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ROBOTIC DISMANTLEMENT SYSTEMS AT THE CP-5 REACTOR D&D PROJECT

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ABSTRACT

The Chicago Pile 5 (CP-5) Research Reactor Facility is currently undergoing decontamination and decommissioning (D&D) at the Argonne National Laboratory (ANL) Illinois site. CP-5 was the principle nuclear reactor used to produce neutrons for scientific research at Argonne from 1954 to 1979. The CP-5 reactor was a heavy-water cooled and moderated, enriched uranium-fueled reactor with a graphite reflector. The CP-5 D&D project includes the disassembly, segmentation and removal of all the radioactive components, equipment and structures associated with the CP-5 facility. The Department of Energy's Robotics Technology Development Program and the Federal Energy Technology Center, Morgantown Office provided teleoperated, remote systems for use in the dismantlement of the CP-5 reactor assembly for tasks requiring remote dismantlement as part of the EM-50 Large-Scale Demonstration Program (LSDP).

The teleoperated systems provided were the Dual Arm Work Platform (DAWP), the Rosie Mobile Teleoperated Robot Work System (ROSIE), and a remotely-operated crane control system with installed swing-reduction control system. Another remotely operated apparatus, a Brokk BM250, was loaned to ANL by the Princeton Plasma Physics Laboratory (PPPL). This machine is not teleoperated and was not part of the LSDP, but deserves some mention in this discussion.

The DAWP is a robotic dismantlement system that includes a pair of Schilling Robotic Systems Titan III hydraulic manipulator arms mounted to a specially designed support platform, a hydraulic power unit (HPU) and a remote operator console. The DAWP is designed to be crane-suspended for remote positioning. ROSIE, developed by RedZone Robotics, Inc. is a mobile, electro-hydraulic, omni-directional platform with a heavy-duty telescoping boom mounted to the platform's deck. The work system includes the mobile platform (locomotor), a power distribution unit (PDU) and a remote operator console. ROSIE moves about the reactor building floor around the reactor assembly and, like the DAWP, is controlled from a console in the control room. The remotely-operated crane control system with installed swing-reduction control system was installed on the CP-5 polar crane and allows a load suspended from the crane to be remotely operated while reducing the induced swing in the load. The system includes a remote-controlled rotational hook, two remote-reading load cells and a lightweight portable operator controller. The last component in this discussion, the Brokk BM250, is a commercially-available electro-hydraulically operated demolition tool. A variety of attachments including a 750 lb. jackhammer, hydraulic shear or 1/3 cubic yard bucket can be quickly installed onto its articulated boom. This paper will primarily discuss the teleoperated robotics systems, DAWP and Rosie, their performance, tooling and lessons learned during the dismantlement of the CP-5 reactor structures. Other aspects of the robotics systems' deployment and use such as operator training and maintenance will be briefly discussed as they pertain to the overall performance of the robots.

I. INTRODUCTION

In the first quarter of FY97, the Department of Energy's Robotics Technology Development Program (RTDP) and the Federal Energy Technology Center (FETC) Morgantown Office provided teleoperated, remote systems for use in the dismantlement of the CP-5 reactor assembly for tasks requiring remote dismantlement. These systems included the Dual Arm Work Platform (DAWP), the Rosie Mobile Teleoperated Robot Work System (ROSIE), and a remotely-operated crane control system with installed swing-reduction control system. Use of the systems was integrated into the Large Scale Demonstration Project (LSDP) that was conducted at CP-5. These systems were used to dismantle various portions of the CP-5 reactor assembly including the vessel assembly and internals, a portion of the one of the large reactor shielding plugs, the innermost segments of twenty-four horizontal beam tubes and the surrounding graphite reflector assembly as part of the EM-40 sponsored D&D program.

The application and deployment of these systems at CP-5 were a collaborative effort by a consortium of national laboratories and industry manufacturers. Participants included ANL Technology Development (TD) division; Convolve, Inc.; Kraft TeleRobotics, Inc.; Idaho National Engineering and Environmental Laboratory (INEEL); Oak Ridge National Laboratory (ORNL); RedZone Robotics, Inc.; Sandia National Laboratory; Savannah River Technology Center; Schilling Robotic Systems, Inc.; and Whiting Crane Services, Inc. ANL was responsible for the overall facility operations and oversight associated with the D&D work and the use of the remote systems at CP-5. The RTDP provided the DAWP hardware and systems, the crane modifications, the operational and technical assistance for robotics deployment and the overall program coordination.

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FETC funded the fabrication of the ROSIE work system. Lastly, the loan of the Brokk machine is a continuing collaboration between PPPL and ANL.

II. CP-5 BACKGROUND

The CP-5 Research Reactor was the principle nuclear reactor used to produce neutrons for scientific research at Argonne from 1954 to 1979. The CP-5 reactor was a heavy-water cooled and moderated, enriched uranium-fueled reactor with a graphite reflector. CP-5 operated for 19 of its 25-year history at a thermal power rating of 5 megawatts and produced a maximum flux of 10^{14} neutrons per square centimeter per second. Over its operational life, the facility produced over 5.4 x 10^{8} thermal kilowatt hours of power and irradiated over 27,000 samples for research purposes.

In September 1979, the reactor was shut down for the final time and all the nuclear fuel and heavy water which could be drained from the process systems was shipped to the DOE Savannah River Site for reprocessing. The facility was placed into a lay-up condition pending funding for decontamination and decommissioning. In April 1990, work was initiated on a "partial" decontamination and decommissioning (SAFSTOR) of the facility in order to alleviate the safety and environmental concerns associated with the site due to the deterioration of building and its associated support systems. In 1992, the complete D&D of the facility commenced which includes the removal of the reactor assembly and all radioactive support facilities, systems and materials. In December 1996, the D&D robotics program started at CP-5 with the delivery of ROSIE and the DAWP.

The CP-5 reactor assembly is housed in a cylindrical containment building (or reactor "shell") that is 70 ft (21.3 m) in diameter and 50 ft (12.8 m) high. The reactor core was contained in a 6 ft (1.8 m) diameter by 10 ft (2.9 m) high aluminum tank. Fuel elements were installed in the center of the tank supported on a flow distribution plenum. The plenum served to distribute the incoming heavy water moderator/coolant through, into and around the fuel assemblies. The heavy water made a single pass through the core and the coolant discharge was transferred to a large heat exchanger where the heat was transferred to a light water cooling system.

The top 3 ft (1.0 m) section of the reactor tank, with its aluminum flange and carbon steel backing ring, was surrounded by 2 in. (5 cm) thick carbon steel annular shield ring. The ring weighed 2000 lbs. (909 kg) and was topped by a steel backing ring that was attached to the reactor tank flange by 36 studs. Below this, the reactor tank was surrounded by a 2-ft (0.61 m) graphite reflector on the sides and bottom. The graphite was very closely fitted together and steel pins were installed in areas where graphite expansion or movement could interfere with internal penetrations. The internal penetrations are comprised of twenty-four various diameter horizontal beam tubes that pass through the biological shield and thermal shield to the reactor tank. Some of the tubes stop outside of the reactor tank while others pass into or through the tank assembly. The beam tubes provided pathways for neutrons radiating from the core for experiments, reactor controls and instrumentation, or for passing materials through the neutron flux of the core. The tubes are constructed from aluminum with an internal liner and contained different components including instrumentation packages, collimators, moderators and external filters all requiring removal prior to segmentation. Outside of the graphite, a water-cooled thermal shield was constructed consisting of a steel tank on the outside of which was placed a 3.5 in. (8.9 cm) layer of lead blocks. In addition, an internal layer of boral sheeting was fastened to the inside of the steel tank. The blocks were closely fitted to the boral and the remaining gap was filled by poured lead. The biological shield surrounds the thermal shield and consists primarily of a steel plate and reinforcing bar framework with a poured layer of high density (290 lb/cu. ft. or 4646 kg/ cu. m.) concrete that is nominally 4 ft 8-1/2 in (1.4 m) thick. A series of inner and outer (annular) shield plug assemblies constructed of steel, high density concrete and lead placed on top of the reactor tank and graphite blocks provided radiation shielding on top of the reactor assembly.

At the end of FY98, the status of the CP-5 dismantlement was as follows. The experimental equipment around the reactor, the heavy water coolant system, reactor operating systems, and shield plug assemblies were removed. The aluminum reactor tank and internals were removed and packaged for disposal. The innermost portions of the thermal shield assembly including the graphite reflector and lead void filler have been removed and packaged. A boral (borated aluminum) liner attached to the steel thermal shield is approximately 80% removed.

As FY98 drew to a close however, the programmatic decision was made to discontinue the use of the teleoperated robotic systems at CP-5. The teleoperated systems, Rosie and the DAWP, are in the process of being decontaminated, disassembled and prepared for transport to other facilities. This decision was influenced by many considerations including funding, ALARA and the reduced cost versus benefit realized with the reduced radiation levels. The EM-50 funding through the LSDP was discontinued following the completion of the technology demonstrations. The most radioactive sections of the reactor assembly were removed (as radiation levels in the reactor cavity were reduced from a background level of 35 R/hr to less than 0.5 R/hr). And lastly, the cost versus benefit aspect of the robotics operations has considerably decreased as the radiation levels became more tolerable and alternate conventional, and possibly less expensive D&D methods could be employed at the facility.

III. DEPLOYMENT AND IMPLEMENTATION

A. Preparation. The DAWP and Rosie were delivered to ANL in November of 1996. At this point the delivery dates had slipped approximately three months due to technical delays that would be better fixed at the ORNL and RedZone facilities. The delays were required in order to fine-tune the equipment and work out some of the bugs in these new systems. This delay was not insurmountable, however, because the start of work on the reactor was scheduled to begin in March 1998 and the facility preparations were completed ahead of schedule. These preparations consisted of facility modifications including removal of obstructions to the robots on the reactor floor, installation of additional HEPA ventilation components, nonstructural modifications to the facility's walls to enhance containment and the installation of appropriate electrical receptacles and controllers to provide adequate power and controls to the robotic systems.

Of greater concern to the project staff was the lack of detailed operating procedures for the perspective operators, no industry-recognized standards on which to base the training, operating, safety and maintenance procedures, and the unknowns associated with training radiological workers with no previous robotics experience on largely unproven equipment. Adding to concerns was the fact that these systems were being deployed in real-world D&D conditions for the first time. Lastly, all of these variables were further aggravated by the fact that the project was operating on an aggressive schedule (even for proven conventional D&D methods), tight funding (providing less than optimum quantities of spare parts and vendor support availability), and the fact that some of the most technically demanding jobs requiring robotic performance were the first ones needed to be accomplished (using brand-new operators with untested systems).

Due to the aforementioned reasons, it became apparent that a lot of work needed to be performed in a short period of time without compromising personnel safety, little room for trial and error and careful coordination with the vendors and associated stakeholders. The collaboration between ANL and ORNL's robotics personnel was critical to this success.

ORNL provided an average of two personnel at the CP-5 facility for more than six months to setup equipment, assist in documentation review and to provide invaluable feedback as the operators were trained, end-effectors (tools) were designed and fabricated and the systems were deployed on, around and inside of the reactor assembly. ANL developed the lesson plans to qualify robotic system operators in a DOE nuclear facility, created standards and administrative procedures to provide safe personnel access to the robots' operating envelopes without the need for installing cumbersome and costly interlocks and barrier protection. And lastly, ANL personnel re-wrote and/or edited the vendors' basic operating and maintenance procedures so non-robot-experienced personnel could use them on a daily basis.

B. Installation. Installation of the two primary robotics systems, Rosie and the DAWP went smoothly. Rosie was transferred into the facility, setup and made operational in three and one-half days. Operator orientation and training began the next working day. Except for a minor hydraulic reservoir leak on Rosie, the system setup was completed without any equipment or software failures at the facility. The DAWP installation time was longer requiring approximately 20 working days. This was due to the need for installing components onto the platform that were not previously mounted, tool modifications in the field and the time-consuming need to setup, program and test the complex operating and control system designed into the DAWP. A future setup of the DAWP would not be expected to take more than five to six days.

C. Procedure Preparation and Training. Due to the project's time and scheduling constraints, the preparation of operating procedures, safety plans and training plans had to take place in parallel with the setup and training of the operators. Because of this, the first trainees were engineering staff. This was a great risk because if it was found that the engineer was unsuitable to learn or operate the various systems, the training and deployment schedules would be severely impacted in a negative way. Fortunately, this did not occur and the fledgling orientation, training and qualification program was born. Drawing on the diverse experience of the CP-5 staff and ORNL support personnel, the preparation of the documentation was completed three weeks ahead of the originally planned schedule and its success was validated by the future successes of the program without the need for extensive revisions to any of the governing procedures or protocols.

Operator training however was not as smooth. This topic alone would require two days to adequately address. Due to the time constraints of this presentation, we will discuss only the highlights and a very brief mention of the major lessons learned. Training on Rosie and the DAWP yielded some interesting statistics. The overall failure rate for Rosie trainees was 40%. The overall failure rate for the DAWP was 30%. In other words over 33% of the average personnel at a D&D project will not be able to be basically trained on a given robotics type system. Next, out of the eventually qualified personnel, less than 30% became proficient operators in normal daily operations.

Of the successful trainees, the average training time needed to basically learn the system and prove that they meet a minimal standard to continue with more advanced training was significant. For Rosie, the average qualification completion time was approximately 6 hours of reading and classroom instruction and 16 hours of run-time on the machine. For the DAWP, the average qualification completion time was approximately 2 hours of reading and classroom instruction and 6 hours of run-time on the machine. Note, that this training only provided an indicator to project management that the trainee has the aptitude and motor skills to allow basic responsibilities as an operator and that they may be suitable for more training and tasks. This does not indicate that the operator will be proficient in operating all of the various end-effectors, can safely, efficiently and reliably operate the system in the long-run or has the stamina, responsibility or motivation to operate the systems on a daily basis. In our experience, this determination took an average of 2 more months to accomplish after the initial training phase and only 10-15% of the originally available candidates became truly proficient and reliable operators for most of the tasks assigned for their performance.

In addition, it took an average of three days per operator per tool to become proficient and reliable in the use of the end-effectors designed and used at CP-5. There were eight primary end-effectors utilized by the DAWP during the remote dismantlement of the reactor assembly and ranged in sophistication from modified crowbars to oil cooled and lubricated worm-drive circular saws. The time needed to qualify the minimum, requisite number of operators was approximately 4 months for Rosie and for the DAWP it was approximately 8 weeks. Even though the operator attrition rate was higher than expected and the resultant training duration for Rosie was increased, the training phase of the deployment was completed less than one month late and, by adding mockup training to the curriculum, made up nearly six weeks on the overall project schedule.

D. Deployment. After the systems were operationally checked, end-effectors were built and tested, operators trained and the other countless preparations completed, the robots were ready to put to the test. The actual deployment of the systems on the reactor was almost anti-climactic. This was a direct result of the stringent training, safety and maintenance practices established in the earlier phases of the program. The DAWP performed two of its most delicate and precise tasks in its first two weeks on the reactor. These tasks were the removal, size reduction and packaging of the reactor regulating rod and the dismantlement, cutting and packaging of the J-tube assembly. These two tasks were successfully completed two weeks ahead of the baseline schedule and reduced the overall project delay to a manageable two weeks. This just gives a flavor of what diverse considerations have to be made when preparing to deploy robotics system in a D&D environment.

IV. DISMANTLEMENT OPERATIONS

During the 74 weeks of robotic operations, many diverse, difficult, tasks were successfully accomplished. Also, there were some disappointments as well. Obviously, a detailed look at all of these accomplishments cannot be addressed in this paper. Instead, I will summarize some of the statistics gleaned from our experience.

At the cessation of robotics operations at CP-5, the total number of operating hours and quantity of material removed from the bio-shield were substantial. A total of 1565.3 hours of remote operations took place at CP-5. Of this time, the DAWP was operated for 1035.0 hours (909.3 hrs. performing D&D tasks), Rosie was operated for 492.5 hours (276.1 hrs. performing D&D tasks), and the Brokk was operated for 37.8 hours (25.8 hrs. performing D&D tasks). This yielded an absolute operating efficiency for the DAWP of 34.97%[1]. A more representative operating efficiency for the DAWP is actually closer to 55%.

During D&D activities which included tasks ranging from the DAWP performing precision disassembly of reactor components (e.g., removing 3/8" capscrews from a piping flange), transfer of over 70,000 lbs of radioactive materials removed from the reactor using Rosie and the remote-controlled polar crane, to the Brokk's harsh demolition work (removal of over 20,000 lbs. of high density concrete from a reactor shield plug assembly), work was able to proceed continuously in rad areas averaging 10 R/hr with ambient work area temperatures as high as 95°F. In fact, most of the down time attributable to equipment was due to end-effector replacements or blade changeouts not failures on the robot systems themselves.

Operators using the DAWP dismantled, size-reduced and packaged the entire reactor tank weighing 1,700 lbs. A total of twenty- four beam tubes constructed of aluminum with differing internal materials were disassembled, size reduced and packaged with a total weight of over 2,000 lbs. The entire graphite reflector assembly, weighing approximately 60,000 lbs., that surrounded the reactor tank with a nominal depth of 24" was disassembled block by block. Approximately 2,000 individual 4" x 4" x varying length blocks with an average weight of 30 lbs. each were handled. Additional materials removed included lead sheeting and void filler weighing over 3,300 lbs. and borated aluminum plates (boral) weighing 1,500 lbs. Lastly, a 2000 lb. carbon steel annular shield ring and backing ring was removed.

Rosie operators transferred nearly 35,000 lbs. of radioactive materials from the reactor cavity that was removed or segmented using the DAWP. Rosie also removed approximately 2000 lbs. of high density concrete from a reactor plug assembly using its demolition hammer and removed approximately 500 lbs. of graphite blocks from

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[1] This figure is very conservative and all encompassing. It is based on the total number hours the unit was operating vs. the total number of hours available. The downtime includes component failure, preventive or corrective maintenance, and other equipment-related failures and it also includes non-robot associated losses such as personnel breaks (e.g., lunch, training briefings, shift turnovers, etc.), external down-time causes (i.e., unavailability of operator, crane support, etc.) and the breakage of tooling, end-effectors or support equipment.

one of the reactor's experimental beam ports.

The remote controlled polar crane transferred the other approximately 35,000 lbs. of material removed by the DAWP. Lastly, the Brokk excavated over 18,000 lbs. of high density concrete from a reactor shield plug assembly.

In all over 89,000 lbs. of radioactive materials were removed or dismantled, size reduced, transported and packaged using the various robotic systems at CP-5. The time-weighted average background radiation level in the reactor cavity during this work was 10.0 R/hr. Actual robotics system operating, support and maintenance personnel exposure was less than 0.5 person-rem. This yielded a personnel exposure savings of approximately 100 person-rem over the operating history of the robots. This work was accomplished without a near-miss, an OSHA lost-time accident or any other personnel safety incidents.

Many interesting discoveries, techniques and experiences arose during the operation of robots at CP-5. Also, some very important lessons learned and these are discussed later in this paper. At this time, some insights may be gained by dispelling some popular robotic myths.

MYTH: Robots can eliminate the use of personnel.

FACT: Operating personnel are essential to the success of a robot-performed activity and because of the unique nature of most D&D tasks, an autonomous system (eliminating personnel) would be very costly and possibly ineffectual especially for smaller scale D&D programs.

MYTH: Robots will greatly increase the productivity of personnel by allowing them to work 24-hour shifts, 7 days per week.

FACT: Robots have increased the amount of time that personnel can perform D&D tasks. This is accomplished by relieving personnel of heat stress and radiological stay time limitations. However, operators will require periodic breaks and operator fatigue and burnout must be considered for extended robot operations.

MYTH: Robots are too slow and cannot perform D&D operations as quickly as hands-on personnel.

FACT: The experience at CP-5 is that robotic D&D operations are almost equally efficient as the conventional D&D methods. Robots do not move as quickly as a human for most work and down-time can be significant. However, robots don't need to worry about heat stress, most radiation or contamination levels and do not get tired. Therefore productivity rates were nearly equal for most tasks. In many cases, a manipulator arm was the only method that could be used to remove materials.

MYTH: Robots are too costly to even be considered for most smaller D&D operations.

FACT: Yes, robots are expensive. However, in situations where the work environment is so harsh or radioactive as to preclude personnel access, the use of robots may enable work to be accomplished that otherwise may not be done or would require equally expensive alternate methods. Also, if multiple projects are to be performed sequentially, much like the cost of other pieces of equipment, the cost of these systems and personnel training may be amortized over a longer time period making the use of robots more cost effective.

V. COST CONSIDERATIONS

Was the use of robotics systems at CP-5 cost-effective? This is a very difficult question to answer and perhaps not one to be addressed here. At CP-5, because of the demonstration program, there was no capital costs for the acquisition of the robotics systems. The only costs impacting the project's budget was spare parts, maintenance costs and the as yet indeterminate cost associated with the possible inefficiency of robotic D&D vs. conventional D&D methods.

Replication costs of the DAWP would be approximately $1.2M and for Rosie approximately $1.4M. However, to put it in perspective, a simplified teleoperated robot setup (for example, one Schilling Titan III arm mounted to a fixed pedestal with a Hydraulic Power Unit, 250 ft. of hoses and control cabling and a minimal complement of cameras and monitors) could be obtained for less than $200K. Over the 74 weeks that the DAWP was operated, total replacement parts cost on the Schilling arms was approximately $20,000. The cost of end-effectors, peripheral tooling, cameras, and parts has not yet been fully determined, but is expected to have been less than $25,000. Since every D&D project is different and each facility has differing equipment needs, it is up to the user to determine the cost vs. benefit factor for robotics use and that is well beyond the scope or allotted time of this paper. However, many of the experiences gained and lessons learned at CP-5 can and should be applied to similar programs complex-wide.

V. BRIEF LESSONS LEARNED / SUMMARY

A fitting conclusion to this discussion would be concise listing of lessons learned during the use of robotics system at the CP-5 D&D Project:

- Regardless of the various requirements and regulations, the very nature and complexity of robotics systems demands the adequate training of operating personnel.

- Expect a nominal personnel training attrition/failure rate of 50%!

- A considerable expenditure of time will be required to train operators.
- Train at least 50% MORE operators than your best estimate of minimum manning requirements.
- DO NOT assume that a person with a good mechanical aptitude, a large amount of experience or otherwise decent technical competency will automatically yield a proficient operator.
- In many instances, a longer amount of non-robotic work experience yields a <u>less</u> successful operator trainee.
- There are many indicators that can be used to help determine whether or not a particular individual is trainable.
- You will need to expend approximately 4 to 10 times more training time to transition from a person who can "operate a robot" to a proficient and dependable operator.
- Operator skills will diminish rapidly if they are not utilized on a routine basis.
- Robotics systems are a major investment and must be treated as one.
- Setup time, training and system complexity may be considerable.
- Ultimately, the benefits of the system must be weighed against the costs.
- Robots will save significant amounts of personnel exposure.
- There is a steep learning curve during the initial deployment of robotic systems.
- Operating efficiencies increase with time.
- Robot efficiency in harsh conditions is basically equal to human efficiency.
- Worker fatigue is nearly eliminated and may allow for longer shift duration (within reason) without compromising personnel safety.
- Teleoperated robots <u>nearly</u> eliminate need for shielding, ventilation and other rad controls.
- Proper maintenance is essential and must be planned and budgeted for accordingly.
- Long-term robotic operations <u>must</u> have an ample supply of proficient operators, spare parts and very competent maintenance support.
- With proper consideration, robotic tooling can be inexpensive, off-the-shelf equipment vs. costly custom designed offerings in the past.
- Prior work experience does not automatically translate into a proficient robotics operator.
- Robots can <u>and will</u> break and do the same unto others, BE CAREFUL.