Innovative Technology Summary Report

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Mobile Robot Worksystem (ROSIE)

Industry Programs and
Deactivation and Decommissioning
Focus Area

Prepared for

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INNOVATIVE TECHNOLOGY
Summary Report

Mobile Robot Worksystem (ROSIE)

OST Reference #1799

Industry Programs and
Deactivation and Decommissioning
Focus Area

Demonstrated at
Argonne National Laboratory-East
Argonne, Illinois

INNOVATIVE TECHNOLOGY
Summary Report

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) have 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.

Rosie was provided by the D&D Focus Area through RedZone Robotics, who also supported the effort by training the CP-5 Robotic Lead, who then trained subsequent ANL personnel as telerobotic operators. Rosie performs mechanical dismantlement of radiologically contaminated structures by remotely deploying other tools or systems. At the CP-5 reactor site, Rosie is a mobile platform used to support reactor assembly demolition through its long reach, heavy lift capability and its deployment and positioning of a Kraft Predator dexterous manipulator arm. Rosie is a tethered, 50 m (165 ft) long, robotic system controlled via teleoperation from a control console that is located outside of the radiological containment area. The operator uses Rosie to move, lift or “offload” radioactive materials using its integral lifting hook or to position the Kraft Predator arm in locations where the arm can be used to dismantle parts of the CP-5 reactor. The specific operating areas were concentrated in two high radiation areas, one at the top of the reactor structure atop and within the reactor tank assembly and the second at a large opening on the west side of the reactor’s biological shield called the west thermal column. In the first of these areas, low level radioactive waste size previously segmented or dismantled by the Dual Arm Work Platform (DAWP) and placed into a steel drum or transfer can were moved to a staging area for manual packaging. In the latter area, the manipulator arm removed and transferred shielding blocks from the west thermal column area of the reactor into waste containers. Rosie can also deploy up to twelve remotely controlled television cameras, some with microphones, which can be used not only for operating Rosie, but also in the operation of the manipulator arm (or any other device that is deployed). Since all of these operations can be performed remotely, no personnel are exposed to any radiation during all operations, except maintenance.

Figure 1. Rosie at CP-5, boom extended with jackhammer end-effector.

Rosie is also used to remotely carry heavy loads. Rosie's boom can lift up to 900 kg (2,000 lb.) using a lifting hook located near the boom tip. This hook is equipped with a load cell which can measure the weight of the load being supported by the hook and display this information on the control console. Loads can be lifted from floor level up to about 6 m (20 ft) off the floor. At the CP-5 reactor site, Rosie is used to transport contaminated materials that have been removed from inside the reactor to a disposal or packaging area some distance away. This significantly reduces the amount of personnel radiation exposure during these operations.

Figure 2. Rosie removing graphite with installed manipulator arm.

In comparison with the baseline technology, which is manual dismantlement using hand or long-reach tools, the main advantage of using the Rosie system is the significant reduction of personnel exposure to radiation. A secondary advantage is that Rosie can handle much higher loads (on the order of 900 kg (2,000 lb.)) than a man is capable of handling. Additionally, the use of Rosie allows the remote movement of loads without tying up existing facility cranes

Controlled by one CP-5 operator, the Rosie system with the Kraft Predator arm attached removed portions (approximately 500 lbs.) of the reactor structure and graphite shielding blocks from the west thermal column of the reactor during approximately 60.1 hours of operations. In addition, Rosie was used to move approximately 5,300 pounds of graphite shielding blocks, 1,400 pounds of lead, 620 pounds of boral, 600 pounds of aluminum and 530 pounds of other low level waste which were removed from the inside of the reactor structure from the top of the reactor to a packaging area. All of this was accomplished with very little operator exposure to radiation.

Technology Status

Rosie-C, the system used at CP-5, was the first full scale application of the teleoperated mobile robotics system. RedZone Robotics is pursing commercialization of Rosie. The information gathered at the CP-5 demonstration will be incorporated into future generations of the Rosie system, with subsequent wide application to the D&D industry.

Key Results

The key results of the Rosie demonstration are as follows:

- The Rosie system with the Kraft Predator arm attached removed approximately 500 lbs. of graphite blocks without exposing personnel to radioactivity. In contrast, the baseline technology of manual dismantlement using hand tools, would have resulted in significant personnel exposure to radiation.

- Using the steel transfer can, Rosie safely off-loaded a total of 8450 lbs. of radioactive materials including graphite blocks, lead sheeting, boral sheeting, aluminum plate, and miscellaneous LLW from the top of the reactor assembly with radiation levels up to 1.2 R/hr.

- Using the high reach capability of the heavy manipulator-mounted cameras, Rosie provided useful, supplemental viewpoints to the DAWP (Dual Arm Work Platform teleoperated robotic system) operators when unique camera angles were needed to support reactor tank and graphite removal operations.

- Rosie 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. Rosie was operating in a radiation field ranging from 0.05 to 2.0 R/hr for the duration of this work. By using this remote system, a significant amount or personnel exposure was avoided. Approximately 2 person-rem of exposure was saved.

- Personnel with little or no robotics experience can be adequately trained to safely and efficiently operate a sophisticated robotics system in a relatively short time period.

- The instrumented lifting hook on Rosie's boom was able to remotely move dismantled graphite blocks from the top of the reactor structure (3 to 4.5 m (10 to 15 ft) high) to a nearby packaging and disposal area at floor level. In contrast, the baseline technology of manually moving these blocks using a crane or other lifting device, would have taken more time and possibly resulted in increased personnel exposure to radiation

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Licensing Information

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

Web Site

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

SECTION 2

TECHNOLOGY DESCRIPTION

System Configuration and Operation

Worksystem Description

Rosie is a mobile robot worksystem developed for nuclear facility D&D. Its primary function is to perform a variety of dismantlement tasks remotely by deploying tools, sensors, and/or other robotic equipment into hazardous areas. Rosie's capabilities and system design address the need for durability and reliability in these environments, and enable performance of tasks such as piping and process equipment removal, structural demolition, component segmentation, waste handling and transport, and wall and floor decontamination.

The system includes a tethered robot, a power distribution unit (PDU), and a control console for robot operation. The robot consists of two major subassemblies, the locomotor and the heavy manipulator. The locomotor is a hydraulically powered, omni-directional platform with onboard tether management. It provides mobility to transport the heavy manipulator, tools, or other payloads within the work area. The heavy manipulator is a four degree-of-freedom, high-payload, long-reach mechanism capable of carrying a wide variety of tools, one or more dexterous manipulators, or any other payload of up to 900 kg (2,000 lb.) throughout a generous work envelope. The tip of the heavy manipulator can extend to reach 8 m (26 ft) above the floor in the straight up position, 4 m (13 ft) beyond the front edge of the locomotor in the straight ahead position, and at least 4.5 m (15 ft) beyond the edges to either side of the locomotor. All wheels are independently driven and steered, making Rosie highly maneuverable in tight or cluttered spaces. Each front wheel can be extended 76 cm (30 in.) to the side for added stability. Rosie can be driven with these wheels extended or retracted. The pivot-mounted rear axle provides compliance when working on uneven floors and crossing obstacles. Rosie is a teleoperated system with low-level automation features that facilitate more efficient remote operations and allow a single operator to maneuver and work effectively.

Locomotor

The locomotor is a hydraulically powered mobile platform with specifications as shown in Table 1. Its frame is an aluminum weldment which supports wheel modules at each corner. Each wheel module has independent drive and steering motions providing an omni-directional capability. The front two wheels are mounted on extensions which can change the front wheel tread width from 193 cm (76 in.) to 345 cm (136 in.). The two rear wheels are mounted on a pivoting beam which allows each wheel ±5 cm (±2 in.) of vertical travel for obstacle negotiation.

Located within the locomotor is the hydraulic power supply, which is a 45 kW (60 HP) supply, providing 114 l/min (30 GPM) of hydraulic fluid at 207 bar (3,000 psi) for all robot motions. The hydraulic fluid reservoir is located at the front center of the locomotor. Directly behind it is the hydraulic pump and its electric drive motor. All of the control valving for the system is located above the pump and motor, inside the locomotor frame. Filters, an accumulator, and the hydraulic fluid cooling equipment are all located on the right side of the locomotor, in one of two side enclosures suspended from the frame. The other side enclosure contains all onboard control electronics for the system. At the rear of the machine is the tether reel which can carry up to 50 m (165 feet) of tether. Up to 100 m (335 ft) of unreeled tether can be included to extend the vehicle's range.

Figure 3. View of Rosie with jackhammer mounted to boom.

Table 1.   Locomotor Specifications

Locomotor Dimensions:		
Width (extensions in)	218 cm	86 in.
Width (extensions out)	356 cm	140 in.
Height	107 cm	42 in.
Length	310 cm	122 in.
Obstacle Climb	10 cm (max.)	4 in (max.)
Ground Clearance	15 cm	6 in.
Minimum Turning Radius	0 cm	0 in.
Driving Speed	0 to 0.6 m/sec	0 to 2 ft/sec
Reservoir Capacity	284 l	75 gal
Fluid	Oil or Water Glycol	
Pump Capacity	114 l/min @ 207 bar	30 GPM @ 3,000 psi
Hydraulic Power Output	45 Kw	60 HP
Tether Reel Capacity	50 m	165 ft
Electric Input Power (to PDU)	480 VAC, 3Ø	@ 125 amps
Weight	3,900 kg	8,600 lb.

Heavy Manipulator

The heavy manipulator is mounted on the deck of the locomotor. It is a four degree-of-freedom mechanism providing a long-reach, high-payload capability for tool deployment. It can carry up to 900 kg (2,000 lb.) with a 6,800 Nm (60,000 in-lb.) moment load, at a distance of 6 m (20 ft) from the shoulder joint. The heavy manipulator consists of four joints; a vertical axis waist rotation motion on the locomotor deck, a shoulder pitch motion, a linear forearm extension, and a wrist pitch at the tip of the forearm. Each of the four joints has integral position feedback and is servo-controlled based on operator commands. The specifications for the heavy manipulator are shown in Table 2.

The heavy manipulator is capable of lifting its rated load in any position. However, due to the possible tip over of the locomotor on which it is mounted, it cannot lift this load at full extension over its entire workspace. With the front wheels fully extended, a 680 kg (1,500 lb.) counterweight mounted on the manipulator turret, and the rear pivoting axle in its locked position, the full load can be carried at full extension for about ±45 degrees of waist rotation. As the waist rotates further, the full extension load capacity must be reduced to prevent tip over of the locomotor.

Table 2. Heavy manipulator specifications

	Motion	Speed
Waist Rotation	+201°, -153°	±0 to 3 deg/sec
Shoulder Pitch	+90°, -20°	±0 to 3 deg/sec
Forearm Extension	3 to 6 m 10 to 20 ft	±0 to 15 cm/sec ±0 to 6 in./sec
Wrist Pitch	±90°	±0 to 3 deg/sec
Payload Capacity	900 kg with 6,800 Nm	2,000 lb. with 60,000 in.-lb.
Boom Tip Services: Hydraulic Electric	 57 l/min @ 207 bar 120 VAC	 15 GPM @ 3,000 psi @ 20 amps
Weight	1,950 kg	4,300 lb.
Counterweight Capacity	0 to 680 kg	0 to 1,500 lb.

Feedback

Rosie's operator is provided with extensive feedback information to support remote operations. Audio and video feedback are provided from two onboard microphones and up to 12 onboard cameras. Position readouts of all heavy manipulator and steering motions are displayed on a touchscreen at the console. Various other onboard sensors provide full system status and health monitoring. Additional user-specified sensors can be installed to provide remote monitoring of key environmental parameters.

Audio/video system. The audio/video system takes multiple camera views and microphone inputs from the robot and displays them at the console. Rosie can support up to 12 cameras including the following:

- Three cameras with focus, zoom, lights, microphone, and pan and tilt motions — two at the shoulders and one at the boom tip.
- Three cameras with remote lights and tilt motions (fixed focus) — two at the boom tip and one at the tether.
- Two cameras with remote lights (fixed focus) — one on top of the shoulder and one at the boom tip (for use at the end of a manipulator arm).
- Four fixed cameras (fixed focus, no lights) — two on each side of the locomotor for driving.

All cameras are modular to allow easy replacement or relocation in order to accommodate different tooling or task requirements.

System status/health. The status and health of the systems are constantly monitored by onboard sensors including hydraulic fluid temperature, pressure, and reservoir level, filter status, main pump and kidney loop pump motor status, and onboard electronics enclosure temperature, so that a fault may be detected before it can cause a complete system failure. Control and sensing signals are monitored automatically and error checking is performed to ensure reliable communications between the onboard controller and the control console.

Position sensing. All of the remotely controlled motions of the system incorporate position sensing. Locomotor wheel steering and drive motions are equipped with resolver feedback which is utilized by the computer control system to coordinate these motions in three different driving modes. This also provides the operator with a quick means to determine wheel steering positions. The four heavy manipulator motions (waist rotation, shoulder pitch, forearm extension, and wrist pitch) also have resolver feedback. This allows computer controlled coordination of the heavy manipulator axes in the Cartesian control mode. The position information for all heavy manipulator axes and all four steering motions are constantly displayed at the operator console. This provides the operator with a clear understanding of the heavy manipulator position and orientation at all times, as well as the steering angles of all four wheels.

The front wheel extensions incorporate limit switches so that the operator can always determine if they are extended or retracted. The tether reel has limit switches so that the tether cannot be completely unwound from the reel, or wound on beyond the reel's capacity.

User-specified feedback. The system has the capacity to support user-specified sensors installed on the robot. It can transmit data from these sensors back to the console for display or recording. Such sensors can be used to provide remote monitoring of key environmental parameters, such as radiation levels, ambient temperature or pressure, the presence of toxic gases, etc.

Control System

Rosie's control system is comprised of an operator control console and onboard control system components linked by a telemetry system. Control system functions are distributed across two primary computers (CPUs) — one in the console and one onboard the robot. The control console CPU displays status and sensor data coming from the robot, interprets signals from joysticks and other switches at the console, and sends appropriate commands to the onboard CPU. The CPU onboard the robot executes the commands sent from the console by closing motion control loops, acquiring sensor data, coordinating axes, and activating video and other onboard equipment. Both CPUs perform continuous error checking and monitoring of communications between the robot and the console.

Using this control system, a single operator stationed at the console can control the Rosie worksystem. Primary system functions—locomotor, heavy manipulator, system power, tether, and cameras—are controlled using switches and joysticks on the console panel. See Control Panel photograph in Figure 4. Vital system status information is displayed on the console status panel. Less frequently used functions and status information are accessed through the touch screen. Three video monitors, with quad-splitting capabilities, display the onboard camera views. The operator can select any camera view for any of the monitors using the touch screen controls. In this way, each operator can configure the control console monitors to suit his or her particular preferences. These views can be easily and quickly changed during operation of the system, as needs arise.

The control system software is transparent to the operator. No keyboard or mouse is required to run the system. The control system is based on a generalized infrastructure developed specifically for telerobotic systems. The system is flexible and extensible to meet future needs, and provides an efficient and effective interface between operator and robot.

Figure 4. Rosie control panel in CP-5 control room.

Control Modes

All axes are servo-controlled enabling precise, variable speed motion control for dexterous positioning either by teleoperation or by computer control. This servo-control allows the computer to coordinate the motions of the locomotor wheels in any of three different steering modes. In addition, the heavy manipulator can be operated in two different control modes. These modes are as follows:

Steering modes. The locomotor wheels are controlled in any of three driving modes:

- 4-Wheel Mode: Front and rear wheels steer in opposition, allowing a turn of any radius, including a pivot about the vehicle's center.
- Crab Mode: All wheels steer in the same direction, allowing the vehicle to translate linearly in any direction.
- Point Mode: Wheels automatically steer to turn the locomotor about a predetermined point. Assigning the tool location as this point allows the vehicle to be repositioned without moving the tool.

Boom modes. The heavy manipulator can be controlled in either of two modes:

- Joint Mode: Allows the operator to individually control each joint on the heavy manipulator at a continuously variable speed.
- Coordinated Mode: Allows the operator to steer the endpoint of the heavy manipulator and all four joints are automatically coordinated to achieve Cartesian motion.

Power and Telemetry

The power and telemetry subsystem allows power and control signals to be transmitted from the console to the locomotor and routed onboard to the various sensors and actuators. A PDU located between the console and robot provides a location to input site electrical power needed for onboard functions. A tether is used to transmit all power, control, and video signals to and from the robot. All signals from the console pass through the PDU and are combined with the power and routed into the tether. The electronics onboard the locomotor are located in a sealed enclosure mounted on the left side of the frame. This enclosure houses transformers, control computing, power supplies, video modulation equipment, and heat exchanger units.

Tooling and Auxiliary Services

A wide variety of tools or dexterous manipulators can be deployed from the heavy manipulator or locomotor deck. Highly accurate variable-speed motion control allows an operator to position tools quickly and perform work tasks efficiently. Rosie's work envelope allows floor to ceiling reach with most tools.

Both hydraulic and electric power are available at the boom tip to power tooling. As much as 57 l/min of hydraulic fluid at 207 bar (15 GPM at 3,000 psi) and 20 amps of 120 VAC power are available. Any user specified tooling can be deployed subject to power and payload (up to 900 kg (2,000 lb.)) constraints, including the following:

- hydraulic pipe shear
- reciprocating saw
- abrasive disk
- impact wrench
- plasma torch
- jackhammer/breaker
- pulverizer
- dual-arm worksystem.
- abrasive water jet
- excavation bucket
- drum grapple
- concrete hole saw
- cable winch
- mechanical scabbler
- dexterous manipulator

Decontamination

In nuclear environments, the ability to decontaminate equipment is critical to allow maintenance, storage, and transportation of equipment without incurring personnel exposure. All onboard components on this system are sealed for pressurized washdown. The system's structures are designed to minimize both exposed surfaces and areas where contamination can collect and be trapped. Areas that can't be sealed are left as open as possible in order to facilitate cleaning and washdown. Realistically however, Rosie has numerous inaccessible openings that would require partial or complete removal for adequate release criteria decontamination. As such, a gross decontamination would suffice prior to a transfer of the locomotor and heavy manipulator to another facility using appropriate Low Specific Activity (LSA) controls.

Radiation Hardening

This system is designed to operate in areas where radiation exposure is present. Materials and components have been selected to reduce the potential for radiation degradation. The robot portion of the system is designed to withstand a cumulative radiation dose of at least 10^5 R. Higher levels of radiation hardening are achievable if necessary by shielding of critical electronics and using more radiation tolerant components.

SECTION 3

PERFORMANCE

Demonstration Objectives

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 all or most of these hazards. For the purposes of this demonstration, these attributes were both desirable and necessary. Additional factors that required evaluation were as follows:

- 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 periodicities) 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.

Demonstration Results

The demonstration was performed at the ANL CP-5 Research Reactor from June through September 1997. Rosie's ability to remotely remove graphite via the Predator arm, move radioactive materials from the reactor assembly to a staging area using a specially designed steel transfer can, and position video cameras in strategic locations to support reactor dismantlement efforts was demonstrated. In addition, the objectives stated above were monitored and evaluated to gauge the relative success of the demonstration.

Rosie was very successful in meeting most of the stated objectives. The three main activities, Rosie's ability to remotely remove graphite via the Predator arm, move radioactive materials from the reactor assembly to a staging area using a specially designed steel transfer can, and position video cameras in strategic locations to support reactor dismantlement efforts were demonstrated. The first item, was the least successful. Not because of Rosie, but rather the demonstrated unreliability of the Predator arm. The Predator arm was clearly not well suited to the severe service it received during graphite removal. Some adaptations to the gripper assemblies by the Project contributed to some of the down time, but frequent hydraulic leaks that could not be attributed to the modifications or the usage by operating personnel. The fact that only 500 pounds of graphite was removed/packaged by the arm out of a total of approximately 5000 pounds originally in the thermal column, sheds some light on the problems that had occurred. However, since Rosie contributed less than two hours of the over 100 hours of downtime during this portion of the demonstration, Rosie cannot be fairly evaluated by this one task. The other two baseline objectives, movement of radioactive materials and positioning cameras were successful.

- The Rosie system, with the Kraft Predator arm attached, removed approximately 500 lbs. of graphite blocks without exposing personnel to radioactivity. In contrast, the baseline technology of manual dismantlement using hand tools, would have resulted in significant personnel exposure to radiation. This was considered a disappointment because of the downtime directly attributable to the manipulator arm. See Figure 5.

Figure 5. Transferring graphite blocks from west thermal column to radioactive waste container.

- Using the steel transfer can, Rosie safely off-loaded a total of 8,450 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. The instrumented lifting hook on Rosie's boom was able to remotely move dismantled graphite blocks from the top of the reactor structure (3 to 4.5 m (10 to 15 ft) high) to a nearby packaging and disposal area at floor level. In contrast, the baseline technology of manually moving these blocks using a crane or other lifting device, would have taken more time and possibly resulted in increased personnel exposure to radiation

- Using the high reach capability of the heavy manipulator-mounted cameras, Rosie provided useful, supplemental viewpoints to the DAWP operators when unique camera angles were needed to support reactor tank and graphite removal operations. Although the DAWP and the facility had a combined total of over twelve remotely positionable cameras, oftentimes additional angles and fields of vision were needed to complete a given task. The pan/tilt/zoom capabilities of the boom tip camera on Rosie was used frequently to provide the critical views the DAWP operators occasionally needed. Although cameras on tripods would have met the needs, a significant amount of personnel exposure would have been incurred moving the tripods and entangling power and video cables. See Figure 6.

Figure 6. Closeup of Rosie showing onboard cameras and tether control system.

The remaining paragraphs will describe the levels of effectiveness that Rosie had in meeting the other stated objectives of this demonstration:

- Considering the relative complexity of the robot and all of the interrelated systems that are used to operate Rosie, the system 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 most significant criticism of the system was not the system but rather the lack of a vendor training program. The Project had to develop 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 It is important to note that approximately 40% of the personnel who began the necessarily short and aggressive training program had the skills required to qualify as Rosie operators. The training of a core group of operators (4) and one supervisor required over 200 hours of cumulative operating time.

- The control console and associated components are well laid out and efficient in their use of space. In particular, the touchscreen console and its 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. See Figure 4.

- All tasks that were required of Rosie were completed successfully. These tasks ranged from very simple, low risk jobs such as camera positioning to moderately complex, high risk jobs including lifting the transfer canister loaded with highly radioactive waste and removing a shield plug from the side of the reactor assembly. See Figure 7. It is worth noting however, that not all of Rosie functions were utilized. Therefore, this demonstration was quite limited in utilizing the wide range of abilities built into the system. For example, there is a "teach/learn" capability that was not used except during training orientation.

Figure 7. Rosie removing a highly radioactive shield plug from the west thermal column.

- Operationally, the system proved capable of performing all tasks asked of it. Although there were two unplanned downtimes for Rosie, neither event caused a safety concern or an operational failure while the robot was being used. The two events accounted for a total of one hour and 50 minutes of non-availability. Details on both of these occurrences are found below in the paragraph addressing reliability.

- The system proves to be quite versatile. With the different utilities available at the end of the heavy manipulator, tooling changes are relatively simple. During the demonstration, the only end effector installed was the manipulator arm. This hydraulic fluid in the arm however was not compatible with the Rosie hydraulic fluid and required the routing of additional lines through the boom assembly. Therefore, this required additional time to accomplish. However, the removal of a demolition jackhammer that was used prior to the demonstration was performed in less than one hour with common hand tools and fittings.

- Rosie 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. Rosie was operating in a radiation field ranging from 0.05 to 2.0 R/hr for the duration of this work. By using this remote system, a significant amount or personnel exposure was avoided. With all of the camera views afforded by Rosie's onboard cameras and the tie in capabilities to the other facility cameras, this system proved to be truly a remote controlled system. The greatest weakness is the system's tether management. The tether is the lifeline for this system. Should the tether become damaged or severed, many or all of the system would fail depending on the damage. Worst case, all functions on Rosie would cease. There would be no "limp home" capability. During the demonstration, only once was the tether run over with no damage. A better system would greatly enhance the operability of the system and minimize the likelihood of a catastrophic shutdown of the system. Refer to section 7, lessons learned.

- Preventive maintenance was not performed during the demonstration. Per the operating manual, the scheduled maintenance periodicity is approximately every 400 hours. This mark was not reached during the demonstration. However, the required work outlined is quite simple and should not take more than one-half to one shift to perform.

- With regards to reliability, there were only two unplanned downtimes for Rosie accounting for a total of one hour and 50 minutes of non-availability. Neither event caused a safety or operational concern. The first event was an multi-pin connector failure that prevented the system from booting up during startup. This prevented the startup of Rosie. Troubleshooting and repair time was 90 minutes. The cause was an exposed pin connector on the electronics chassis in the control room that had been damaged, possibly by contact with a passer-by. A ribbon type connector replacement was installed that minimizes the chances of damage from incidental contact. The second item causing delays was an aberrant sensor on the hydraulic reservoir level detector. This malfunction caused spurious critical low level alarms to come in on the control console, although at no time was there an actual alarm condition. During the initial failure, a manual Emergency Stop was initiated by the operator during a movement of Rosie and fortunately no load was being transferred. Following the initial event, the alarm came in quite frequently and warranted replacement by the vendor. The replacement part functioned properly for several weeks after installation and then it too failed. Since then the alarm was jumpered out of service since other warning features provide redundant indications of an actual problem. This failure caused a 20 minute downtime initially and was considered a nuisance afterward until the alarm was disabled. For more information on the level sensors, refer to section 7, lessons learned.

- The final objective to be discussed is the operating efficiency. Any remote controlled system used in a D&D environment will, by its very nature, be less efficient than a person performing the work. Unless work can be automated, this objective would be nearly impossible to meet. For D&D operations, the more critical aspect is, can the system do work that otherwise could not normally be accomplished? In this light, the Rosie system can be evaluated. Because of the system's primary mission, to provide a mobile work platform suitable for use in a hostile environment, this objective is met. With regards to the former objective, the planned length of work must at a minimum be doubled or trebled when using a remote system. During initial deployment, this value is actually higher. However, with operational experience the multiplication factor may be reduced. This objective must be clearly understood by potential users when deciding whether or not to use robotics systems. If the "enabling" capability of the system does not outweigh the decreased operational efficiency, other options may need evaluation.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

The Rosie 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 Rosie system takes up a large amount of space physically, and is ideal for large areas with open floor space. This technology showed the following characteristics at the CP-5 demonstration:

- The Rosie system can be used to deploy different types of equipment and tools. Manipulator arms (i.e., the Kraft Arm), hardware (i.e., Jackhammer) and various other tools can be changed as needs arise. See Figure 8.

Figure 8. Rosie's long reach ability with manipulator arm attached.

- The Rosie 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 Rosie will require personnel to be exposed to some contamination on Rosie.

- Rosie can be moved to a low dose or protected area for tooling changes and maintenance operations, reducing personnel exposure during these procedures.

- Rosie is not subject to many breakdowns, although minor leaks in the hydraulic system may arise. Also, some minor software anomalies were observed to occur. As knowledge of the systems was gained and operator experience increased these problems became less evident. Throughout a total of approximately 450 hours run time to date, only one breakdown caused a total shutdown and posed a potential accident scenario. Even so, this event posed no danger to personnel, had little risk for causing significant damage to equipment or materials and resulted in little downtime (due mostly to problem investigation and subsequent recovery actions.)

- Rosie can effectively handle loads which are larger and heavier than personnel could handle manually with hand tools.   See Figure 9.

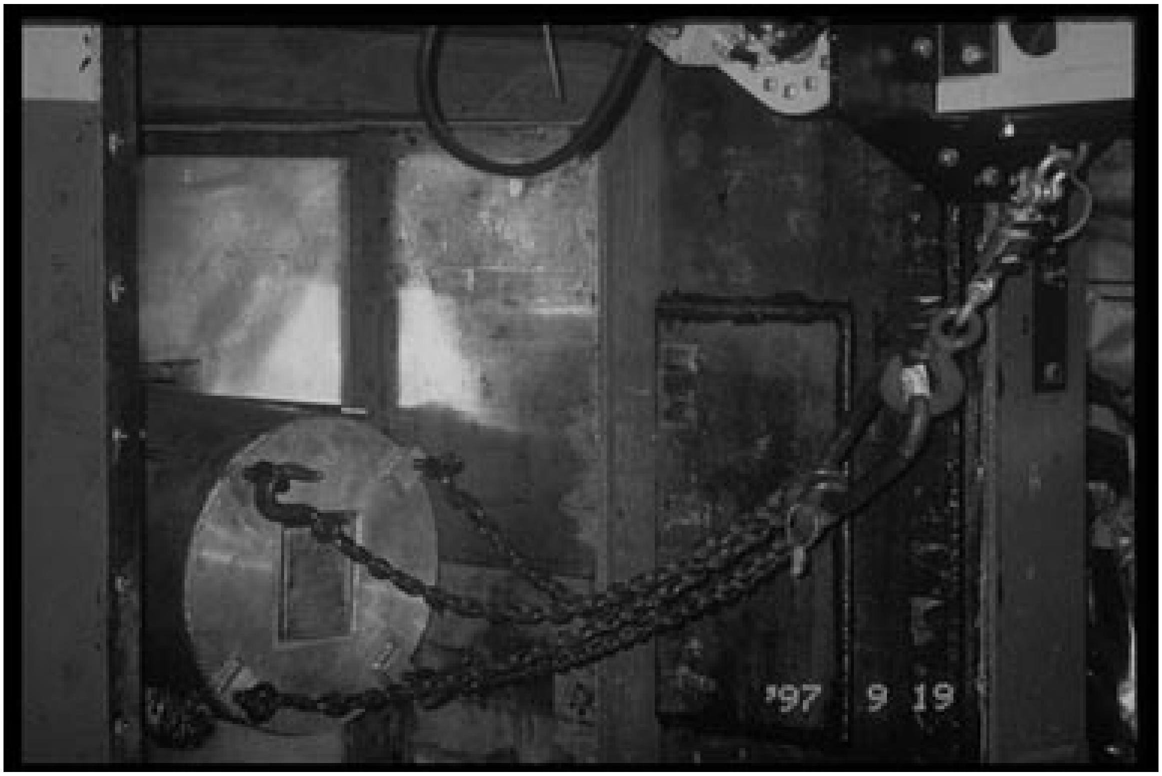

Figure 9. Closeup of Rosie removing an 870 pound shield plug.

- Rosie can be difficult to maneuver in small areas or tight locations. The combination of the boom and the platform are ideal for large areas, but can be constricting in confined areas.

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

Competing Technologies

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 Rosie system was specifically designed for D&D operations in hazardous environments, and there are no other known systems which have the full range of capabilities, including the adaptability to differing environments and tasks, and the video and audio feedback capabilities to allow it to be fully remotely controlled. Where exposure levels are beyond engineered controls, Rosie can be as essential tool. 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.

There are some systems available that can perform some of the functions of the Rosie system. One system is a dedicated, commercially available hydraulic concrete breaker. It is remotely controlled through a tether by an operator, but the operator must be within line-of-sight of the work area, since the system has no video feedback capabilities. Additionally, this system performs solely as a hydraulic breaker and has no provisions for different or supplemental tooling.

Patents/Commercialization/Sponsor

No patents were issued or are pending on the Rosie system.

Commercialization is being pursued by the vendor.

The Department of Energy, EM-50 program sponsored the design and development of Rosie-C.

SECTION 5

COST

Introduction

This cost analysis compares the relative costs of the innovative technology of Rosie and the baseline technology of manual demolition. This information will assist decontamination and decommissioning (D&D) planners in making 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 Department of Energy (DOE) complex. However, this is a limited representation of actual costs because the analysis uses only data observed during the demonstration. The demonstration consisted of demolition and packaging of 500 pounds (of a potential 5,000 pound total) of the shield material in the west thermal column assembly. The demonstration includes moving 8,450 pounds of low level radioactive waste. The cost analysis does not include the demolition work which generated most of the 8,450 pounds of waste (previous demolition of the bio-shield and segmentation of the reactor tank). Some of the observed costs will include refinements to make the estimates more realistic (such as elimination of cost for vendor personnel and cost for shipping from vendor's site since the equipment is assumed to be site owned and operated with site labor). 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).

Methodology

Rosie is an advanced robotics platform that can be used as a demolition system. This innovative technology was demonstrated at Argonne National Laboratory (ANL) under controlled conditions that facilitated observation of the work procedures and their typical duration. Its cost analysis is based on two pieces of work: 1) observing the demolition and removal of 500 pounds (of the 5,000 pounds total) from the west thermal column assembly (subassembly of the CP-5 reactor shield); and 2) observing the remote transfer of 8,450 pounds of low level radioactive materials from high radiation area to a low radiation staging area for packaging the waste. This low level radioactive waste was previously loaded into transfer canisters having a rated capacity of 2,000 pounds and the demonstration consisted of moving the previously filled canisters. The analysis is based on Government ownership of Rosie and operation by site workers. The analysis uses an hourly rate for Rosie which is computed by amortizing the purchase price over a 20 year service life and annual maintenance costs of $10,000 each year is included in the hourly rate.

The cost estimate for the baseline technology was based on observations of site personnel using a 50 pound demolition hammer and other hand tools (e.g., crowbars and lifting and handling equipment). The observations include demolition and removal of 4000 pounds of graphite from the west thermal column assembly , and the observed production rates were used in the cost estimate with the quantity of 500 pounds (to match the quantity for Rosie). The removal of low level radioactive materials from the high radiation area to the low radiation staging area was not performed, and the cost estimate is based on assuming the production rates for the baseline are slightly less than for Rosie. The demolition hammer and the crane are assumed to be rented.

The basic activities being analyzed originate from the Hazardous, Toxic, and 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. Consequently, 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" of the rates used at ANL. The impacts resulting from this omission is judged 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, such as trucks for transport or Health Physics

Technician (HPT) radiological survey equipment, are based on an hourly government ownership rate that is computed using the Office of Management and Budget (OMB) Circular No. A-94. Quoted rates for the vendor's costs are used in this analysis for performing training of the site's personnel and includes the vendor's G&A, overhead, and fee mark-up costs. Additionally, the analysis uses an eight-hour workday with a five-day workweek.

Cost Data

To determine whether it would be more cost effective to purchase, lease, or use a vendor provided service, each option must be evaluated. The options and the corresponding costs are listed below.

Table 3. Innovative technology acquisition costs

Acquisition Option	Item	Cost
Equipment Purchase	Rosie	$1,400,000
Equipment Lease	Rosie	Not Available for Lease
Vendor-Provided Service	Equipment Operator Training	Not Available $75/hr $75/hr

In addition to the purchase of the equipment, spare parts are required ($25,400 - $38,700). Scheduled maintenance amounts to approximately a half shift of labor for every 400 hours of operation (this does not include the time required to decontaminate prior to performing the maintenance).

Observed unit costs and production rates for principal components of the demonstrations for both the innovative and baseline technologies are presented in Table 4 below.

Table 4. 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**
Remote Demolition	$2.24/lb	120 lb/hr	Manual Demolition	$0.72/lb	100 lb/hr
Remote Loading	$1.62/lb	167 lb/hr	Manual Loading	$0.07/lb	1000 lb/hr
Remote Off Loading	$1.00/lb	268 lb/hr	Manual Moving	$0.69/lb	241 lb/hr

The unit costs and production rates shown do not include mobilization, set up, maintenance/repair, or other costs associated with non-productive portions of work. 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 Remote Demolition is the unit cost shown for the Loosen and Knock Down line items of Table C-1 and Table C-2 of Appendix C, Remote Loading is the unit cost shown for the Load in Bin for Table C-1 and Packaging Graphite for Table C-2, and Remote Off Loading is the unit cost shown for Off Load Low Level Radioactive Material for Tables 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 an individual 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, consequently, the costs for an individual job are unique. The innovative and baseline technology estimates presented in this analysis are based upon a specific set of conditions or work practices found at CP-5 and are summarized in Table 5. This table is intended to help the technology user identify work differences that can result in cost variances.

Table 5. Summary of cost variable conditions

Cost Variable	Rosie	Manual Demolition
Scope of Work		
Quantity and Type	Estimate based on demolition and packaging of 500 pounds from the west thermal column assembly and moving 8450 pounds of low level radioactive materials	Estimate based on demolition and packaging of 500 pounds from the west thermal column assembly and moving 8450 pounds of low level radioactive materials. Actual demonstration had 4000 pounds removed from the west thermal column and no moving of low level radioactive materials
Location	Reactor core at CP-5.	Reactor core at CP-5.
Nature of Work	1) The material removed from the west thermal column reactor was placed into a waste container for shipment (voids required to not exceed 10%). 2) Low level waste (which was generated by demolition of the top of the reactor and this demolition is not part of this analysis) was transferred from the high radiation area to the low radiation staging area. Canister containing the waste was rated at 2000 pound capacity.	Assumed the same as for Rosie.
Work Environment		
Worker Protection	Hard hat, safety goggles, ear protection, gloves, and TLD for maintenance operations only. Otherwise, for normal Rosie operations only a TLD was worn in the control room.	Goggles, double gloves, ear protection, full protective clothing, double outer boot covers, respirator, and dosimetry.
Level of Contamination	Rosie's work area was classified as a contamination area and a high radiation area. Operator worked away from the contamination and high radiation areas.	Classified as a contamination, high airborne contamination area , and a high radiation area.
Work Performance		
Acquisition Means	Equipment is site owned and site personnel are used as operators. Training is vendor provided.	Site personnel with site-owned equipment.
Production Rates	Productivity is based on 500 lb of demolition at 120 lb/hr for demolition and 167 lb/hr for loading. The productivity for loading and unloading is 300 lb/hr. The productivity for moving is 268 lb/hr.	Based on the 4,000 lb of graphite removal over five months. The productivity used for demolition is 100 lb/hr. The productivity for loading is 1000lb/hr. The productivity rate for moving is assumed 241 lb/hr.
Equipment & Crew	One Rosie equipped with a manipulator arm plus a crew of one Mechanic as an operator	One 50-lb demolition hammer, other small tools, and two D&D workers for the work at the west thermal column assembly. One truck mounted hydraulic crane and one operator and rigger for the work moving radioactive material.

Table 5. Summary of cost variable conditions (continued)

Cost Variable	Rosie	Manual Demolition
Work Process Steps	1. Transport equipment to site 2. Travel for vendor's operators to the site and vendor support of set up 3. Set up equipment 4. Modify building utilities 5. Demolition of west thermal column and place in waste container 6. Move waste which were generated previously by demolition of the reactor top 7. Prepare equipment for shipping 8. Load equipment 9. Transport equipment to local storage 10. Transport equipment	1. Transport rented equipment to work area 2. Set up step off area 3. Demolition of west thermal column and place in waste container 4. Move waste which were generated previously by demolition of the reactor top 5. Decon and survey for free release 6. Load equipment 7. Transport equipment to rental

Potential Savings and Cost Conclusions

For the conditions stated in Table 5 and assumptions established in Appendix C, the Rosie innovative technology is approximately three times the cost of the manual demolition baseline. These costs are presented in Figure 10.

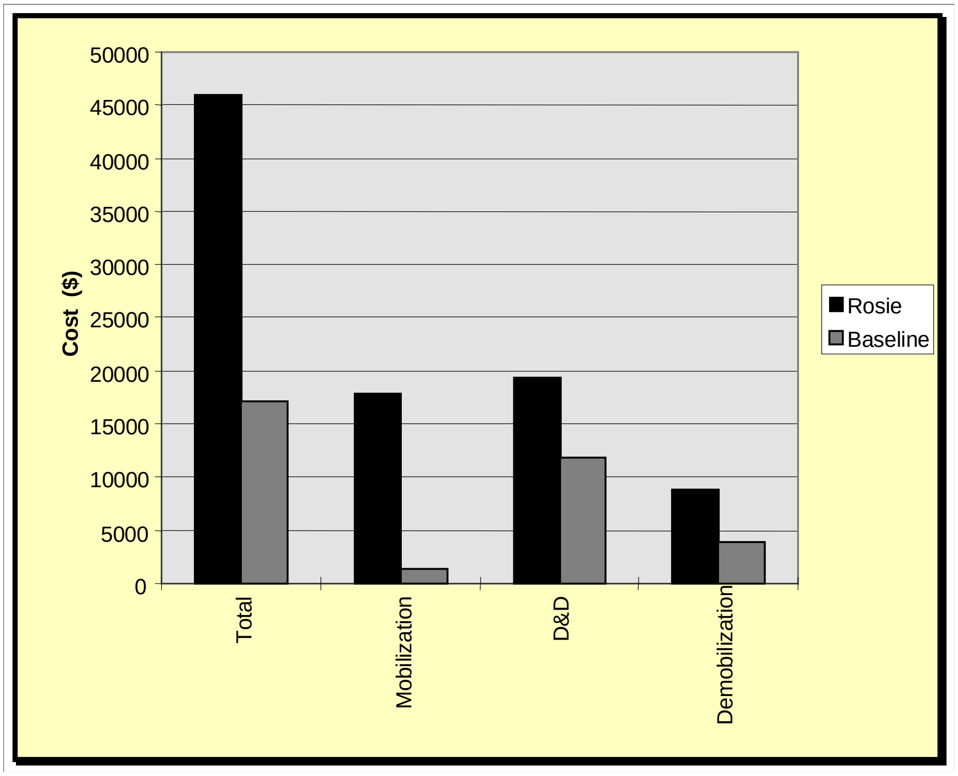

Figure 10. Technology comparison.

Mobilization, demolition, and demobilization costs are each much greater for Rosie than the manual demolition. The main reason for Rosie's high cost is its hourly equipment rate, which is about 3 times the rate of a typical crew for the baseline method. But, the comparison of the Rosie rates with the labor rates is complicated by the exposure that the worker receives. The exposure that the workers receive in the course of performing the work using baseline methods is approximately $20,000 (based on an estimated exposure of 2 person rem and a computed site cost of $10,000 per person rem). The savings in exposure helps off set almost all of the difference in cost between the Rosie 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. In the severe situations, the Rosie system may be a cost effective alternative.

The cost analysis did not include costs for training Rosie operators (since this is a one time cost). But, this is a significant cost consideration for small jobs and make the difference between Rosie being a cost effective choice. Based on the demonstration, the training related cost is approximately $57,000.

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

The regulatory/permitting issues related to the use of the Rosie Mobile Robot Work System 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 Rosie Mobile Robot Work System technology is a relatively new, largely untested 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. The very nature of 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 2 person-rem.

The use of the Rosie Mobile Robot Work System 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 only notable problem with the Rosie system during its operations at the CP-5 reactor site was the failure of the fluid level sensors in the hydraulic reservoir on the Rosie locomotor. Both the LOW LEVEL and CRITICALLY LOW LEVEL sensors failed within a few months. They were both subsequently replaced and the failed sensors were returned to the manufacturer for examination. No cause for the failures was found, but it is suspected that the very low electrical currents through the contacts causes them to increase their resistance over a long period of time. The sensor circuits on the Rosie system may be modified in the future to increase these current levels in order to correct this situation.

One of the limitations Rosie had at the CP-5 project was the telescoping boom was not long enough to reach inside the reactor, yet the platform was bulky and difficult to maneuver on the reactor floor. Rosie did prove extremely useful as a movable lifting platform and for the observations of operations inside the reactor tank. Additionally, in situations where the base was stable and the boom extended and retracted, as when removing the graphite from the thermal columns, Rosie proved efficient and effective. The remote lifting capabilities of Rosie were very useful during CP-5 operations since the facility's polar crane was in use almost continuously for positioning of the DAWP. Rosie was able to perform many lifting operations that would have caused delays for reactor tank dismantling operations.

Technology Limitations

Rosie is a viable D&D tool in its present state. However, robotics technology is continually improving, and subsequent generations should incorporate these improvements and lessons learned. Improvements to the tether could include mechanisms which would reduce its vulnerability to damage. Although the tether is extremely well protected in it's present state, it is still a weak link in terms of potential damage to the robot, and had been a source of accidents to novice operators. Additionally, Rosie has limited maneuverability in confined areas and areas with low ceilings.

Additionally, improvements could be made in the detection of objects when extending the boom or maneuvering the locomotor platform. The camera angles do give a very good vantage points, but the cameras and end effectors are vulnerable to damage if there is accident involving the boom tip or platform. Technology development should focus on reducing the possible damage to the robot and corresponding down-time in the event of an accident with the tether or the boom tip.

Technology Selection Considerations

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

Appendix A

REFERENCES

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Rosie-C Maintenance Manual, dated February 28, 1997, prepared by RedZone Robotics, Inc.

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Appendix B

ACRONYMS AND ABBREVIATIONS

ALARA	As Low As Reasonably Acceptable
ANL	Argonne National Laboratory
CC	cut concrete (an activity)
CF	cubic feet (foot)
CFM	cubic feet per minute
CY	cubic yards
D&D	Decontamination and Decommissioning
Decon	decontamination
Demob	demobilization
DOE	Department Of Energy
Equip (Eq)	equipment
FCCM	Facilities Capital Cost Of Money
FETC	Federal Energy Technology Center
H&S	Health and Safety
HR	hour
HTRW	Hazardous, Toxic, Radioactive Waste
LF	lineal feet (Foot)
LLW	Low Level Waste
LS	lump sum
LSA	Low Specific Activity
Min	minute
Mob	mobilization
NESP	National Environmental Studies Project
NRC	Nuclear Regulatory Commission
PCs	protective clothe(s) (clothing)
PLF	productivity loss factor
PPE	personnel protective equipment
Qty (Qnty)	quantity
RA	Remedial Action
RB	remove (concrete) blocks (an activity)
RSP	remove soil and pipe (an activity)
SAFSTOR	Safe Storage
SF	square feet (foot)
TLD	Thermoluminescent Dosimeter
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.

Innovative Technology – Rosie

MOBILIZATION (WBS 331.01)

Load Equipment

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

Assumptions: 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 (rates from Dataquest-Rental Rate Blue Book, 1997). 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). Rosie rate computed by amortizing purchase price over 20 years.

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.

Vendor Support for Set Up

Definition: Set up of Rosie will be supported by one vender technician for duration of setup of the equipment. This includes transport, per diem, rental car, and labor during the set up.

Assumptions: Vendor provided quote for round trip travel from Pittsburgh to Chicago, rate for technician, and per diem.

Set Up Equipment

Definition: Prepare equipment for operation includes calibration and leak testing of the hydraulic system.

Assumptions: Duration based on observations from the demonstration.

Modify Building Electrical System

Definition: Modify the site's electrical system to allow a 440-volt electric source.

Assumptions: This cost element requires 80 hours of an electrician's time and $1,500 worth of supplies.

Survey and Prepare Equipment

Definition: Survey equipment for radiological contamination and prepare for use (includes wrapping cables and body with plastic to minimize potential contamination).

Assumptions: Duration of 2 hours for two Health Physics Technicians (HPTs). Material cost is negligible.

DECONTAMINATION AND DECOMMISSIONING (WBS 331.17)

West Thermal Column

Loosen and Knock Down:

Definition: Rosie uses the manipulator arm to break apart the graphite assembly and allow them to drop to the floor.

Assumptions: The demonstration removed 500 pounds of material (of the 5000 total in the assembly) in 4.17 hours. This is a production rate of 120 lb/hr. Test engineer observed that the work could be performed with one mechanic.

Load in Bin:

Definition: The manipulator arm is used to pick up the material from the floor and load it into a waste container.

Assumptions: Rate of work is controlled by need to carefully position the waste in the container (located on top of the bio-shield) in a way that the voids do not exceed 10% (waste acceptance requirement). The 500 pounds of waste were loaded in 3 hours for a production rate of 167 lb/hr.

Attach Manipulator Arm:

Definition: Attachment of the manipulator arm to Rosie.

Assumptions: Based on the observed duration from the demonstration.

Remove Manipulator Arm:

Definition: Removal of arm.

Assumptions: Based on the observed duration.

PPE for Attach/Remove:

Definition: The attachment and removal of the manipulator arm required donning and doffing protective clothing (other operation activities did not require PPE).

Equipment	**Cost Each Time Used**	**Number Used Per Day**	**Cost Per Day**
Booties	0.25	4	1.00
Tyvek	3.40	4	13.60
Gloves (inner)	0.17	8	1.36
Gloves (outer pair)	0.75	1	0.75
Glove (cotton Liner)	0.14	8	1.12
Total			$22

Top Of Reactor

Off Load Low Level Radioactive Material:

Definition: Previous demolition work generated low level radioactive waste which was loaded into transfer canisters at the top of the bio shield. The demolition and placing of waste into the canisters is not part of this analysis. But, this activity covers the transfer of that waste plus the waste from the west thermal column (total of 8,450 pounds of waste). The waste contained in the canisters includes graphite blocks, boral plates, lead sheeting, and aluminum plates. The canisters are typically rated for a 2,000 pound capacity and are transported from the high rad area (at the top of the bio shield) to a low rad staging area.

Assumptions: Based on demonstration observations, 8,450 lbs was moved in 31.5 hours. This is a production rate of 268 lb/hr.

HPT Support

Definition: Health Physics technicians support to the work.

Assumptions: Negligible support required based on the experience of the test engineer.

Productivity Loss Factor

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

Assumption: The production rates (previously computed) do not account for work breaks or safety meetings. 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
+Protective Clothing	0
= Subtotal	1.00
X	
Resp Prot	1.00
=Subtotal	1.00
X	
Breaks & Meetings	1.15
=Total	1.15

DEMOBILIZATION (WBS 331.21)

Dismantle Rosie

Definition: Take Rosie apart for eventual shipment.

Assumptions: Duration based on judgment of the test engineer.

Prepare Equipment for Transfer

Definition: Preparation for eventual shipment assuming no requirement for free release. Includes decontamination of wheels, cursory decontamination of body.

Assumption: Duration and crew based on judgment of the test engineer.

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 utilized in the innovative technology are shown in Table C-1.

Table C-1. Innovative technology cost summary – Rosie

Work Breakdown Structure (WBS)	Unit Cost (UC) Labor HRS	Labor Rate	Equipment HR	Equipment Rate	Other	Total UC	Total Quantity (TQ)	Unit of Measure	Total Cost (TC) note	Innovative Technology Comments
MOBILIZATION (WBS 331.01)								**Subtotal**	**$ 17,835**	
Load Equipment	8	$146.90	8	$ 333.47	$ 0	$3,842.96	1	Each	$ 3,843	Truck @ $19.78/hr, crane @ 77.80/hr, teamster $39.85/hr, operator $39.85/hr, & 2 D&D workers @ 33.60/hr and Rosie standby at $235.89/hr.
Transport to Site	2.75	$ 146.90	2.75	$ 333.47	$ 0	$ 1,321.02	1	Each	$1,321	Transport from warehouse to work location. Same as above plus standby.
Vendor Support of Setup		$		$	$2,885	$ 2,885.00	1	Each	$ 2,885	Air travel round trip Pittsburgh to Chicago $500, per diem $150/ day for 3 days, labor for 24 hours at $75/hr., and rental car 3 days @ 45/day.
Set Up Equipment	16	$ 33.60	16	$ 235.89	$0	$ 4,311.84	1	Each	$ 4,312	D&D worker @ 33.60/hr and Rosie @ $235.89/hr standby.
Modify Building Electrical System	80.00	$ 49.67	0	$ 0	$1,500	$ 5,473.60	1	Each	$ 5,474	Electrician time of 80 hours is needed for installation of a 440-volt power source plus $1,500 worth of supplies (other costs).
DECONTAMINATION AND DECOMMISSIONING (WBS 331.17)								**Subtotal**	**$19,299**	
West Thermal Column										
Loosen and Knock Down	.0083	$ 33.60	.0083	$ 235.89		$ 2.24	500	Lb	$ 1,118	Includes demolishing graphite structure at a rate of 120 lb/hr. Operation by one D&D worker @ $33.60/hr and Rosie @ $235.89/hr.
Load In Bin	.006	$ 33.60	.006	$ 235.89		$ 1.62	500	LB	$ 808	Includes demolishing graphite structure at a rate of 167 lb/hr with same crew.
Attach Manipulator Arm	14	$ 67.20	14	$ 235.89		$ 4,243.26	1	Each	$ 4,243	Install, check , and calibrate using 2 D&D workers @ 33.60/hr each and Rosie standby.
Remove Manipulator Arm	.5	$ 67.20	.5	$ 235.89		$ 151.55	1	Each	$ 152	Same crew.
PPE for Attach/Remove					$ 22	$ 22.00	6	Person Days	$132	PPE for attaching and removing arm for two people for two days.
Top of Reactor										
Off Load Low Level Radioactive Material	.0037	$ 33.60	.0037	$ 35.89	$ 0	$ 1.0	8,450	Lb	$ 8,426	Move debris from high rad area to low rad staging area at a rate of 268 lb/hr. One mechanic and Rosie.
HPT Support					$0	$ 0			$ 0	No HPT support required.
Productivity Loss Factor	16.40	$ 33.60	16.40	$ 235.89		$ 4,419.64	1	Lump Sum	$ 4,420	Accounts for loss of productivity such as suit up and safety meetings. Factor of 1.15 for a 15% loss.
DEMOBILIZATION (WBS 331.21)								**Subtotal**	**$ 8,857**	
Dismantle Rosie	8	$ 67.20	8	$ 235.89		$24,424.72	1	Each	$ 2,425	2 mechanics and Rosie standby.
Prepare for Transport	4	$ 102.36	4	$ 235.89	$ 52	$ 1,268.36	1	Each	$ 1,268	Minor decon. and preparation Includes labor for two D&D workers , 1/4 HPT, Rosie standby and cost for disposal of one cubic foot of low level waste @ $52/cubic foot.
Load Equipment	8	$146.90	8	$ 333.47	0	$ 3,842.96	1	Each	$ 3,843	Similar to Mobilization.
Transport Equipment	2.75	$146.90	2.75	$ 333.47		$ 1,321.02	1	Each	$ 1,321	Similar to Mobilization.
Note: TC = UC * TQ								**TOTAL:**	**$ 45,991**	

Baseline Technology - Manual Demolition

MOBILIZATION (WBS 331.01)

Transport to Site

Definition: Truck mounted crane and demolition hammer transport from nearby rental to CP-5 and unloads.

Assumption: Duration assumed to be 4 hours. 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.

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).

DECONTAMINATION AND DECOMMISSIONING (WBS 331.17)

Set Up (each morning)

Definition: The time required for setting up in one location and performing equipment checks and maintenance each morning.

Assumptions: The duration is 15 minutes each morning with a crew of two D&D workers.

West Thermal Column

Loosen and Knock Down:

Definition: The crew uses bars and the hammer to break apart the graphite assembly and pile them near the waste container.

Assumptions: The demonstration removed 4,000 pounds of material in ten 8-hour days. Assuming 4 productive hours per day, this is a production rate of 100 lb/hr.

Packaging Graphite:

Definition: The material removed from the thermal column is placed into the container which is located at the top of the bio shield. This involves less work than the comparable cost element for Rosie, because the workers can drop the removed material closer to the container as they remove it.

Assumptions: The 4,000 pounds of waste were loaded in 4 hours for a production rate of 1000lb/hr.

Productivity Loss Factor:

Definition: This cost element provides for donning and doffing of protective clothing and respiratory protection, rest periods, safety meeting, project planning meetings, and other activities that are not graphite structure removal activities.

Assumptions: The observed production was four hours out of an eight-hour day. Thus, the non-productive time is 50%.

Top Of Reactor

Off Load Low Level Radioactive Material:

Definition: Previous demolition work generated low level radioactive waste which was loaded into a transfer canister at the top of the bio-shield. The demolition and placing of waste into the canisters is not part of this analysis. But, this activity covers the transfer of that waste plus the waste from the west thermal column (total of 8,450 pounds of waste) to a staging area. The waste contained in the canister includes graphite blocks, boral plates, lead sheeting, and aluminum plates. The canister is rated for a 2,000 pound capacity and are transported from the high rad area (at the top of the bio shield) to a low rad staging area.

Assumptions: Assumed to be performed by a truck mounted crane. The production rate is assumed to be 10% less than the production rate observed for Rosie based on the experience of the test engineer (production rate of 268 lb/hr X 0.90 = 241 lb/hr).

Productivity Loss Factor:

Definition: This cost element provides for safety meeting, project planning meetings, and other activities that are not graphite structure removal activities.

Assumptions: This is proportioned to 5.59 hours our of an eight-hour day. Thus, the non-productive time is 2.41 hours, or 31%, of each eight-hour day.

<u>Personal Protection Equipment</u>

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

Equipment	Cost Each Time Used	Number Used Per Day	Cost Per Day
Respirator	$10.00	1	$10.00
Respirator Cartridges	9.25	2	18.50
Booties	0.25	4	1.00
Tyvek	3.40	4	13.60
Gloves (inner)	0.17	8	1.36
Gloves (outer pair)	0.75	1	0.75
Glove (cotton Liner)	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).

HPT Support

Definition: This activity includes full time HPT support to check and survey work.

DEMOBILIZATION (WBS 331.21)

Decontaminate and Survey Out

Definition: Equipment and personnel are decontaminated and surveyed for free release.

Assumption: The duration of 24 hours is assumed (based on the experience of the test engineer). One cubic foot of waste is assumed.

Transport Equipment

Definition: Transport from CP-5 to local rental, and includes truck mounted crane and demolition hammer.

Assumptions: Similar to mobilization.

The activities, quantities, production rates, and costs utilized in the baseline are shown in Table C-2.

Table C-2. Baseline technology - Manual demolition cost summary.

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 Technology Comments
Mobilization (WBS 331.01)								**Subtotal**	**$ 1,296**	
Transport to Site	4.0	$ 73.45	4.0	$ 60.00	$ 0	$ 533.80	1	Each	$ 534	Teamster $39.85, 1 D&D workers @ 33.60. Includes demolition hammer standby @ $5/hr and truck mounted crane standby at $55/hr.
Setup Step Off Area	8.0	$ 67.20		$	$ 300	$837.60	1	Each	$ 838	Construct temporary walls by 2 D&D workers @ 33.60/hr each using $300 of materials.
Decontamination and Decommissioning Activities (WBS 331.17)								**Subtotal**	**$ 11,866**	
Set Up (each morning)	0.25	$ 67.20	0.25	$ 5.00	$ 0	$18.05	6	Days	$ 108	Two D&D worker @ $33.60/hr each and demolition hammer standby for equipment checks and maintenance
West Thermal Column										
Loosen and Knock Down	0.01	$ 67.20	0.01	$ 5.00	$ 0	$ 0.722	500	Lb	$ 361	Same crew and production rate of 100 lb/hr.
Packaging Graphite	0.001	$ 67.20	0.001	$ 5.00	$ 0	$ 0.07	500	Lb	$ 36	Same crew. Productivity is 1000 lb/hr.
Productivity Loss Factor	2.75	$ 67.20	2.75	$ 5.00		$ 198.55	1	Lump Sum	$ 199	2.41 hours of each 8-hour day for meetings, suit up, etc. (50% of work time).
Top of Reactor										
Off Load Low Level Radioactive Material	.0041	$ 89.52	.0041	$ 77.80		0.69	8450	Lb	$ 5,862	Move debris from high rad area to low rad staging area using 1 operator, @ $39.85, 1 rigger @ $49.67, and truck mounted crane @ $77.80/hr. Production rate is 241.2 lb/hr.
Productivity Loss Factor	10.74	$ 89.52	10.74	$ 77.80	$	$ 1,797.01	1	Lump Sum	$ 1,797	2.41 hours of each 8-hour day for meetings, suit up, etc. (31% of work time).
Personal Protection Equipment					$ 46.33	$ 46.33	12	Person Days	$ 556	PPE costs $46.33 /day per person.
HPT Support	52.62	$ 56.00	0	$ 0	$ 0	$ 2,946.72	1	Each	$ 2,947	One HPT @ $56/hr
Demobilization (331.21)								**Subtotal**	**$ 3,975**	
Decontaminate and Survey Out	24	$ 81.20	24	$ 60.00	$ 52	$ 3,440.80	1	Each	$ 3,441	Two HPTs @ $56/hr and one D&D worker @ $33.60/hr and equipment standby. Includes waste disposal of one cubic foot of waste.
Transport Equipment	4	$ 73.45	4	$ 60.00	$ 533.80	$ 533.80	1	Each	$ 534	Similar to Mobilization..
								TOTAL	**$17,137**	

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