroud will place the divers almost in contact with the tube bundles so dose may preclude this option. Dose will be lower on the shroud exterior, but there is risk of breaching the tubes when cutting from this side. Breach of a steam tube would introduce highly irradiated water into water inside the SG and risk an environmental release of radiation. Dose reduction dictates that an efficient cutting method be chosen to limit the diver's stay times. Plasma arc cutting would likely be the method of choice, but may risk damaging the tubes. Placing a shield on the shroud interior to protect the tubes could be an option but would again bring the diver close to the radiation source. These and other issues are still under discussion.

Although ALARA planning is still in progress, preliminary indications are that the use of divers may be the only viable approach if ALARA goals are to be met while keeping cost and schedule in check. Performing the work in the dry would likely result in project exposures and costs several times that of the diver approach.

UNMANNED INTERVENTION WITH ROBOTS

Robotic intervention is still relatively new to D&D projects. Robotic technology led by military research and development has evolved exponentially over the past ten years. There are more than 20,000 robots in active service with the U.S. military in Iraq and the military projects that it may be more than fifty percent robotic in the near future. These advances in technology have now become available and are applicable for other uses such as D&D work. With the advent of powerful onboard processors, machine vision, sophisticated computer simulation and modeling, innovative programming techniques, LED lighting and other advances in robotic technology, robots can now perform many tasks previously difficult or impossible without continuous human intervention.

It is important to note that actual mobile robots are distinctly different from remotely operated vehicles (ROVs) or remote tools. While ROVs require continuous human control, robots are pre-programmed, are capable of functioning autonomously, and are able to make decisions and alter actions in response to various sensory inputs. Nevertheless, humans retain final override capability. When equipped with machine vision for guidance, i.e. the ability to 'see' and process information, robots can perform many tasks that heretofore could only be accomplished by human operators. Robots performing these tasks offer significant reductions in dose, cost, and schedule. In fact, for underwater applications where dose rates or contamination levels preclude diving, robotics provides the best, or perhaps, the only solution. Diver and robotic intervention offers better results by literally or virtually bringing the worker closer to the task. In both cases, this is performed without compromising worker safety.

Inspection Tasks

Robots specifically designed for inspection provide superior methods of inspecting almost any area where there is a concern for worker safety. Today's high-resolution cameras combined with mobile robots and other sensors allow for high quality inspection under the most difficult conditions. A further advantage is that since the results are stored digitally, inspection results are not only accessible in real-time on-site; they are permanently available and easily retrievable for later review.

Wet or dry inspection is equally practical and efficient. The robot depicted in Figure 2 is an inspection robot utilized in a recent surface inspection of the deteriorated coating of a wet reactor suppression chamber at a commercial nuclear utility. The data strip in the lower portion of the picture shows the output of the robotic inspection: on the left high-resolution human viewable pictures; on the right 3 Dimensional measurements of the defects for import into a CAD program.

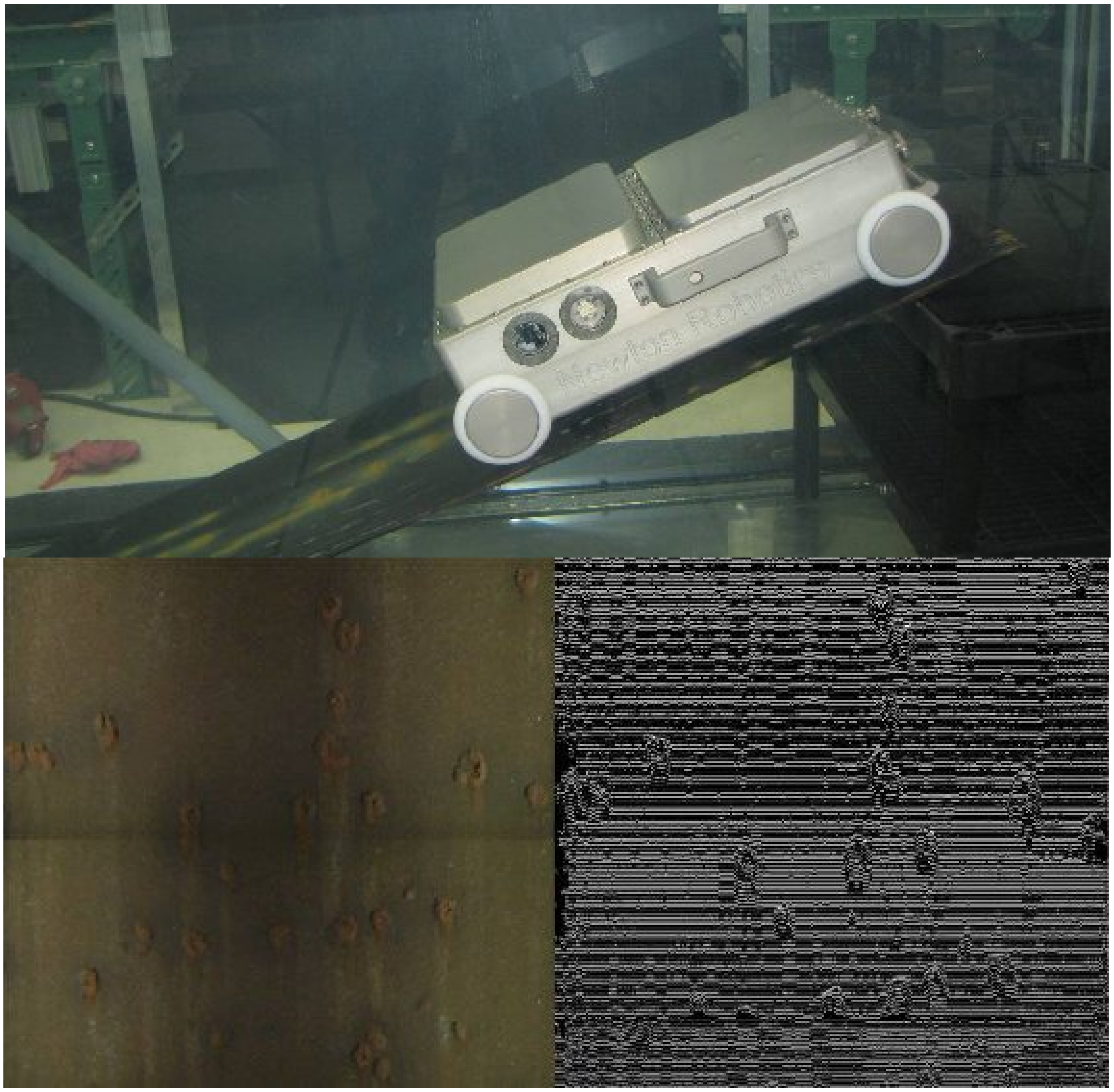

Fig. 2. Upper picture: Surveyor robot gathering data underwater; Lower picture: Left human viewable pictures; Right matching 3D measurements of the defects.

Robots have the capability of performing a variety of inspection tasks. For example, multiple measuring heads can be use by an inspection robot to simultaneously provide data in varied formats. Thus, one robot can provide human viewable cameras, machine vision cameras, IR cameras, ultrasonic thickness sensors, as well as cleaning arms if required to prepare the surface. As a further component of the inspection process, since the robot knows its exact location and that position is a component of the stored data, a robot can always be directed to return to a precise location for further data gathering if requested by a human reviewer.

For inspection service robots may be battery operated storing all of the gathered data internal to the robot for download after the robot returns to the entry/exit area. With modern battery technology, battery operated inspection robots can operate for as long as 10 hours on a single charge; thus not requiring any tether or cables. In dry service, all data can typically be transfer via WiFi in digital format and is available real-time for human review.

Robot Guidance Methodology

Robot guidance is typically accomplished via a combination of pre-planed paths and actions that can be altered by pre-programmed modifications in response to real time machine vision information derived during operation. Additionally, human override or positioning via tele-operation is typically available from a control panel located outside of the hazardous area. Continuous data from the robots including human viewable pictures can be supplied to the control panel for monitoring.

An example of this type of robot guidance would be the methodology utilized in recoating the Torus pictured in Figure 3. In this case, a complete 3D model of the Torus was constructed from design drawings. The model was corrected using data gathering robots and photogrammetry. All robot movements were simulated in powerful simulation software and then those pre-determined movements were programmed into the robots. Any unanticipated objects or conditions found in the actual Torus are 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.

The use of machine vision coupled with mobile robots allows for significant gains in the ability of robots to perform complicated functions without human interaction. Just as with any human activity, the ability to see where you are located in relation to the work and the ability to continuously check to see not only the progress of the required work but also confirm successful conclusion is invaluable. This feature dramatically increases the efficiency with which a task can be performed.

Figure 3 shows a model of a torus and the robots 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 reduce dose by up to ninety-five percent.

In this particular task, several teams of ten robots each will perform 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.

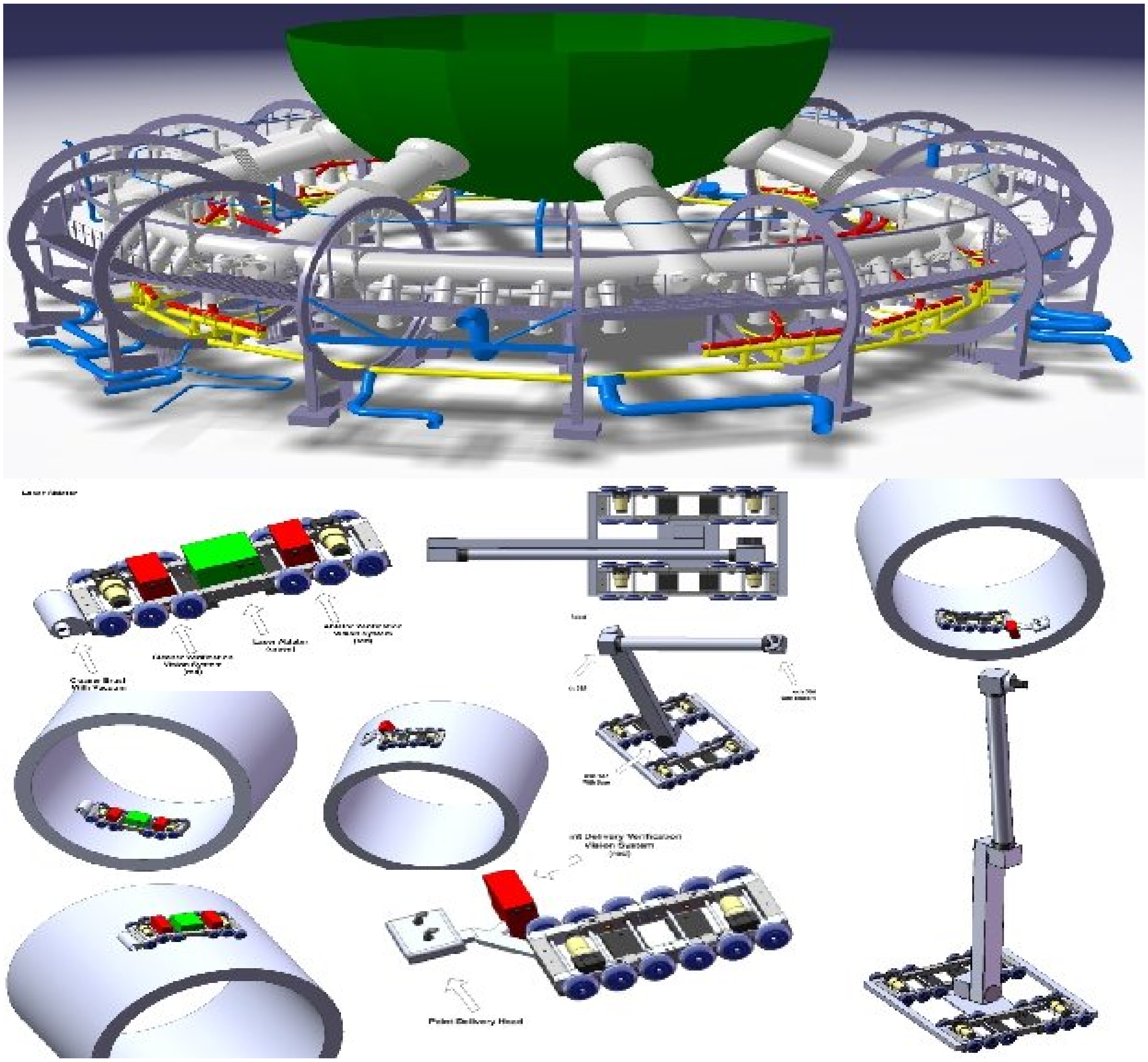

Fig. 3. Upper picture: BWR Torus to be Stripped and Recoated with robot teams; Lower picture: Robotic members of the teams to Strip and Recoat the Torus

Robots Designed for Specific Tasks and Efficient End-effectors

Mobile robots have the unique advantage that the robot and its various end-effectors can be specifically designed for the required task. This specificity of design allows for maximum efficiency in the performance of the required work. Additionally, the ability to design the robot to directly fit the required movements, particularly in hazardous areas, allows for extremely rugged design and in service performance. When multiple robots are utilized in a team, commonly one or more of the robots is equipped with the necessary tools to retrieve any other member of the robot team that may have a fault or is unable to extricate itself from some unexpected hazard.

A specific example of this unity of purpose can be found in the robot teams designed to clean, strip and recoat the torus shown in Figure 3. Each team consists of general surface preparation robots using both mechanical and laser ablation to strip the old coating coupled with machine vision to determine if the coating is fully removed. Pipe OD and ID surface preparation robots also use both mechanical and laser ablation to strip the old coating and machine vision for quality control but are 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 will prepare all areas not accessible to the main surface preparation robot.

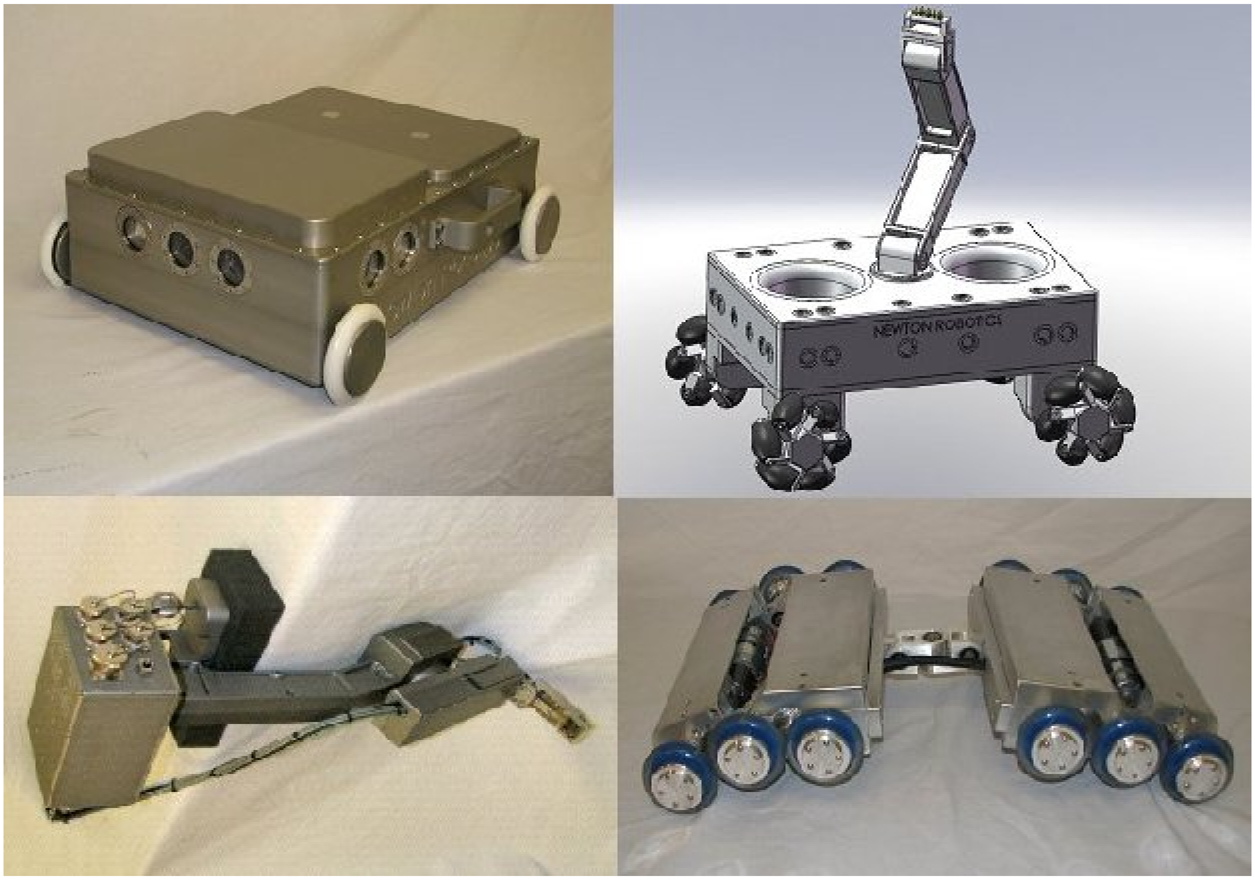

Fig. 4. Examples of robots designed for specific purposes: Clockwise from the upper left: Surveyor data gathering robot; Concrete Removal robot using high pressure water jets; Bridge and Sign inspection robot; Valve Seat inspection robot for hazardous areas

A surface coating (paint applying) robot will use precise machine vision control of spray heads to prevent over spay and confirm all surfaces have been properly coated. Design variations will allow robots to accommodate curved surfaces. Self-movable robot platforms in this team are capable of placing and or removing and replacing any other robot in the team that many encounter difficulty.

Robots have the ability to utilize sensor inputs to precisely control their movements and the use of associated tools and methods. An example of this ability is demonstrated by the fact that often in coating with robotic methods, no overspray exists; thus masking is typically not required and none of the variation in the coating film thickness that exists with human painters occurs.

As a further advantage of the use of robots in certain services, methodology can be utilized that would not be practical or even possible with human workers. For example, the use of laser ablation with very high power lasers and machine vision control of the laser dots for the ablation of or the removal of material creates hazards to humans that can be ignored with robotic service providers.

CONCLUSION

Whether by human or robotic intervention, innovative approaches to D&D can offer new ways to reduce radiation exposure and other health risks while reducing cost and schedule. The use of divers has proven beneficial at commercial nuclear sites since 1968 but is considered an innovation at DOE sites. Robotic technology is advancing a rate that could not be imagined only five years ago. Robots can support humans or completely remove them from risk while performing extremely complex tasks with precision yet are rarely being used.

Unfortunately, new ideas are often difficult to promote. Barriers to the diving approach include the fact that diver capabilities are not well understood, there are erroneous perceptions about safety and effectiveness, other craft & labor see diving as a threat to job security, and a lack of a standardized operational approach. The robotic approach may be even less well understood. Although their capabilities are well know to the military, commercial application of these technologies is in its infancy.

Identifying diving and robotic opportunities at DOE facilities is very difficult. There is minimal history of using either and their services are not being actively solicited. Attempts to generate support are often met with fear, disinterest, and skepticism. Further complicating the effort is the fact that there are typically several layers of contractors between the diving or robotic contractor and the work. Each layer has a vested interest in retaining and taking credit for completing tasks. Determining the full potential for these technologies will require educating contractors, the labor force, and DOE.