INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0389

Dual Arm Work Platform Teleoperated Robotics System

Deactivation and Decommissioning Focus Area

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Summary Report

Dual Arm Work Platform Teleoperated Robotics System

OST Reference #1787

Deactivation and Decommissioning Focus Area

Demonstrated at
Argonne National Laboratory-East
Argonne, Illinois

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Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://OST.em.doe.gov under "Publications."

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SECTION 1

SUMMARY

Technology Description

The US Department of Energy (DOE) and the Federal Energy Technology Center (FETC) has developed a Large Scale Demonstration Project (LSDP) at the Chicago Pile-5 Research Reactor (CP-5) at Argonne National Laboratory-East (ANL). The objective of the LSDP is to demonstrate potentially beneficial Decontamination and Decommissioning (D&D) technologies in comparison with current baseline technologies.

The Dual Arm Work Platform (DAWP) system was used to perform mechanical dismantlement of the radioactive reactor and bio-shield structures. The DAWP manipulated standard, commercially available tools (i.e., circular saws, jackhammers, etc.) using two Schilling Titan III hydraulic, teleoperated manipulator arms that were controlled from a remote location. At the CP-5 reactor facility, the two arms were mounted to a steel work platform (DAWP) designed to hold the associated tooling, utilities, and cameras supporting the operation of the manipulator arms and providing a sturdy base for lifting the assembly into the reactor assembly using the facility's polar crane. Once positioned the system segmented, dismantled and moved the radioactive material to a transfer canister. Operators would use the DAWP in conjunction with Rosie, a tethered, teleoperated robotic system to off-load radioactive materials to a lower radiation dose staging area for final manual packaging into appropriate disposal/transport containers. Aluminum, lead, boral, and graphite low level radioactive waste was size reduced by the DAWP and handled in this manner throughout this demonstration.

The DAWP demonstration focused on the use of the DAWP to segment and dismantle the CP-5 reactor tank and surrounding bio-shield components (Including the graphite block reflector, lead and boral sheeting) and performing some minor tasks best suited for the use of teleoperated robotics that were not evaluated in this demonstration. The DAWP was provided by a consortium of national laboratories and industry manufacturers. Individual components and subassemblies were purchased from or provided by Schilling Robotics Systems, RedZone Robotics, Inc., ORNL and INEEL.

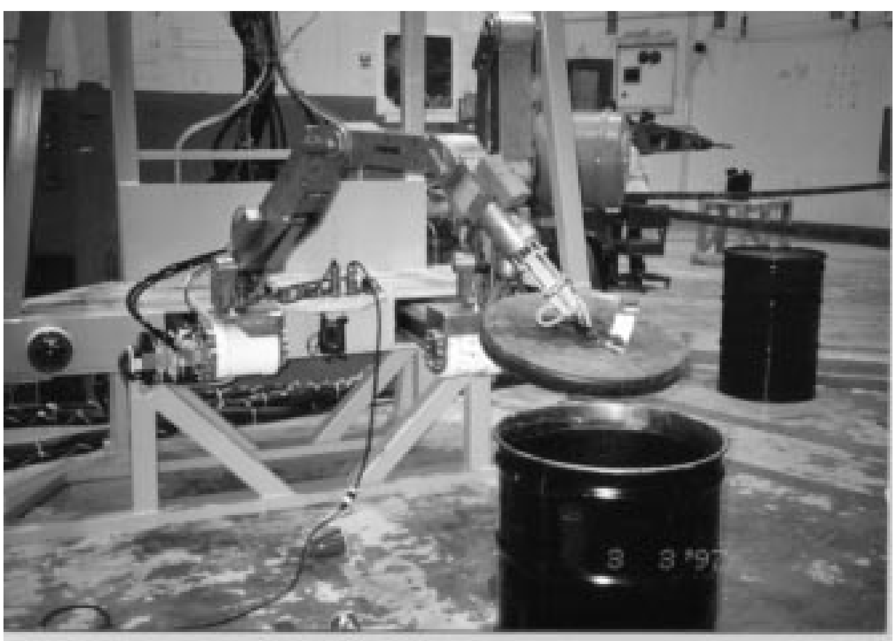

Figure 1. The DAWP during operator training

The demonstration was performed at the Argonne National Laboratory (ANL) CP-5 Research Reactor from June through September 1997. The DAWP's ability to remotely cut and dismantle the aluminum reactor tank; disassemble the graphite, boral, and lead subassemblies; and transfer these materials to a staging area was tested. The current system can be operated by someone approximately 250 feet away without direct line-of-sight.

The Titan III manipulator arms are made from titanium and stainless steel. The arms provide six degrees-of-freedom and are powered by a 3000 psi hydraulic system. Each arm is capable of lifting 240 lbs. The grippers on the arms are capable of exerting a 1000 lb. crushing force and a rotational torque of 75 lb-ft. Various power tools were specially adapted for use with the manipulator arms. The tools were modified at the site by removing interfering blade guards, locking triggers in the "on" position, attaching cable lanyards, adapting the power cords and installing "T-handles" that provide handholds for the manipulator arms' grippers. The tools ranged from crow bars to sophisticated saws that have built-in oil cooling systems and were operated from the control panel.

Technology Status

The DAWP system is not a commercially available product at this time. The CP-5 implementation was its first D&D application. The demonstration of the DAWP was to determine the areas on which improvements must be made to make this technology commercially viable. The results of the demonstration are included in this greenbook. It is the intention of the developers to incorporate lessons learned at this demonstration and current technological advancements in robotics into the next generation of the DAWP.

CP-5 is a heavy-water moderated and cooled, highly enriched, uranium-fueled thermal reactor designed to supply neutrons for research. The reactor had a thermal-power rating of 5 megawatts and was continuously operated for 25 years until its final shutdown in 1979. These twenty-five years of operation have produced activation and contamination characteristics representative of other nuclear facilities within the DOE Complex. CP-5 contains many of the essential features of other DOE nuclear facilities and can be safely utilized as a demonstration facility for the evaluation of innovative technologies for the future D&D of much larger, more highly contaminated facilities.

Key Results

The key results of the demonstration are as follows:

- The DAWP removed 5300 lbs. of graphite blocks, 1400 lbs. of lead sheeting, 620 lbs. of boral, 2000 lbs. of carbon steel;

- Untorqued and removed 26 of the 36 carbon steel studs that were installed in the reactor tank's top flange;

- Size reduced and dismantled a significant portion of the aluminum reactor tank (following approximately 200 linear feet of cuts through 3/8 - 3/4" aluminum plating), and removed the resultant 600 lbs. of aluminum plate from the reactor tank assembly.

- The DAWP was controlled by two operators working in an adjacent control room. In this way, personnel could maintain a safe distance from the radiation in the CP-5 reactor. The DAWP was operating in a radiation field averaging 0.75 to 2.0 R/hr for the duration of this work. By using this remote system, conservatively speaking, approximately 15 person-rem of exposure was saved.

- Data was obtained concerning the training of previously untrained technicians into competent DAWP operators. This demonstration has shown that technicians were considered trained after an average of approximately 8 hours formal training and approximately 40 hours of mock-up training.

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Licensing Information

No licensing or permitting activities were required to support this demonstration.

Web Site

The CP-5 LSDP Internet address is http://www.strategic-alliance.org.

TECHNOLOGY DESCRIPTION

System Configuration and Operation

The DAWP consists of a platform base, two Schilling Titan III six degree-of-freedom (DOF) hydraulically-driven manipulators, a remote viewing system, a lighting system, a tool control system, and a tether that supplies the hydraulics, power, and control signals to drive the DAWP functions.

Platform Base

The platform base provides the framework for the manipulators and remote systems in a crane-deployable package. The platform is fabricated of steel plate and has bolted and gasketed access panels to all of the internal hydraulic, electrical, and electronic components. The base weighs 4950 lb. Each manipulator is mounted on a 2 DOF actuator package that places a rotary actuator at the end of linear actuator. The linear actuators have 18 inches of range to extend the arm base out into the work space; the rotary actuators have 90 degrees of rotation so that the manipulator base can be moved from horizontal to extend the envelope down. Position of these actuators can be set anywhere between the two limits of motion.

Schilling Titan III Manipulators

DAWP's manipulation capabilities are provided by two commercially available Schilling Titan III hydraulic manipulators. These manipulators have the "gamma" option which has smooth external surfaces for easier decontaminability. Each arm has a maximum extension of 78 inches and a maximum lift capacity of 240 lb. at full extension. The gripper capacity when fully open is 6 inches; maximum grip force is 1000 lb. Electrical cabling and hydraulic valving and routing are all done internally to the arms. Each wrist has a force/torque sensor to measure the contact forces applied to objects in the task space.

Figure 2. The DAWP size reducing and packaging a highly activated reactor component.

Cameras/Lights

DAWP deploys two color stereo camera systems and seven standard NTSC auxiliary cameras. The upper stereo camera is mounted on a pan/tilt mechanism on a linear slider which is the width of the upper crossmember of the DAWP lifting structure. The lower stereo camera is mounted on a pan/tilt mechanism between the manipulators facing down. Five of the auxiliary units are color with pan, tilt, zoom, and focus capability and are mounted in a Plexiglas housing for environmental sealing. Four of these cameras are mounted on the front face of the DAWP structure. The fifth is mounted to the underside of the DAWP lifting fixture and designed to provide an overview of the DAWP deck and tool plate. Black and white cameras are housed on each manipulator wrist. In addition, video and power connections are provided on the platform deck for tooling cameras. Task lighting is provided by lights mounted on the DAWP.

Tool Support

DAWP provides for control of five electrical and two hydraulic tools. The control system can control two electrical tools (or two functions on one tool) or one hydraulic tool at any one time, but all electrical and hydraulic ports can be occupied at one time by a full suite of tools designed for a series of tasks. The electrical tools have environmentally sealed connectors located across the front center of the top of the DAWP deck. Each tool port can control either 110VAC or 220VAC tools depending on how the individual tool connector is wired to the tool. The control mode is on/off only. The hydraulic tool control ports are located on the top deck on either side of the row of electrical ports and have quick release “no leak” fittings. Valving internal to the DAWP provides bi-directional control of the hydraulic fluid for the tool. A vertical tool plate is provided for tool fixturing via 1/4-20 mounting holes on 2 in. centers.

Tether

DAWP is designed to minimize (but not eliminate) the on-board electronics and hydraulic valving for radiation tolerance and decontaminability. Therefore, a relatively large diameter tether is required to link the platform to the hydraulics source and control system. The completed length between the basement-mounted power source and the DAWP is 100 ft, but the useable length after accounting for floor pass-thru, cable routing, strain relief, and mounting at both ends is 60 ft. The tether is broken out into two bundles and wrapped with a canvas sheath. One bundle contains all electrical power and signal cables. Electrical power delivered through the tether to DAWP consists of 110/220VAC used for the tools, 110VAC used for on-board power supplies, and 12/24VDC used for the various on-board subsystems. The other tether bundle is hydraulic supply and return only. The two bundles are wrapped separately so that electrical cables will not be damaged in the event of a hydraulic leak. To avoid tangling, the two bundles are strapped together with cable ties to keep them parallel.

Field-mounted Control Hardware and Hydraulic Power Unit (HPU)

For CP-5, 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. DAWP uses a commercial Schilling-supplied HPU, mounted on wheels so that it may be readily moved. A cooler is provided in the circuit to keep the hydraulic fluid at an acceptable temperature at all times. The hydraulic fluid used in the DAWP (manipulators, base degrees of freedom, and hydraulic tooling) is HoughtoSafe™ 620 water-glycol. Maximum useful operating temperature of the fluid is 140 degrees F. The DAWP electrical tether bundle terminates at the field rack located on the service level. This equipment rack houses the necessary control interfaces to the DAWP and communicates with the operator station in the control room. The rack itself is a standard 19-in. instrument rack mounted on rollers. In order to maintain control system temperatures at a reasonable level, the field rack has an air conditioner located on the rear door.

Master Control Rack

A master control rack is located in the CP-5 control room on the left side of the operator station and provides the computing power for the DAWP operator control station. It is a standard 19 in. instrument rack, contains two VME computer backplanes, and is also air conditioned. Communications between the field rack and the master rack in the control room is handled by a bus repeater. A 125 ft. long four bundle fiber optic cable connects the two racks.

A Sun Microsystems-compatible Themis VME backplane computer provides all of the DAWP operator control station graphical user interface (GUI) functions. The Themis is tied to the real-time control VME rack by an ethernet network link. A primary hard disk drive, backup drive, CDROM drive, and tape backup drives are also provided. The Themis hard drive contains all of the network-loadable software for the real-time controller. Operator GUI input is done by a trackball and selector switch on each side console of the operator chair. All DAWP real-time control functions as well as the operator's interaction with all buttons, knobs, and switches are handled by the real-time control VME backplane located in the top of the master rack.

Operator Control Station

The DAWP operator control station consists of a video console, control chair, master controller station, and the VirtualwindoW stereo viewing system. The video console consists of four 19 in instrument racks, containing video monitors, graphics monitors, and the VirtualwindoW controller. The racks are arranged such that the remote views and control menus are located at ergonomic angles to permit easier viewing by the operator. The control chair is fixed to a raised floor and maintains the orientation of the operator to the video console and the master controller station and provides manual input to the GUI and camera control and tooling functions from two side consoles. The master control station provides a mount for the two Schilling minimaster controllers. VirtualwindoW is composed of a stereo monitor at eye level directly ahead of the operator in the video console, CrystalEyes LCD glasses, and a microphone headset for voice command.

Figure 3. Training an operator at the DAWP console.

Each side console is a mirror image of the other and has all of the same functions available. Functions include trackball and selector switch for the GUI, joysticks for camera positioning, switches for camera lens control, and two foot switches, left and right, for tool activation. The GUI is divided into two menus, one for each graphics monitor. The menus handle platform base electrical power, HPU control, various manipulator functions depending on the control modes selected, tools, remote viewing, lights, camera to joystick assignment, tool to footswitch assignment, and videoswitching. Control of actual manipulator teleoperation is primarily through the minimaster LCD screen-based menu system.

SECTION 3

PERFORMANCE

Demonstration Plan

Demonstration Goals

During the D&D process, the handling of highly radioactive materials, the deployment of tools and sensors and the dismantlement of components built from many different materials can be a long, labor intensive process that has the potential for high exposure rates, heat stress and injury to personnel. Mobile robotics systems provide solutions to these hazards. The requirements of this demonstration were that the DAWP perform the dismantlement of the CP-5 reactor vessel and other miscellaneous tasks within budget and on schedule while justifying the expense by a savings in cumulative doses received by project personnel. As part of this goal, the following are additional factors that were evaluated :

- System and peripherals must be operator-friendly. Ideally, the system must be designed to allow personnel currently available to the D&D project to become trained as operators in a reasonable time frame.
- The operating and control system should be user-friendly. Controls should be well laid out, ergonomics suitable for a large differing group of persons, normal operations should be logical and easy to execute. System parameters and alarm indicators shall be accessible and easy to evaluate and respond to.
- 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.
- The system must be flexible and easily adapted to changing conditions, tooling requirements and operational needs.
- The system must truly be remotely operated. Adequate distance or shielding must be available to operators such that exposures to radiation, hazardous materials and conditions are minimized.
- Preventive maintenance must be minimal with only moderate to long term frequencies (minimum 3 to 6 month) under normal or expected operating conditions. When the need arises, the maintenance should be simple and straightforward with a duration of less than one work shift. Replacement parts and common wear items should be available for purchase at a reasonable cost.
- Reliability is of paramount importance. Downtime and system or component failures translate into additional costs, possible personnel exposure, and if unexpected, possible safety implications.
- The system, if possible, should be able to perform remote tasks nearly as rapidly as conventional practices would allow OR have the ability to perform tasks that otherwise would be difficult, impossible or impractical to perform.

Figure 4. The DAWP Suspended from the Crane Removes Trash from the Reactor Top

Demonstration

The DAWP continues to serve as the mechanism for dismantling the reactor vessel and remove the graphite moderator. As the demonstration has progress, performance indicators were the amount of time to train qualified operators, how well the schedule and budget were met, and any major problems and malfunctions. Tasks have included the remote size reduction of the control rod, the dismantlement of the aluminum reactor tank, the removal of 36 bolts connecting the seal ring to the reactor vessel flange, and the jackhammering and subsequent removal of the graphite moderator. While performing these tasks, numerous tools were adapted to the DAWP "T" handle and evaluated with regards to both the success of the tool at dismantling the reactor, and the DAWP's success at manipulating the tool. Although the LSDP demonstration is now complete, the DAWP will continue to be used to dismantle the reactor.

Results

The demonstration was performed at the ANL CP-5 Research Reactor from June through September 1997. Overall the DAWP proved itself as a viable tool for use in applications where exposure level would preclude the use of personnel.

The DAWP was very successful in meeting most of the stated objectives. The DAWP was successful in the three areas of demonstration, including (1) showcasing DAWP's ability to dismantle and removed the reactor vessel, graphite, and miscellaneous low level waste from the reactor, (2) work in conjunction with Rosie, a mobile teleoperated robot, to move radioactive materials from the reactor assembly to a staging area using a specially designed steel transfer can, and (3) perform remote miscellaneous tasks (i.e., size reduction of activated material, removal of bolts, etc.) that the DAWP was not necessarily designed to do, but for which remote operations were required. Initial startup problems were slow in overcoming. However, much of this can be attributed to this being the first full scale demonstration of the DAWP, with an associated steep learning curve.

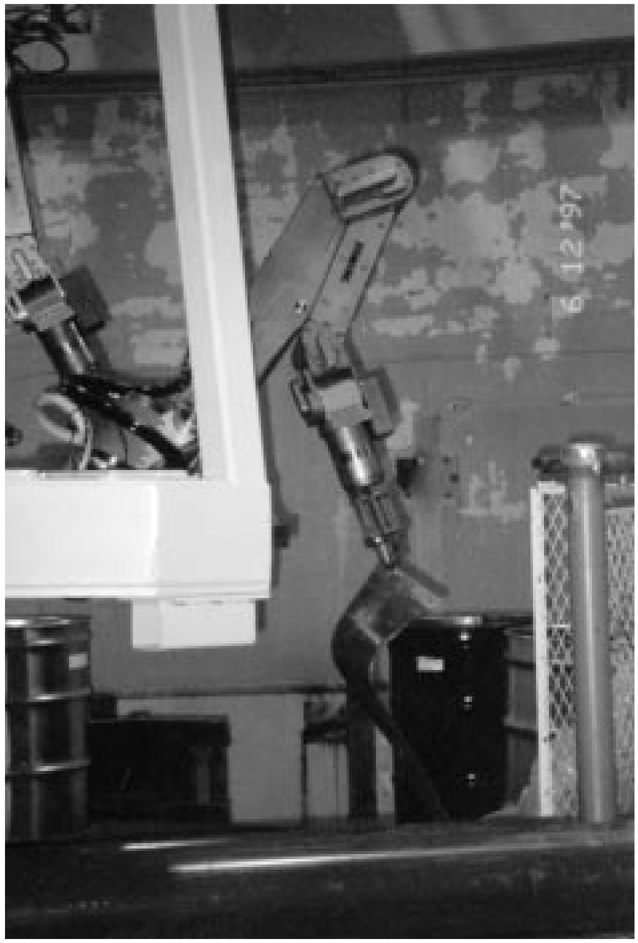

Figure 5. The DAWP Removes Material from the Reactor Top for Disposal

The greatest problem was associated with leaks within the arms, due primarily to the use of HoughtoSafe™, a glycol-based non-hazardous hydraulic fluid. HoughtoSafe™ was used to prevent introducing hazardous materials into a radioactive environment. However, the commercially available Shilling manipulator arms were not designed for this fluid, and many leaks and resulting down time occurred at the beginning of the demonstration. It is believed that the HoughtoSafe™ degraded the fittings in the arms. While there was not an operations or personnel safety concern, this was the primary reason for these leaks and resulted in very significant down times.

Additional results are described below:

- Much was learned about the field operation of the DAWP. Many improvements were made while the demonstration was ongoing, including improvements to the cooling system, cameras and plexiglass camera housings, operator interface, and the operating software. These improvement greatly increased the productivity of the DAWP and are expected to be incorporated into the next generations of the DAWP.

- Using a jackhammer fitted to the T handle, the DAWP demonstrated that the graphite could easily be broken up. The DAWP, in conjunction with the Rosie mobile teleoperated robot, safely off-loaded a total of 8450 lbs. of radioactive materials including graphite blocks, lead sheeting, boral, and aluminum plate from the top of the reactor assembly with radiation levels up to 1.2 R/hr.

- Using a circular saw, the DAWP successfully demonstrated that it could be lowered into the reactor tank via the facility crane (20 ton polar crane) and cut the tank into manageable sections. This work included removing or working around a boral seal plate above the graphite and miscellaneous wires and materials. This proved very encouraging, as much of this material was a significant hindrance to the operators. The DAWP also showed it could perform extremely delicate and intricate operations. Additionally, the dose rate in the tank reached 20 R/hr, and thus a substantial savings on personal exposure was achieved.

- Considering the relative complexity of the DAWP and all of the interrelated systems, the DAWP is quite efficient in reducing the complexity down to a well-managed, concise operating structure. This efficiency greatly contributed to the training program that was developed for CP-5 personnel. The project developed its own training program during the installation and setup of the robot. This caused some delays in controlling critical path work. Had a suitable training protocol been established prior to mobilization, the time loss would have been minimized or averted. Of the trained personnel, a substantial minority (approximately 40%) of candidate personnel lack the skills needed to qualify as a DAWP operator in the necessarily short and aggressive training program. The training of a core group of operators (4) and one supervisor required over 200 hours of cumulative operating time.

- The DAWP was typically controlled by one operator working in an adjacent control room. In this way, personnel could maintain a safe distance from the radiation in the CP-5 reactor. By using this remote system, a significant amount or personnel exposure was avoided.

- The greatest weakness is the system's tether management. The tether is the lifeline for this system. Movement of the system required careful attention to tether manipulation. Additionally, if a break in the communication between the CPU and the arms occurred (through a break in the tether or a computer glitch) the arms would automatically release grip tension, thus dropping any tools, materials, etc. into the reactor. Improvements to the system would greatly enhance the operability of the system and minimize the likelihood of a catastrophic shutdown of the system.

- The control console and associated components are well laid out and efficient in their use of space. In particular, the control chair, console, and control functions provide a great amount of control functions in a small (approx. 15" monitor) area. The control panel was adjustable and no operators complained of any discomfort due to the layout or ergonomics of the panel or seating arrangement.

Figure 6. The View of Cutting Operations through Viewing Monitors from the Console Chair

- The DAWP has a voice-activated camera that interfaces with the head movements of the operator. This feature was found to be handy in certain situation (i.e., tight situations, or when a number of camera views were required) but preferred to have the camera on one setting without operator control during the routine tasks.

- The DAWP proved to be versatile and capable of performing all tasks required. Tool change-outs were fairly easy, and operation of the tools became fairly routine. However, tasks assigned to the DAWP generally took much longer to perform than what would be required by hand. This is due to the manual dexterity an individual would have performing tasks by hand, as opposed to the dexterity limitations imposed by performing tasks remotely via the manipulators.

- The stereoscopic camera was found to be more of a hindrance than a benefit during the D&D activities. The stereoscopic camera does not have the ability to zoom, and the stereo vision was found to cause headaches after prolonged use.

- The DAWP software includes an I-GRIP computerized representation of the reactor and the individual components. This model can be used to experiment with different dismantling techniques and sequences prior to actual D&D. However, the computer model was based on existing facility drawings, which were often inaccurate. Because the source drawings were inaccurate, the I-GRIP model was inaccurate. Therefore, while this could potentially be a very helpful tool, the I-GRIP model was rarely used during the demonstration.

Figure 7. A Technician performs Maintenance on the DAWP

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

The DAWP system is applicable to radiological and/or hazardous waste sites where exposure levels prevent the use of prolonged human exposure, and the reduction of exposure levels is either impossible or impractical. The system was found to be versatile, and could be adapted to most hazardous environments. This technology showed the following characteristics at the CP-5 demonstration:

- The DAWP system can be used to deploy different types of equipment and tools in a variety of different tasks. The arms are capable of manipulating saws, jackhammer, and survey instrumentation.

- The DAWP system can be effectively handled by one operator working remotely in an environmentally controlled area. Productivity limitations are based on operator fatigue and attentiveness, suitability to the required tasks, and system reliability, not exposure or ALARA concerns. However, maintenance on DAWP may require personnel to be exposed to some contamination on DAWP.

- The DAWP can effectively handle loads which are larger and heavier than personnel could handle manually with hand tools.

- The DAWP can be moved to a low dose or protected area for maintenance operations, reducing personnel exposure during these procedures. The DAWP is capable of disengaging and re-engaging tools remotely, so that a variety of tasks can be performed without down time or removing the robot from the hazardous environment.

- The DAWP did undergo numerous troubles upon startup. The primary problem arose with the hydraulic fluid. Each arm had to be decontaminated and sent back to the manufacturer to be rebuilt. It is believed the HoughtoSafe™ either disintegrated o-rings in the arm or otherwise caused damage within the arms. The result was often heavy leaks which required the cession of work. The DAWP was able to function with only one arm. However, future operations are highly encouraged to purchase a spare arm, to be attached if an arm in use breaks down.

- Other problems occurred with the overheating of the system (a second heat exchanger was added, resolving the problems), some software glitches, and minor troubles with manipulating the tools. As operational knowledge of the robots and the proficiency of the operators increased, most of these problems were resolved.

- Having an on-site technician capable of performing routine and preventative maintenance is essential in avoiding costly decontamination of parts.

Competing Technologies

The DAWP system was specifically assigned to the CP-5 reactor dismantlement work to provide remote capability for use on tasks that had elevated radiation levels and where worker exposure was an issue. As this is an emerging technology, there are no known systems capable of performing all the tasks for which the DAWP is capable. This includes the DAWP adaptability to differing environments and tasks, and the video and audio feedback capabilities to allow it to be fully remotely controlled.

The typical approach in projects with high exposure levels is to use custom designed built-for-the-task remotely operated equipment using as many commercial components as possible. Generic off-the-shelf total manipulator systems for remote work, especially with the crane hook deployment feature as required for CP5 and with the high lift capacity necessary to deploy heavy D&D-oriented tools, are not generally available. However, Schilling does make the Gemini™, a two-armed hydraulic manipulator system which uses their Titan manipulators and is crane-deployed.

The competing technology is the use of personnel, long reach tools, conventional technology (including standard D&D tools) and engineered controls to reduce exposure. The DAWP can be an essential tool where exposure levels are beyond engineered controls. However, the system is expensive and does have limitations in confined areas. It is up to the individual sites to determine whether the system expense justifies the reduction in exposure.

Patents/Commercialization/Sponsor

There are currently no patents pending on the DAWP technology .

SECTION 5

COST

Introduction

This cost analysis compares the relative costs of the innovative technology of the Dual Arm Platform to a baseline technology of manual dismantling. The information presented will assist decontamination and decommissioning (D&D) planners in decisions about using the innovative technology in future D&D work. This analysis strives to develop realistic estimates that represent D&D work within the DOE complex. However, this is a limited representation of actual costs because the analysis uses only data observed during the demonstration. The demonstration included removal of lead and boral sheeting (which cover the graphite blocks forming the bio-shield assembly) and removal of the stud and carbon steel ring at the top of the reactor as a precursor to segmentation of approximately 1/3 of the reactor tank, removal of 5,420 pounds of bio shield materials (graphite and boral), and ultimate removal of approximately 9,920 pounds of low level radioactive waste (comprised of aluminum, graphite, boral, lead, and steel. The demonstration did not include other reactor core dismantlement activities such as the removal of piping, plenum, etc. Some of the observed costs will include refinements to make the estimates more realistic (such as adjusting for learning curve with the new equipment). These are allowed only when they will not distort the fundamental elements of the observed data (e.g., do not change the productivity rate, quantities, and work elements, etc.). The Dual Arm Work Platform Report (ANL, 1997) provides additional cost information and is available upon request from the Argonne National Laboratory (ANL).

Methodology

This cost analysis compares an innovative technology for remote demolition using the Dual Arm Work Platform to manual dismantling. The Dual Arm Work Platform technology was demonstrated at ANL.

The manual method is assumed to use a robotic arm which is suspended from a crane. The baseline method was not demonstrated, but is developed from previous budget estimates for the D&D of the reactor core and the test engineer's experience with previous manual demolitions.

The selected basic activities being analyzed come from the Hazardous, Toxic, Radioactive Waste Remedial Action Work Breakdown Structure (HTRW RA WBS) and Data Dictionary, USACE, 1996. The HTRW RA WBS, developed by an interagency group, is used in this analysis to provide consistency with the established national standards.

Some costs are omitted from this analysis to facilitate understanding and comparison with costs for the individual site. The ANL indirect expense rates for common support and materials are omitted from this analysis. The overhead and general and administrative (G&A) rates for each DOE site vary in magnitude and their application. Decision-makers seeking site specific costs can apply their site's rates to this analysis without having to first "back-out" the rates used at ANL. The impact resulting from this omission is considered to be minor since overhead is applied to both the innovative and baseline technology costs. Engineering, quality assurance, administrative costs and taxes on services and materials are also omitted from this analysis for the same reasons.

The standard labor rates established by ANL for estimating D&D work are used in this analysis for the portions of the work performed by local crafts. Costs for site-owned equipment, are based upon an hourly government ownership rate that is computed using the Office of Management and Budget (OMB) Circular No. A-94. The equipment rate for the DAWP is derived directly from the actual cost to build it (excluding project management or engineering in support of procurement, fabrication or testing) and this cost is amortized for an hourly rate. Additionally, the analysis uses an eight hour work day with a five day week. The production rates and observed duration used in the cost analysis do not include "non-productive" items such as work breaks, donning and doffing clothing, loss of dexterity (due to cumbersome personal protective equipment (PPE)), and heat stress. These "non-productive" items are accounted for in the analysis by including a Productivity Loss Factor (PLF). The PLF is a historically based estimate of the fraction of the work day that the worker spends in non-productive activities.

Cost Data

In determining the most cost effective method of procurement, all acquisition options (purchase, lease, or vendor provided service) must be consider. The cost of construction is shown below.

Table 1. Innovative Technology Acquisition Costs.

Acquisition Option	Item	Cost
Purchase or Rent	Dual Arm Work Platform	Not Available
Equipment Construction	Dual Arm Work Platform	$1,210,000

The DAWP is not available from a commercial source at this time. The cost shown in Table 1 is for labor and material costs for construction of this equipment. The maintenance and repair of the DAWP was observed to be approximately 20% of the working time initially and 15% as workers became skilled with the DAWP.

Unit costs and production rates for principal components of the demonstrations for both the innovative and baseline technologies are presented in Table 2.

Table 2. Summary of Unit Costs and Production Rates Observed During the Demonstration.

Innovative Technology			Baseline Technology		
Cost Element	**Unit Cost**	**Production Rate**	**Cost Element**	**Unit Cost**	**Production Rate**
Cut Reactor Tank	$108 per foot	3 ft/hr	Cut Reactor Tank	$154 per foot	2.7 ft/hr
Dismantle Graphite and Boral	$6.49 per pound	50 lb/hr	Dismantle Graphite and Boral	$11.36 per pound	32 lb/hr
Remove Debris	$2.33 per pound	140 lb/hr	Remove Debris	$3.03 per pound	140 lb/hr

The unit costs and production rates shown do not include mobilization, set-up, maintenance/repair or other losses associated with non-productive portions of the work (such as suit-up, breaks, etc.). The intention of this table is to show unit costs at their elemental level which are free of site specific factors (such as work culture or work environment influences on productivity loss factors). Consequently, the unit cost for the Cut Reactor Tank is the unit cost shown for the Cut Reactor Tank line item of Table C-1 and Table C-2 of Appendix C. The other two items are similarly from individual line items in Table C-1 and C-2. Tables C-1 and C-2 can be used to compute site specific costs by inserting quantities and adjusting the units for conditions of a individual D&D job.

Summary of Cost Variable Conditions

The DOE complex presents a wide range of D&D work conditions as a result of the variety of site functions and facilities. The working conditions for an individual job directly affect the manner in which D&D work is performed and the costs for individual jobs are unique. The innovative and baseline technology estimates presented in this analysis are based on a specific set of conditions or work practices found at CP-5, and are summarized in Table 3. This table is intended to help the technology user identify work differences that can result in cost variances.

Table 3. Summary of Cost Variable Conditions.

Cost Variable	Dual Arm Work Platform	Manual Dismantling
Scope of Work		
Quantity and Type	Sheeting over bio-shield at top of reactor - 1900 lbs Removal of studs at top or reactor - 26 (of the 36 total) Removal of carbon steel ring at top of reactor - 1 Segmenting reactor tank - 209 feet cut (1/3 of total) Dismantle bio-shield assembly - 5,420 (partial) Remove low level radioactive debris - 9,920 pounds	Assumed the same as the innovative.
Location	Reactor core.	Same as innovative.
Nature of Work	Removing sheeting over the graphite blocks involves removal to a canister located at the top of the bio-shield wall. Once the studs at the top of the reactor are exposed, those are cut. The carbon steel ring at the top of the reactor is then removed. Cutting the reactor tank and removal of the graphite and boral bio shield alternate back and forth. The debris is placed in to a canister for eventual transfer to a staging area (not part of this analysis.	The robotic arm is controlled using cameras mounted on a shielded work platform above the opening at the top of the reactor.
Work Environment		
Worker Protection	PPE not required except for attaching tools or performing maintenance.	Anti-contamination coveralls with hood and respirator required at all times.
Level of Contamination	Maintenance performed in area classified as a contaminated area and a radiation area. Operators work from non radioactive area.	Classified as a high contaminated, high air born and high radiation area.
Work Performance		
Acquisition Means	Equipment constructed. Not currently available from a vendor.	Site personnel with site owned robotic arm and rented support equipment
Production Rates	Remove Sheeting - 292 lb/hr Remove Studs - 10 minutes per stud Cut Reactor Tank - 3 ft/hr Dismantle Graphite and Boral - 49.5 lb/hr Remove Debris - 139 lb/hr	336 lb/hr 15 minutes per stud 2.7 ft/hr 32 lb/hr 139 lb/hr
Equipment & Crew	One supervisor (part-time), one D&D worker, and one HP.	One supervisor (part-time), two D&D workers, and one HP.
Work Process Steps	1. Set up DAWP 2. Video inspection of demolition site 3. Remove lead and boral sheeting 4. Remove studs 5. Remove carbon steel ring 6. Cut reactor tank 7. Dismantle Graphite and Boral 8. Remove debris from reactor 9. Decontaminate and release 10. Disassemble and store	1. Design and install shielded platform 2. Install remote operated arm 3. Set-up video console 4. Video inspection 5. Remove sheeting 6. Remove studs 7. Remove carbon steel ring 8. Attach saw 9. Cut reactor tank 10. Dismantle Graphite and Boral 11. Remove debris from reactor 12. Decontaminate and free release rental equipment 13. Return rental and store arm

Potential Savings and Cost Conclusions

The innovative technology is estimated to be approximately half the cost of baseline for this demonstration. Figure 8 summarizes the estimate.

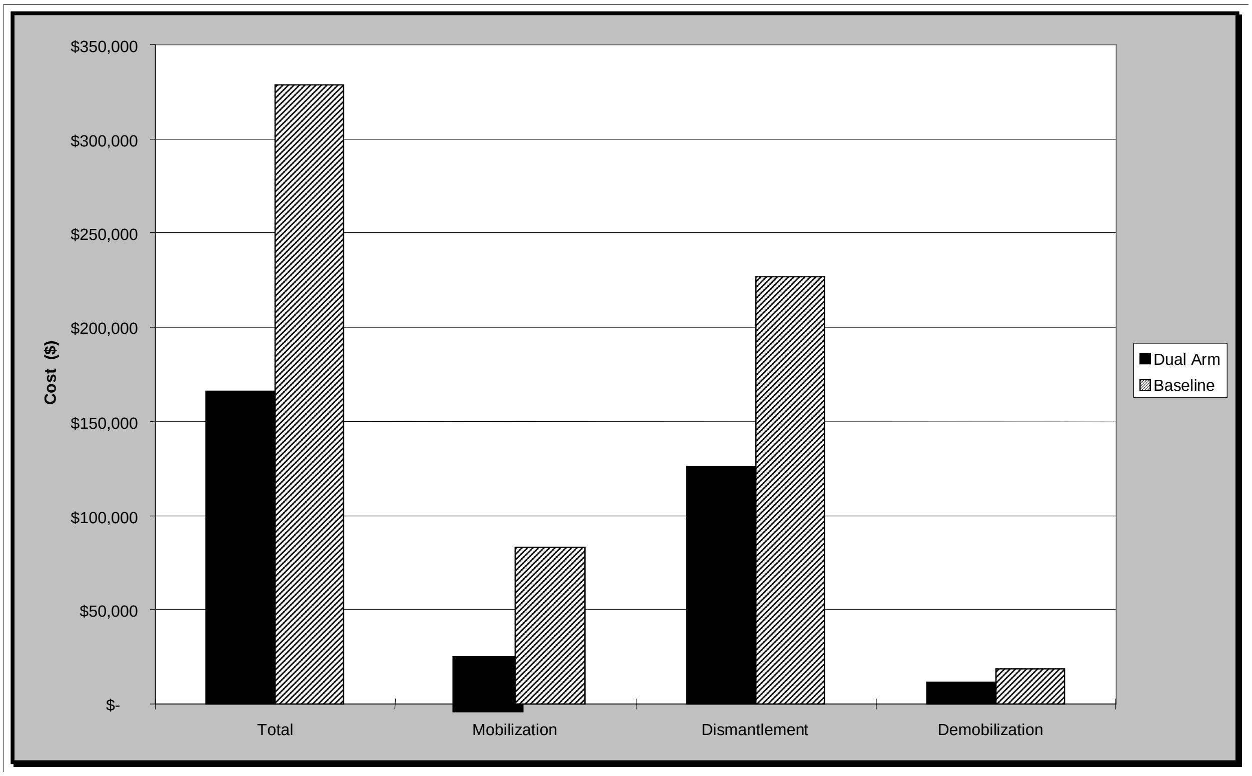

Figure 8. Summary of Costs

While the baseline technology has lower costs for the initial set-up and higher production rates for the cutting of the reactor vessel, the DAWP provides savings by using a smaller crew (lower labor costs), avoiding unproductive time, and a cost savings per reduced person-rem. The exposure that the workers receive in the course of performing the work using baseline methods is approximately $150,000 (based on an estimated exposure of 15 person-rem and a computed site-specific dollar value of $10,000 per person-rem). The savings in exposure helps off set almost all of the difference in cost between the DAWP and the baseline technology.

The work conditions (radiation exposure conditions) for this demonstration did significantly reduce the production rates for the manual method. In other work situations where the radiation exposure is higher than for this demonstration or where the work conditions are more adverse, the productivity of the workers would be less than the production observed for this demonstration and the potential savings in person rem may be higher. Based on the site-specific radiological conditions, the DAWP system may be a cost effective alternative.

The baseline costs also include designing and installing a shielded platform over the top of the reactor. Although the cost of this shield will vary according to the radiological conditions at different sites, at CP-5 this cost is essential to bring the project exposure down to 15 person-rem using the baseline method. This is included in the capital costs as a one time cost of approximately $62,000, and use of the DAWP will avoid this cost in addition to the $150,000 savings in exposure as described above.

The DAWP avoids having workers in the radiation area (except for maintenance, repair, or attaching a different tool) and avoids lost productivity for donning and doffing protective clothing, working in respirators, and other factors associated with work in radiation areas. The baseline method will always have workers in radiation areas, and this affects worker productivity. The saving that DAWP potentially provides over the baseline involves issues of crew size and work practice which are very site dependent. Additionally, the production rates for the baseline were determined as a percentage (which varies from 10% to 35% depending upon the individual work item) less than the production rates observed for the DAWP. The baseline cost is sensitive to this assumed percentage. Consequently, the amount of savings is uncertain and expected to vary over a wide range from one situation to the next.

Another issue for DAWP is its cost to build. The $1.21 million for labor and materials required to build DAWP may be beyond the budget available for some DOE sites. This cost analysis was based on an amortized cost for DAWP over 20 years of continual work (with annual repairs of $10,000). While the equipment is expected to remain functional for 20 years, this may exceed the scheduled work required for many sites.

Finally, the costs shown do not consider the learning curve required for workers to become skilled in using the DAWP. The workers in this demonstration required a significant amount of time to become proficient with the DAWP.

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

The regulatory/permitting issues related to the use of the DAWP technology at the ANL CP-5 Research Reactor consisted of the following safety and health regulations:

- Occupational Safety and Health Administration (OSHA) 29 CFR 1926

—1926.300 to 1926.307	Tools-Hand and Power
—1926.400 to 1926.449	Electrical - Definitions
—1926.28	Personal Protective Equipment
—1926.52	Occupational Noise Exposure
—1926.102	Eye and Face Protection
—1926.103	Respiratory Protection

- OSHA 29 CFR 1910

—1910.211 to 1910.219	Machinery and Machine Guarding
—1910.241 to 1910.244	Hand and Portable Powered Tools and Other Hand-Held Equipment
—1910.301 to 1910.399	Electrical - Definitions
—1910.95	Occupational Noise Exposure
—1910.132	General Requirements (Personal Protective Equipment)
—1910.133	Eye and Face Protection
—1910.134	Respiratory Protection
—1910.147	The Control of Hazardous Energy (Lockout/Tagout)

Disposal requirements/criteria include the following Department of Transportation (DOT) and DOE requirements:

- 49CFR Subchapter C Hazardous Materials Regulation

—171	General Information, Regulations, and Definitions
—172	Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements
—173	Shippers - General Requirements for Shipments and Packagings
—174	Carriage by Rail
—177	Carriage by Public Highway
—178	Specifications for Packaging

- 10CFR 71 Packaging and Transportation of Radioactive Material

If the waste is determined to be hazardous solid waste, the following Environmental Protection Agency (EPA) requirement should be considered:

40 CFR Subchapter 1 Solid Waste

For Robotics:

- ANSI/RIA R15.06-1992; American National Standard for Industrial Robots and Robot Systems - Safety Requirements

- DOE OSH Technical Reference (OTR); Chapter 1 - Industrial Robots
- OSHA Technical Manual; Section III, Chapter 4, Industrial Robots and Robot System Safety
- DOE-STD-1090-96; Hoisting and Rigging

NOTE: There are no current regulations mandated to be applicable to the specific control or operation of teleoperated robotic systems. The aforementioned documents provide useful and necessary guidance but, do not pertain directly to the deployment of this or similar systems.

The generated waste form requirements/criteria specified by disposal facilities used by ANL include:

- *Hanford Site Solid Waste Acceptance Criteria*: WHC-EP-0063-4
- *Barnwell Waste Management Facility Site Disposal Criteria*: S20-AD-010
- *Waste Acceptance Criteria for the Waste Isolation Pilot Plant*: WIPP-DOE-069

Safety, Risks, Benefits, and Community Reaction

The DAWP System technology is a relatively new enabling technology that inherently provides many safety benefits in the D&D work spectrum. As with any large industrial apparatus, there are also some risks that are more than offset by the benefits. Most benefits are self-evident by the previous descriptions and discussion including the remote operability of the system that removes the operator from the dangers of the immediate work area, the overall reliability of the system, and the system's ability to monitor and diagnose its own parameters and provide an immediate warning to the operator. Some safety concerns that arise are part of the very same technology that provides the benefits namely, the system has many sources of hazardous energy including a high voltage electrical system, moderate pressure hydraulics and whatever additional sources a user may wish to install. Teleoperated robots introduce unique safety questions that must be resolved by the user. However, the benefits to providing the ability to perform dismantling, demolition, surveillance and decontamination activities remotely in a hazardous, sometimes inaccessible environment far outweigh the known controllable hazards introduced. During the demonstration, not a single incident occurred that could have been construed as dangerous to operating personnel. Instead, a significant safety gain was made in that personnel exposure to radiation was decreased by approximately 15 person-rem.

The use of the DAWP technology rather than conventional manual D&D would have no measurable impact on community safety or socioeconomic issues.

SECTION 7

LESSONS LEARNED

Implementation Considerations

The primary considerations when implementing the DAWP are the benefits of the reduced project personnel exposure verses the costs and possible delays in schedule associated with remote operations. Although the system is a viable D&D technology, the initial costs are high and the cost of operation can vary widely. None of the identified limitations of this technology were found to significantly hinder the project. However, for small projects or for projects in which the exposure levels can be reduced via engineered means, the cost outlay for the DAWP may not be acceptable. For large scale projects or projects in which engineered methods of exposure reduction are not an option, the DAWP is an excellent alternative.

Technology Limitations and Needs for Future Development

Although the DAWP is a viable D&D tool, it is not a commercially available product at this time. The CP-5 implementation was its first application. Numerous area of improvement were found. Some are lessons learned, and some will require improvements in the technology, to be included in subsequent generations of the DAWP. The following are highlights:

- Setup time and complexity were considerable; a commercial version should consider the 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.

- The HoughtoSafe™ water-glycol hydraulic fluid was selected based on recommendations made several years ago concerning environmental impact and low flammability of the fluid. Since that time, waste acceptance criteria appears to be tightening against glycol, and testing at CP-5 has shown that water-glycol is corrosive to electrical connections internal to the manipulator. A mineral oil-based fluid would be a better choice in future systems.

- 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. A commercial version should consider a custom made tether and tether management system.

- Some maintenance activities required that the manipulator arm be sent back to Schilling for repairs, and a considerable source of down time was attributed to shipping out one or both arms for maintenance. Commercial user of the DAWP are highly encouraged to purchase a third spare arm, and if possible, train a nuclear technician in the maintenance of the DAWP. This will save both in down time, decontamination of the arms, and vendor costs.

Technology Selection Considerations

Ultimately the benefits of a teleoperated remote system such as the DAWP must be weighed against the cost of the system. In high exposure projects the DAWP can be extremely useful for performing tasks while reducing dose to personnel.

Appendix A

REFERENCES

(1) AIF, 1986 Guidelines for Producing Commercial Nuclear Power Plant Decommissioning Cost Estimates, May 1986, National Environmental Studies Project of the Atomic Industrial Forum, Inc., 7101 Wisconsin Avenue, Bethesda, MD 20814-4891.

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(3) Hazardous, Toxic, Radioactive Waste Remedial Action Work Breakdown Structure and Data Dictionary. 1996, Headquarters United States Army Corps of Engineers, 20 Massachusetts Avenue, N.W., Washington, D.C., 20314-1000.

(4) Means, Heavy Construction Cost Data, 1997, R.S. Means Co., Inc., 100 Construction Plaza, Kinston, MA.

(5) Strategic Alliance for Environmental Restoration, CP-5 Large-Scale Demonstration Project, *Technology Summary Sheet for the Demonstration of DAWP: Dual Arm Work Platform*, Argonne National Laboratory, January 1998.

(5) Strategic Alliance for Environmental Restoration, CP-5 Large-Scale Demonstration Project, *Data Report for the Demonstration DAWP: Dual Arm Work Platform,,* Argonne National Laboratory, January 1998.

Appendix B

ACRONYMS AND ABBREVIATIONS

ACE	Activity Cost Estimate (Sheets)
ALARA	As Low As Reasonably Achievable
ANL	Argonne National Laboratory
CF	Cubic Feet (Foot)
CFM	Cubic Feet Per Minute
COE	Corps Of Engineers
CP-5	Chicago Pile 5 Research Reactor Facility
D&D	Decontamination And Decommissioning
DDFA	Decontamination And Decommissioning Focus Area
Decon	Decontamination
Demo	Demonstration
Demob	Demobilization
DOE	Department Of Energy
DOE-CH	DOE- Chicago
DOE-RL	DOE- Richland (WA)
DAWP	Dual Arm Work Platform
Eq	Equal
Equip	Equipment
ER	Environmental Restoration
ESH	Environment, Safety and Health
FCCM	Facilities Capital Cost Of Money
FETC	Federal Energy Technology Center
GUI	Graphical User Interface
H&S	Health And Safety
HP	Health Physics
HPU	Hydraulic Powered Unit
Hr	Hour
HTRW	Hazardous, Toxic, Radioactive Waste
ICT	Integrating Contractors Team
INEEL	Idaho National Engineering Environmental Laboratory
LCD	Liquid Crystal Display
LF	Lineal Feet (Foot)
LLW	Low Level Waste
LS	Lump Sum
LSDP	Large Scale Demonstration Project
Min	Minute
Mob	Mobilization
NESP	National Environmental Studies Project
ORNL	Oak Ridge National Laboratory
OT	Overtime
PC	Personal Computer
PCs	Protective Clothing
PLF	Productivity Loss Factor

PPE	Personnel Protective Equipment
Qty (Qnty)	Quantity
RA	Remedial Action
SAFSTOR	Safe Storage
SF	Square Feet (Foot)
SBIR	Small Business Innovative Research
Tech	Technician
UCF	Unit Cost Factor
UOM	Unit Of Measure
USACE	U.S. Army Corps Of Engineers
WBS	Work Breakdown Structure
WPI	Waste Policy Institute

Appendix C

TECHNOLOGY COST COMPARISON

This appendix contains definitions of cost elements, descriptions of assumptions, and computations of unit costs that are used in the cost analysis. Some general assumptions which apply to both the innovative and the baseline are:

- The hourly rates for equipment owned by the Government (DAWP, robotic arm, video camera, etc.) are computed based on guidance contained in OMB Circular 94A using a discount rate of 5.8% (rate designated for 1997).
- Hourly rates for site labor are based on standard rates for ANL for 1997 and do not include mark up for over head.

Innovative Technology - Dual Arm Work Platform

Mobilization (WBS 331.01)

Load Equipment
Definition: Load equipment onto truck at on-site warehouse where equipment is being stored.

Assumptions: Forklift is assumed to be gas, 5K, and rental rate of $8 plus operation cost of $3.65 with 9.3% procurement cost added for total rate of $12.73 per hour (taken from Dataquest construction equipment pricing book). Flatbed truck is assumed to be 15K lb, 4x2, rental rate of $7 plus operation cost of $11.10 with 9.3% procurement cost added for total rate of $19.78 per hour.

Transport to Site
Definition: Truck transports equipment from nearby warehouse to CP-5 and unloads.

Assumption: Distance to a site warehouse varies, but is less than 2 miles. Unloading takes 2 hr.; driving, 0.5 hr; and returning to the equipment pool, 0.25 hr.

Set-up Hardware & Software

Definition: Set up of the hardware and loading of the software required to run the DAWP.

Assumptions: One week is required to set up the hardware and software with a crew of two technicians based on demonstration observations.

Facility Electrical Installation

Definition: Electrical installation is required to support the Dual Arm Work Platform inside the facility where the demolition is performed.

Assumptions: The electrical installation is assumed to require one week based on experience of the test engineer.

Dismantlement (WBS 331.17)

Video Inspection
Definition: The time required to inspect the reactor tank to determine demolition area and for work sequencing.

Assumptions: The duration is assumed to be eight hours based on demonstration observations.

Remove Lead and Boral Sheets
Definition: Manipulator arm used to remove lead and boral sheets which cover the graphite (bio-shield assembly) and place this material into a transfer canister (for future transport to a staging area).

Assumptions: The demonstration resulted in 1400 pounds of lead and 500 pounds of boral being moved in 6.5 hours. The average production rate is computed to be 292 lb/hr.

Remove Studs
Definition: Remove studs attached to the flange at the top of the reactor tank using the Dual Arm Work Platform.

Assumptions: Time observed to remove studs is approximately 10 minutes each. During the demonstration, 26 of the 36 studs were removed.

Remove Carbon Steel Ring
Definition: The carbon steel ring (part of the interface between the bio shield and the reactor) is located at the top of the reactor and is bolted to the reactor with studs. This ring is removed in one piece.

Assumptions: Observed duration for this was 5 hours.

Cut Reactor Tank
Definition: The reactor tank is segmented.

Assumptions: A circular saw connected to the Dual Arm Work Platform is used to cut the aluminum reactor tank. Crews were assumed based on the judgement of the test engineer and the production rate is based on observations from the demonstration (68.5 hours required to cut 209 lineal feet = 3 ft/hr).

Dismantle Graphite and Boral

Definition: The arm is equipped with a demolition hammer (with chisel bit) to break apart the blocks of graphite and boral in the bio shield. The removed material is placed into a transfer canister.

Assumptions: The observed quantities of graphite were 5,300 lb and for boral 120 lb which were removed in 109.5 hours for a production rate of 49.5 lb/hr.

Remove Debris
Definition: The low level radioactive material which was removed (lead and boral sheeting which covered the graphite, carbon steel from the steel ring, aluminum from the tank segmenting, and graphite and boral from the bio shield) is placed into a transfer canister. As the debris is moved, the mixed waste (lead) is segregated from the low level radioactive waste.

Assumptions: The observed quantity of debris was 9,920 lb (5300 lb graphite, 620 lb boral, 1400 lb lead, 2000 lb carbon steel, 600 lb aluminum) which was moved in 71.5 hours for a production rate of 139 lb/hr.

Consumables

Definition: Material consumed during demolition.

Assumptions: Twenty-three gallons of hydraulic fluid at $8/gallon, eleven saw blades at $13 each, five camera domes at $256 each, and four camera handles at $400 each are representative of actual amounts consumed during normal D&D work.

PPE
Definition: This cost element provides for the personal protective clothing used when workers enter the radiation area for repair, maintenance, or attach a different tool (assumed to be 20% of the work time).

Equipment	Quantity in Box	Cost Per Box	Cost Each	No. of Reuses	Cost Each Time Used	No. Used Per Day	Cost Per Day
Respirator			1,933	200	10	1	10.00
Resp. Cartridges			9.25	1	9.25	2	18.50
Booties	200	50.00	0.25	1	0.25	4	1.00
Tyvek	25	85.00	3.4	1	3.4	4	13.60
Gloves (inner)	12	2.00	0.17	1	0.17	8	1.36
Gloves (outer pair)			7.45	10	0.75	1	0.75
Glove (cotton Liner)	100	14.15	0.14	1	0.14	8	1.12
Total							46.33

Daily Meeting
Definition: This cost element provides for safety meeting and project planning meetings during the work.

Assumptions: The estimate assumes one 30 minute safety meeting per day (based on typical practice at ANL).

Productivity Loss Factor
Definition: Productivity losses occur during the course of the work due to work breaks. This activity does not cover work in the radiation zone (maintenance, repair, etc.). Consequently, the productivity loss is minimal.

Assumption: The task duration used do not account for work breaks. Consequently, these types of costs are estimated and added to the innovative cost in this cost element. The duration of work performed in the controlled area (activities outside the controlled area, such as evaluation of the data, are not included in the computation) is adjusted by a factor of 1.10 to account for these losses (particularly work breaks and suiting up) based on the factors shown below (AIF, 1986):

Base	1.00
+Height	0
+Rad/ALARA	0 (not considered since most work is waiting)
+Protective Clothing	0.0 (only an issue during maintenance)
= Subtotal	1.00
X	
Resp Prot	1.00 (no factor used, losses included in observed times)
=Subtotal	1.00
X	
Breaks	1.10
=Total	1.10

Maintenance and Repair
Definition: Maintenance, repair, and attachment of tools require entry into the radiation/contamination area to work directly on DAWP.

Assumptions: The test engineers assessment of the time spent on maintenance, repair, and tool attachment in the radiation zone is estimated as 20% of the work time. This time is inclusive of donning and doffing PPE and other productivity losses related to radiation area entry.

Demobilization (WBS 331.21)

Decontamination

Definition: Dual Arm Work Platform equipment is surveyed for contamination and decontamination is performed, as needed, prior to storage or transport to another D&D location.

Assumption: A duration of three days was assumed based on experience of the test engineer and 4 ft^3 of low level waste is assumed.

Load Equipment

Definition: Disassemble equipment and place on truck for future transport.

Assumptions: Similar to mobilization.

Return to Warehouse

Definition: Transport from CP-5 to local warehouse for storage.

Assumptions: Similar to mobilization

The activities, quantities, production rates and costs observed during the demonstration are shown in Table C-1 Cost Summary Table – Dual Arm Work Platform.

Table C-1. Cost Summary - Dual Arm Work Platform.

Work Breakdown Structure (WBS)	Unit Cost (UC) Labor HRS	Labor Rate	Equipment HRS	Equipment Rate	Other	Total UC	Total Quantity (TQ)	Unit of Measure	Total Cost (TC)	Innovative Technology Comments
Mobilization (WBS 331.01)								**Subtotal**	**$28,919**	
Load Equipment	8.00	$146.90	8.00	$238.24		$3,081.12	1	LS	$3,081	Truck @ $19.78, forklift @ $12.73, teamster $39.85, operator $39.85, & 2 D&D workers @ 33.60 and standby for DAWP at $205.73/hr.
Transport to Site	2.75	$146.90	2.75	$238.24		$1,059.14	1	LS	$1,059	Transport from warehouse to work location. Crew is same as above.
Set-up Hardware & Software	40.00	$88.36	40.00	$205.73		$11,763.60	1	Each	$11,763	Two technicians for one week at $44.18/hr each to set-up hardware and load software for operation of the DAWP and standby for DAWP.
Facility Electrical Installation	40.00	$49.67	40.00	$205.73	$ 2,800	$13,016.00	1	Each	$13,016	One week to convert the facilities electrical system to support the DAWP with a crew of one electrician at $49.67/hr and DAWP standby.
Dismantlement (WBS 331.17)								**Subtotal**	**$125,879**	
Video Inspection	8.00	$118.78	8.00	$205.73		$2,596.08	1	Each	$2,596	Video inspection of the site demolition area. Crew consists of one D&D worker at $33.60/hr, 3/8 of a supervisor at $77.80/hr, and one HPT at $56.00/hr and DAWP standby.
Remove Lead and Boral Sheets	0.0034	$118.78	0.0034	$205.73		$ 1.11	1,900	LB	$2,112	Average productivity rate of 292 lb/hr. Same crew.
Remove Studs	0.167	$118.78	0.167	$205.73		$54.09	26	Each	$1,406	Average rate of 10 minutes per stud. Same crew.
Remove Carbon Steel Ring	5	$118.78	5	$205.73		$ 1,622.55	1	Lump Sum	$ 1,623	Same crew.
Cut Reactor Tank	0.333	$118.78	0.333	$205.73		$ 108.06	209	FT	$ 22,585	Production rate of 3 ft/hr. Same crew.
Dismantle Graphite and Boral	0.020	$118.78	0.020	$205.73		$ 6.49	5,420	LB	$ 35,177	Production rate of 49.5 lb/hr. Same crew.
Remove Debris	0.0072	$118.78	0.0072	$205.73		$ 2.33	9,920	LBS	$23,159	Production rate of 139 lb/hr. Same crew.
Consumables						$3,207	1	LS	$3,207	Includes hydraulic fluid, saw blades, camera domes, and camera handles.
PPE					$ 46	$46	6	Person-Day	$298	$46.33 /day of work in radiation zone per person for Personal Protection Equipment (radiation zone entry is 20% of the work duration)
Daily Meeting	0.50	$118.78	0.50	$205.73		$162.25	44	Each	$7,139	One safety meeting each morning prior to beginning work. Same crew.
Productivity Loss Factor	27.3	$118.78	27.3	$205.73		$8,859.12	1	Each	$8,859	Productivity Loss Factor of 1.10 (adjustment to work duration for breaks, does not cover work in the radiation zone)
Maintenance & Repair	54.6	$118.78	54.6	$205.73		$17,718.25	1	LS	$17,718	Work conducted in the radiation zone, amounts to 20% of the work duration.
Demobilization (WBS 331.21)								**Subtotal**	**$11,234**	
Decontamination	24.00	$81.20	24.00	$205.73	$ 208	$ 8,102.32	1	Each	$7,094	Labor (two D&D workers and 1/4 HPT for three days) plus equipment at a standby rate. Four cubic feet of solid low level waste are generated and disposed at a rate of $52/cubic foot.
Load Equipment	8.00	$146.90	8.00	$238.24		$3,081.12	1	LS	$3,081	See Mobilization
Return to Warehouse	2.75	$146.90	2.75	$238.24		$1, ,059.14	1	LS	$1,059	Return equipment to warehouse.
Note: TC = UC * TQ								**TOTAL:**	**$166,032**	

Baseline Technology - Manual Dismantling

Mobilization (WBS 331.01)

Load and Transport Rental Equipment
Definition: Load trailer with rented forklift and electric hammer. Drive rented truck mounted crane pulling trailer from rental to site. Unload equipment at site.

Assumptions: Forklift is assumed to be electric with a 5,000 pound capacity and a rental rate of $475/week (quote from Hyster, 9892 40th Ave. S., Seattle WA, 206 722-5800). Crane assumed to be a truck mounted hydraulic crane with 70' boom. Hourly rate is $55 and operation cost is $22.8 (from Dataquest 1997). Demolition hammer is 50 pound electric powered. Rate from AED Green Book (48th edition, Machinery Inf. Div. of K-111 Directory Corp) for electric hammer 41-55 lb size is $40/day. Flatbed truck is assumed to be 15K lb, 4x2, rental rate of $7 plus operation cost of . cost, $11.10 with 9.3% procurement cost added for total rate of $19.78 per hour. Assume 16 hours for load, transport and unload.

Load and Transport Remote Arm
Definition: Truck transports equipment from nearby warehouse to CP-5 and unloads.

Assumption: Forklift is assumed to be gas, 5K, and rental rate of $8 plus operation cost of $3.65 with 9.3% procurement cost added for total rate of $12.73 per hour (taken from Dataquest construction equipment pricing book). Flatbed truck is assumed to be 15K lb, 4x2, rental rate of $7 plus operation cost of. cost, $11.10 with 9.3% procurement cost added for total rate of $19.78 per hour. Assume loading requires 8 hours. Distance to a site warehouse varies, but is less than 2 miles. Unloading takes 2 hr; driving is 0.5 hr; and returning to the equipment pool is 0.25 hr. Hourly rate for Remote Arm is based on amortized purchase price.

Set Up Step Off Area
Definition: Set up area for donning and doffing PPE and step off area from buffer zone to the radiation area.

Assumptions: The effort takes approximately one day for a 10' X 10' X 3' wall and requires approximately $300 of materials (based on test engineer experience).

Design Fabricate, and Install Shielded Platform
Definition: Provides shielding over the opening at the top of the reactor as well as providing a work platform.

Assumptions: The platform has a thickness of 2 - 4 inches for shielding and handrails for worker safety. Materials and fabrication costs are estimated by the test engineer to be $50,000, design time of 120 hours, and installation requires a forklift, 2 D&D workers, and one operator for 3 days. Total cost is approximately $61,850.

Set-up Video Monitoring Area
Definition: Time required to set up cameras, monitors, VCR's and splitters on the shielded platform.

Assumption: The effort is assumed to be one week based on past experience of the test engineer. Equipment consists of eight cameras ($1.57/hour each) with pan, tilt, zoom, and lights, four monitors ($0.37/hour each), three splitters ($0.73/hour each), and 2 VCR's ($0.13/hour each). The video equipment is assumed to be Government owned with the purchase price amortized over the equipment service life.

Install Remote Operated Arm/Tooling
Definition: Connect remote operated arm to a the existing crane mounted in the reactor room (assume a rate of $52.26/hr based on the rate for a tower crane with a 148 foot reach from EP-1110-1-8). The arm is equipped with long reach tools and includes operational checks for arm.

Assumption: Remote operated arm is connected to the crane for demolition. Duration based on past budget estimates and experience of the test engineer. Additionally, the rented truck mounted crane is used to position and brace the arm and the rented fork lift is on standby (used in later operations for assisting with off loading the debris.

Dismantlement (WBS 331.17)

Video Inspection
Definition: The time required to inspect the reactor tank to determine demolition area and for work sequencing.

Assumptions: The duration is assumed to be eight hours based on the test engineer's experience.

Remove Lead and Boral Sheets
Definition: Robotic arm used to remove lead and boral sheets which cover the graphite (bio-shield assembly) and place this material into a transfer canister (for future transport to a staging area).

Assumptions: The production rate is assumed to be 15% greater than for the DAWP due to additional time required for positioning the crane (in addition to the arm) or 336 lb/hr.

Stud Removal Preparation
Design and preparation for stud removal. When in place, this will provide bracing and restraint for the arm as it cuts.

Assumptions: Duration an crew based on test engineers experience.

Remove Studs
Definition: Remove studs attached to the flange at the top of the reactor tank using the robotic arm.

Assumptions: Time observed to remove studs is approximately 15 minutes each (assumed to be 50% more than the DAWP due to the nearly vertical view from the platform of the work below results a poor view/perspective of the work).

Remove Carbon Steel Ring
Definition: The carbon steel ring (part of the interface between the bio shield and the reactor) is located at the top of the reactor and is bolted to the reactor with studs. This ring is removed in one piece.

Assumptions: Assume that the remote arm is the same as the observed duration for DAWP (5 hours).

Set Up Saw
Definition: Attach electric abrasive saw to the remote arm.

Assumption: Duration based on test engineer's experience.

Cut Reactor Tank
Definition: The reactor tank is segmented.

Assumptions: A circular saw connected to the robotic arm is used to cut the aluminum reactor tank. The production rate is assumed to be reduced (as compared with DAWP), based on the judgement of the test engineer) by 10% due to adjusting the restraint system for each movement and the poor visibility of the work for a rate of 2.7 ft/hr).

Dismantle Graphite and Boral

Definition: The arm is equipped with a demolition hammer (with chisel bit) to break apart the blocks of graphite and boral in the bio shield. The removed material is placed into a transfer canister.

Assumptions: The production rate is assumed to be 20% - 50% DAWP's rate (use 35% of 49.5 lb/hr = 32lb/hr).

Remove Debris

Definition: The low level radioactive material which was removed (lead and boral sheeting which covered the graphite, carbon steel from the steel ring, aluminum from the tank segmenting, and graphite and boral from the bio shield) is placed into a transfer canister. As the debris is moved, the mixed waste (lead) is segregated from the low level radioactive waste.

Assumptions: The production rate for DAWP is assumed (139 lb/hr).

Consumables

Definition: Material consumed during demolition.

Assumptions: Twenty-three gallons of hydraulic fluid at $8/gallon and 20 abrasive saw blades at $6 each (total of $304).

Daily Meeting

Definition: This cost element provides for safety meeting and project planning meetings during the work.

Assumptions: The estimate assumes one 15 minute safety meeting per day (based on typical practice at ANL).

PPE

Definition: This cost element provides for the personal protective clothing used during the work activity.

Equipment	**Quantity in Box**	**Cost Per Box**	**Cost Each**	**No. of Reuses**	**Cost Each Time Used**	**No. Used Per Day**	**Cost Per Day**
Respirator			1,933	200	10	1	10.00
Resp. Cartridges			9.25	1	9.25	2	18.50
Booties	200	50.00	0.25	1	0.25	4	1.00
Tyvek	25	85.00	3.4	1	3.4	4	13.60
Gloves (inner)	12	2.00	0.17	1	0.17	8	1.36
Gloves (outer pair)			7.45	10	0.75	1	0.75
Glove (cotton Liner)	100	14.15	0.14	1	0.14	8	1.12
Total							46.33

The PPE costs are predominantly from the ANL activity cost estimates for 1996 (costs for outer gloves, glove liners, and respirator cartridges are from commercial catalogs).

Productivity Loss Factor

Definition: Productivity losses occur during the course of the work due to PPE changes, ALARA, reach height inefficiencies, etc.

Assumption: The task duration for cutting the vessel, removing studs, and removing debris do not account for work breaks or PPE changes or work in the radiation zone (other activities such as Set Up Saw and Move Saw are assumed to include productivity losses in the observed times). Consequently, these types of costs are estimated and added to the innovative cost in this cost element.

Base	1.00
+Height	0
+Rad/ALARA	0.15
+Protective Clothing	0.15
= Subtotal	1.30
X	
Resp Prot	1.25
=Subtotal	1.63
X	
Breaks	1.10
=Total	1.78

Demobilization (WBS 331.21)

Decontaminate
Definition: Decontamination of robotic arm and other equipment and free release of rental equipment.

Assumption: The duration of three days for the remote arm and an additional day for the rental crane and also for the forklift (to free release these) is assumed on the experience of the test engineer. Low level radioactive waste generated by the decon is assumed to be 8 cf (two times the amount for DAWP because of the additional rental equipment to be free released).

Load and Transport Rental Equipment
Definition: Load, transport, and unload rented equipment back to rental store.

Assumptions: Similar to mobilization.

Load and Transport Robotic Arm
Definition: Load, transport, and unload robotic arm back to storage area.

The activities, quantities, production rates and costs utilized in the baseline are shown in Table B-2 Baseline Technology – Manual dismantling.

TABLE C-2. Baseline Technology - Manual Dismantling.

Work Breakdown Structure (WBS)	Unit Cost (UC) Labor Hour	Labor Rate	Equipment Hour	Equipment Rate	Other	Total UC	Total Quantity (TQ)	Unit of Measure	Total Cost (TC)	Baseline - Manual Dismantling Comments
Mobilization (WBS 331.01)								**Subtotal**	**$ 83,163**	
Load and Transport Rental Equipment	16	$119.55	16	$103.06		$3,561.76	1	LS	$ 3,562	Truck @ $19.78, forklift @ $11.88, crane @ $66.40 (½ operating rate $77.80 and ½ standby rate $55), hammer @ $5, 2 teamsters at $39.85, and operator $39.85.
Load and Transport Remote Arm	10.75	$146.90	10.75	$116.20		$ 2,828.33	1	LS	$ 2,828	Truck @ 19.78, forklift @ 12.73, teamster $39.85, operator $39.85, 2 D&D workers @ 33.60, and robotic arm standby @ 116.20.
Set Up Step Off Area	8	$ 67.20			$ 300.00	$ 837.60	1	Lump Sum	$ 838	Construct temporary walls by 2 D&D workers @ 33.60/hr each using $300 of materials.
Design, Fabricate, and Install Shielded Platform					$ 61,850	$61,850.00	1	Lump Sum	$ 61,850	Work platform over opening at the top of the reactor provides shielding to workers.
Install Remote Operated Arm/Tooling	40	$83.27	40	$16.49		$3,990.40	1	**Lump Sum**	**$ 3,990**	Video equipment @ 16.49 set up on shielded platform by 1 D&D worker and 1 electrician @ $49.67.
Install Remote Operated Arm/Tooling	24	$152.38	24	$268.23		$10,094.64	1	**Lump Sum**	**$ 10,095**	Attach arm @ 116.2 to CP-5's crane @ $52.26 using 2 D&D workers, 3/8 supervisor @ $77.80, 1 HPT @ 56. Rental crane @ $ 66.4, hammer @ $5, and forklift @ $11.88 and video equipment @ $16.49 on standby or partial standby.
DISMANTLEMENT 331.17								**Subtotal**	**$ 226,279**	
Video Inspection	8	$ 152.38	8	$ 268.23		$ 3,364.88	1	Each	$ 3,365	Crew includes 2 D&D workers @ $33.6 each, 3/8 supervisor @ $77.80, 1 HPT @ $56, video equipment @ $16.49, and standby for arm @ $116.20, CP-5 crane @ $52.26, rental crane @ $66.40, hammer @ $5, and forklift @ $11.88.
Remove Lead and Boral Sheets	.0039	$ 152.38	.0039	$ 268.23		$ 1.64	1,900	LB	$ 3,117	Average productivity rate 336 lb/hr and same crew.
Stud Removal Preparation	24	$72.50	8	$268.23		$3,885.84	1	LS	$ 3,886	Crew is one D&D worker and Supervisor for two days to design and fabricate and one day to install with equipment on standby during installation.
Remove Studs	.25	$ 152.38	.25	$ 268.23		$ 109.36	26	Each	$ 2,843	Remove studs at rate of 15 minutes per stud with same crew.
Remove Carbon Steel Ring	5	$ 152.38	5	$ 268.23		$ 2,103.05	1	Each	$ 2,103	Same crew.
Set Up Saw	8	$152.38	8	$ 268.23		$ 3,364.88	1	Each	$ 3,365	Attach electric abrasive saw to the remote arm. Crew includes two D&D workers at $33.60/hr, 3/8 of a supervisor at $77.80/hr, one HPT at $56.00/hr, saw at $0.17/hr, crane at $70.59/hr, robot arm at $110.47 plus cameras.
Cut Reactor Tank	.3663	$152.38	.3663	$ 268.23		$ 154.07	209	FT	$ 32,201	Production rate of 2.7 ft/min with same crew.
Dismantle Graphite and Boral	.027	$152.38	.027	$ 268.23		$ 11.36	5,420	LB	$ 61,552	Production rate of 32 lb/hr with same crew.

Remove Debris	.0072 $152.38	.0072 $268.23		$ 3.03	9,920	LB	$ 30,042	Production rate 139 lb/hr with same crew.
Consumables			$ 960	$ 960	1	Lump Sum	$ 304	Includes hydraulic fluid and saw blades.
Daily Meetings	0.5 $152.38	0.5 $ 268.23	0	$ 210.31	50	Each	$ 10,515	Daily meetings of 1/2 hour with equipment on standby.
Personal Protection Equipment			$ 46	$ 46.33	150	Person- Day	$ 6,950	$46.33 /day per person for 3 workers (in zone at one time) Personal Protection Equipment
Productivity Loss Factor	157 $152.38	157 $ 268.23		$66,035.77	1	Each	$ 66,036	Productivity Loss Factor of 1.78 (applies to duration of time in radiation zone (except for the design time for stud removal preparation) increasing duration by 78%)
Demobilization (WBS 331.21)						**Subtotal**	**$ 18,693**	
Decontaminate	$81.20 40	40 $215.97	$ 416	$12,302.80	1	Lump Sum	$ 12,303	Labor for 2 D&D workers and ¼ HPT plus equipment standby (same crew as above minus the CP-5 crane). Eight cubic feet of solid low level waste are generated and disposed of at rate of $52/cubic foot.
Load and Transport Rental	16 $ 119.55	16 $ 103.06		$ 3,561.76	1	Lump Sum	$ 3,562	Similar to mobilization.
Load and Transport Arm	10.75 $ 146.90	10.75 $ 116.20		$ 2,828.33	1	Lump Sum	$ 2,828	Similar to mobilization.
Note: TC = UC * TQ						**TOTAL:**	**$328,135**	